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Looking Upstream: An Analysis of Low Water Levels in Lake Powell and the Impacts on Water Supply, Hydropower, Recreation, and the Environment: A Companion Report to The Bathtub Ring

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Looking Upstream: Analysis of Low Water Levels in Lake Powell and the Impacts on Water Supply, Hydropower, Recreation, and the Environment

A Companion Report to

The Bathtub Ring: Implications of Low Water Levels in Lake Mead on Water Supply, Hydropower, Recreation, and the Environment

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Disclaimer

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Project Significance

The Colorado River, an icon of the American West, is one of the most significant and important natural resources to the region. The river originates in the Rocky Mountains, cascading down 14,000 feet before traversing 1,450 miles through the Southwest and Mexico, towards the Gulf of California (CWA 2015). It is the largest body of surface water in each of the seven states it passes through (Getches 1997) and drains a 246,000 square mile basin, roughly the size of France (EDF 2015). As shown in Figure 1 below, the Colorado River Basin encompasses parts of seven US states and two Mexican states.

Figure 1. Colorado River Basin Map (USBR 2015a).

Through the course of its journey, the Colorado River provides water to approximately 40 million people and irrigates nearly 4.5 million acres of farmland. It sustains 22 federally recognized tribes, passes through seven national wildlife refuges, four national recreation areas, and eleven national parks, providing the setting for a recreational economy crucial to the region. Hydroelectric dams on the River have the capacity to produce more than 4,200 megawatts of electricity (USBR 2015a), enough to power between three and four million average U.S. homes (Harrison 2008) if the dams were producing at full capacity. Reservoirs in both the Upper and Lower Basins provide a total storage capacity of 60 million acre feet (MAF) (USBR 2012a). Approximately 29 MAF (USBR 2012b) can be stored in Lake Mead above Hoover Dam and just over 26 MAF above Glen Canyon Dam in Lake Powell (USBR 2014a), making these two reservoirs the largest in the nation.

The Colorado River relies heavily on snowmelt from the Rocky Mountains. Warm season precipitation provides only limited water to the system at the time of year when it is in highest demand. The annual volume of flow can be seen in Figure 2 below. Current flows are a fraction of their original volume and little water is left to reach the river's traditional outflow in the Gulf of California (NRC 2007).

Lake Mead and Lake Powell have not been full for quite some time. In 2000, Lake Mead was 90 percent full, but now only holds 40 percent of its total capacity. Similarly, Lake Powell currently only fills 45 percent of its available storage (USBR 2016a). The declining reservoir levels highlight the uncertainty of whether the Colorado River will continue to meet future needs.

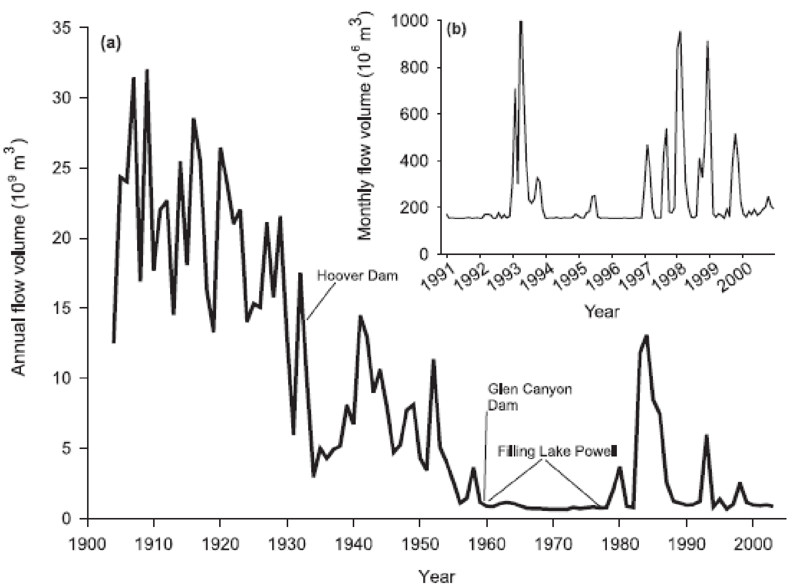


Figure 2. Annual flow volume over time below Yuma Main Canal at Yuma, Arizona, (station 09521100), for years 1904–2003 (Melis et al. 2008).

Exacerbating these challenges are the immense demands placed on the river by human use. One of the most regulated rivers in the world, the Colorado River Basin is over-allocated (Christensen et al. 2004). Currently, the amount of water distributed among users throughout the basin exceeds the average long-term historical natural flow of the river. These pressures are expected to increase as population projections indicate continued growth in the region (USCB 2010). As major cities in the Colorado River Basin grow, the agricultural and municipal water demands are also projected to increase, threatening the water available for nonconsumptive uses such as recreation, environmental protection, and hydropower generation (USBR 2015a). The problem is compounded by anticipated climate change impacts. Studies show that the Southwest could witness extended and drastic dry (and wet) conditions that have implications for the hydrologic cycle driving Colorado River supplies (Garfin et al. 2014). Water sustainability challenges characterized by high demand and low supply will likely last into the future.

The extent of these imbalances were highlighted by an analysis published in 2012 by the United States Bureau of Reclamation (USBR) entitled *The Colorado River Basin Water Supply and Demand Study* (*The Basin Study)* (USBR 2012a). *The Basin Study* reported that between 1999 and 2007, Colorado River reservoirs fell from 55.8 MAF to 29.7 MAF (USBR 2012a). Shortages in the Basin stem from a deficit where overall demand of the Colorado River outweighs water supply. *The Basin Study* also describes the range of supply and demand imbalances projected for the future. Estimates of the imbalance between demand and supply vary from 0 to 6.8 MAF, with a median projection of unmet demand being 3.2 MAF in 2060 (Figure 3) (USBR 2012a). This comprehensive analysis has provided significant momentum for basin-wide planning efforts.

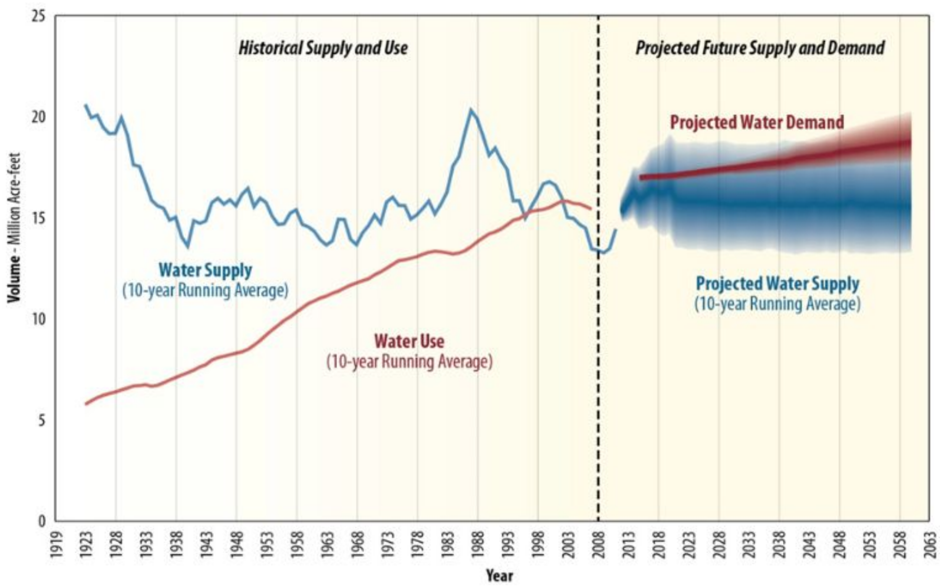


Figure 3. Historical and future projections of supply and use in the Colorado River Basin (USBR 2012a).

Even with the significant amount of study focused on the Colorado River, the need for transparent and integrated cross-sector information about the impacts of shortages remains. While it is difficult to predict exactly what would happen if the river reaches critically low levels, it is important to consider what this might look like in order to better prepare for the future. Toward this effort, a report was published in 2015 entitled *The Bathtub Ring: Implications of Low Water Levels in Lake Mead on Water Supply, Hydropower, Recreation and the Environment* (*The Bathtub Ring)* (Jiang et al. 2015). This analysis was confined to the Lower Basin, and therefore tailored to the specific policies and geographic considerations that impact water delivery, recreation, and hydropower associated with Lake Mead and Hoover Dam.

A companion study to *The Bathtub Ring* report is needed to understand the implications of chronic shortages in Lake Powell and to comprehensively consider impacts across the entire Colorado River Basin. *Looking Upstream* similarly considers impacts associated with drought, while taking into account the inherent differences between the Upper and Lower Basins. Although management and operation of these reservoirs are coordinated, their functions and physical locations differ, and therefore each region of the basin is impacted differently during times of shortage.

A significant difference between Lake Mead and Lake Powell is the location of each within their respective basins. Situated at the top of the Lower Basin system, shortages and releases at Lake Mead directly impact users below Hoover Dam. Lake Powell, however, is a downstream collection point of Colorado River water that has fully traversed and served the Upper Basin before arriving at Glen Canyon Dam. In addition to hydroelectric power generation, Glen Canyon Dam exists largely to store and systematically release water to Mead, and ensure the Upper Basin meets its *1922 Colorado River Compact* obligations to release 75 MAF of water to the Lower Basin over the course of any ten-year period.

Should storage in Powell be insufficient to meet this obligation (pursuant to the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead*), the body of laws dictating management provides some certainty as to how curtailments would be implemented among the Upper Basin states. Such curtailments would be legally complicated and difficult to enact, and thus, decision-makers have focused their efforts on avoidance strategies to prevent the need for curtailments altogether.

To this end, many collaborative efforts are underway. The Upper Colorado River Commission and the four Upper Basin states are jointly active in creating contingency plans to keep Lake Powell from dropping below the level necessary to produce hydropower. The contingency plans, currently in draft phase, include efforts to move water from upstream reservoirs in the Upper Basin to sustain levels at Lake Powell, augment the hydrologic system such as through cloud seeding and the removal of highly water consumptive vegetation, and employ demand management strategies focusing on storing "saved" water in Lake Powell (Colorado River District n.d.). While action is underway to help prevent Lake Powell from dropping below minimum power pool, there is a lack of understanding regarding what these impacts would actually entail.

The goal of this report is to provide clear and integrated cross-sector information on potential impacts to Lake Powell if the reservoir is to be operated at low water levels. It is our hope that a better understanding of these impacts will strengthen current efforts and trigger fruitful dialogue between decision-makers who are crafting solutions to basin-wide imbalances and drought contingencies. Specifically, this report synthesizes existing information on the impacts of declining reservoir levels in Lake Powell and conducts additional analyses of data where possible to better understand potential impacts.

Project Objectives

Similar to *The Bathtub Ring*, this report focuses on four primary areas likely to be impacted by declining reservoir levels: water supply, hydropower, the environment, and recreation. Where appropriate we chose to mimic the analyses completed for Lake Mead in the first report. We also considered important differences between the Upper and Lower Basins to inform a modified approach. Similarly, we tailored scope and methods that were relevant to each individual section of this report. We found that the availability of information and data differed across subject areas and therefore some sections of this report are entirely qualitative while others incorporate quantitative analyses.

Below are brief summaries and objectives of the individual sections that follow. Specific background, methods, and results can be found within each individual section.

Water Supply

To fully understand the impacts of operating Lake Powell at low levels, we must assess how doing so may affect the Upper Basin. Declining water supplies at Lake Powell impact water users upstream in the Upper Basin due to delivery obligations to the Lower Basin. The main objective of the *Water Supply* section is to describe the factors contributing to the Upper Basin's vulnerability to water shortages. We begin by providing an overview of the hydrologic factors affecting water availability in the region. Next, we assess Upper Basin water use by exploring historical trends of water demand. State profiles are used to review recent water demand by sector in each state to highlight state specific concerns. Future water demand forecasts for the Upper Basin are also summarized to understand how water use may change over time. Lastly, we analyze legal factors to provide context for ambiguities and management uncertainty should reservoir levels drop low enough to require Upper Basin curtailments to meet downstream obligations. Literature review and expert consultations were used to address these areas of inquiry.

Hydropower

Changes in reservoir elevations at Lake Powell could impact the ability of Glen Canyon Dam to produce electricity (USBR 2007c). Our analysis focuses on the potential economic consequences of such impacts. Specifically, we consider how the cost of power purchased by utilities in the region might change. Dams along the Colorado River are operated and power is marketed according to variety of federal regulations. Some of these regulations are consistent across the basin, but many vary. Our first objective is to determine how Glen Canyon Dam power is marketed. This is an essential component of determining how customers could be impacted if power generation decreases. For our analysis, we relied heavily on publicly available agency information and personal communications. Personnel at the Western Area Power Administration who are directly responsible for coordinating the sale of power generated at Glen Canyon Dam and other regional dams were instrumental in explaining in detail how power from Glen Canyon is marketed.

Our second objective is to predict the range of potential cost increases if certain key elevations are reached in the reservoir. We develop a model using information from the USBR on the power generation capacity of Glen Canyon Dam and information on the cost of power. Detailed descriptions of the final model, calculations, data sources, results, and limitations are included in the section.

Recreation

Lake Powell is a popular hub for diverse land and water-based activities in the Glen Canyon National Recreation Area. Because recreation is closely tied to enjoyment of the water and the use of shoreline infrastructure, drought and declining lake levels may impact future visitation and the regional economies that depend on it. Our report assesses potential impacts of declining lake levels on recreational activity through a statistical analysis of the relationship between Lake Powell visitation and lake elevation, using a model designed by Neher et al. in a 2013 study. We also assess the absolute minimum elevation thresholds of different public access points, such as boat ramps and the Castle Rock Cut, relative to key lake elevations.

Environment

Stewardship of environmental resources relies on the ability of managers to manage people and their interactions with the natural world. The construction of Glen Canyon Dam, and the development of the entire Colorado River Storage Project, has impacted the health of the environment compared to pre-dam conditions. Managers who create and enforce programs and policies are tasked with reconciling the multiple and sometimes competing demands of diverse stakeholder groups. Understanding the ecological impact of those management decisions is the focus of this section. By analyzing the impact on native species as well as the challenges of dealing with sediment and salinity, we begin to see the compounding environmental issues that developed as a result of dam construction. We also assess how a more uncertain water supply future and lower reservoir levels may complicate the efforts of managers to adequately address these issues.

Background Information

Upper Colorado River Basin Governance

The Colorado River Basin, in addition to water laws dictated by individual states, is managed in accordance with the Law of the River. The Law of the River includes interstate compacts, congressional acts, binational treaties, court decisions and contracts affecting how the Colorado River is allocated and operated (Adler 2008). This section introduces the prior appropriation doctrine governing the allocation of water throughout most of the western United States, the components of the Law of the River most important to the governance of the Upper Colorado River Basin, and the history of coordinated operations of Lakes Powell and Mead through the *Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs* and the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead*.

The Upper Basin states regulate the allocation and use of their waters through a legal framework known as the prior appropriation doctrine. This legal system is characterized by priority; during times of shortage, senior water rights holders receive their full allocation before junior holders. Seniority is established based on the date each water user diverts and uses the resource. Each user that diverted water after the first historical appropriation becomes junior to that user. Additionally, water rights holders must put their water to "beneficial use," or else lose their rights to access. Beneficial use refers to a list of specified uses that the law has dictated as appropriate, and may be defined differently by each state. Together, prior appropriation, beneficial use, and "use it or lose it" policies create certainty around who receives water during times of drought while preventing water users from hoarding unused water so that water is available to as many water rights holders as possible (Wilkinson 1989). Generally speaking, senior water rights holders in the American West are apportioned to agricultural uses, reflecting the agricultural livelihoods of homesteaders in the 1800's. Referred to as present perfected water rights, these water rights were obtained before the signing of the *1922 Colorado River Compact* and have been given highest priority. Today the prior appropriation system ensures that many of the more recent urban users in the Upper Basin are junior to agricultural users, effectively increasing their legal vulnerability to water shortages.

The first major Law of the River component is the *1922 Colorado River Compact* (US Congress 67). The *Compact* divided the Colorado River region into an Upper Basin and a Lower Basin with Lee's Ferry, Arizona as the point of division (Figure 1).[1] Article III(a) allocates 7.5 MAF per year of consumptive use to each basin while Article III(b) allows the Lower Basin to increase its consumptive use by an additional one MAF/YR as supplies allow. The *1922 Compact* also left room for a later allocation defined in the *Mexican Water Treaty of 1944* calling for the delivery of 1.5 MAF to Mexico. Moreover, Article III(d) requires a minimum flow volume at Lee's Ferry of 75 MAF for any period of 10 consecutive years. Altogether, the total amount of Colorado River water allocated on paper is between 16.5 and 17.5 MAF (in periods of surplus). The initial total annual flow designation used for the basis of these allocations, however, relied on hydrologic data compiled during the 10 wettest of the past 100 years (NRC 2007). The Colorado River

[1] An important distinction must be made between the legal phrases of "States of the Upper Division" and the "Upper Basin". The "States of the Upper Division" include Wyoming, Colorado, Utah, and New Mexico, whereas the "Upper Basin" also includes a small portion of Arizona that technically receives Colorado River water above Lee's Ferry. For the purposes of this report, when we use the term Upper Basin we are referring to the states of Wyoming, Colorado, New Mexico, and Utah (in essence, the "States of the Upper Division" definition) unless otherwise noted.

Basin's average flow is actually significantly less at approximately 15 MAF (NRC 2007), resulting in a potential allocation shortfall between 1.5 and 2.5 MAF.

Three additional agreements are especially important to understanding the management of Colorado River water in the Upper Basin:

- The *Upper Colorado River Basin Compact of 1948* outlines each state's percent allocation of the Upper Basin's full 7.5 MAF apportionment and created the Upper Colorado River Commission as the administrative agency to manage the interstate apportionment in the Upper Basin (US Congress 80). The *Upper Colorado River Basin Compact of 1948* also provides some certainty as to how a compact call would be implemented among the Upper Basin states. Any Upper Basin state that used more water than they are entitled under the *1922 Compact* and *Upper Basin Compact* must deliver that amount to Lee's Ferry before any other Upper Basin state is curtailed. If no Upper Basin state has exceeded their compact apportionment, then Upper Basin states either face curtailments proportional to their consumptive uses in the prior year, or curtailments mirror the apportionment percentages outlined in the *Upper Basin Compact*. Which theory applies remains a contested issue. Specific curtailments in each individual Upper Basin state is in accordance to that state's water law (Kenney et al. 2011).

- The *Colorado River Storage Project Act of 1956* allows the Secretary of the Interior to construct and manage water storage projects and hydropower facilities in the Upper Basin. Specifically, four major storage dams on the upper Colorado River and its tributaries were authorized: (1) Glen Canyon on the main stem of the Colorado River on the border between Arizona and Utah; (2) Flaming Gorge on the Green River on the border between Utah and Wyoming; (3) Navajo on the San Juan River in New Mexico, and (4) the Wayne N. Aspinall Unit, which consists of three dams and reservoirs, Blue Mesa, Morrow Point and Crystal, on the Gunnison River in Colorado. Prior to this act, the Upper Basin was unable to secure funding for water storage projects, limiting Upper Basin states' ability to develop their full 7.5 MAF apportionment. These storage projects hold surplus water captured during wet winters for use in dry years when supplies are low. Most notably, Glen Canyon Dam was authorized "as an insurance measure to make sure the Upper Basin could meet their delivery obligation to the Lower Basin" (Hecox et al. 2012).

- The *Colorado River Basin Project Act of 1968* authorizes further development of water storage projects in both the Upper and Lower Basins. For the purposes of this report, it is important to note that this act required the Secretary of the Interior to work with basin states to create the first ever long-range operating criteria for reservoirs in the Colorado River system (US Congress 90).

These primary agreements, and other provisions outlined in the Law of the River, dictate USBR's operation of the Colorado River system's major reservoirs and diversions. In each state, water deliveries are managed by the state engineer who administers the appropriation of that state's water resources. As of today, there is no coordination among the Upper Basin states as to the amount of water sent to Lake Powell to meet water delivery obligations to the Lower Basin (Kuhn 2016).[2]

[2] The CRSP reservoirs upstream of Lake Powell operate pursuant to their Records of Decisions and Flow Recommendations in order to promote recovery of endangered fish species. This will be discussed more depth in a later section.

Long-Range Operating Criteria

The *Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs* (*LROC*), pursuant to the *Colorado River Basin Project Act of 1968*, was first prepared and adopted in 1970. The *LROC* allows for an annual release rate no less than 8.23 MAF of water from Lake Powell to Lake Mead in order to maintain equal levels between the two reservoirs. If water levels in the Upper Basin storage units drop low enough that a release of 8.23 MAF to Lake Mead would compromise annual consumptive uses in the Upper Basin, releases promulgated in the *LROC* will not be made (Secretary of the Interior 1970).

The *LROC* requires the Secretary of the Interior, in consultation with governor-designated representatives of the seven basin states, to review at least every five years the efficacy of current operating guidelines and make appropriate changes necessary to achieve storage project goals. Additionally, every January the Secretary of the Interior is required to present a report, called the *Annual Operating Plan* (*AOP*), to Congress and the Governors of the seven basin states detailing the current hydrologic conditions of the Colorado River Basin, the releases made from reservoirs over the past operating year, and the projected operations for the forthcoming year. *AOPs* detail a range of potential operations and issue recommendations for three different categories of projected hydrologic conditions: (1) most probable, (2) probable maximum, and (3) probable minimum (Secretary of the Interior, 1970).

Due to some of the largest inflows on record, Lake Powell and Lake Mead remained nearly full during the period of time after the adoption of *LROC* and throughout the 1990's. *LROC* protocols for coordinated operation of Lakes Powell and Mead proved sufficient during this time of plenty. Although it continued to increase, the water demand throughout the Colorado River Basin remained below the amount apportioned by the *1922 Compact*. Shifting hydrologic conditions and even higher demands in the late 1990s, however, rendered the *LROC* framework inadequate and additional strategies became necessary to coordinate operations between Powell and Mead. One of these strategies, the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* is of particular importance to this report as it dictates improved coordinated management of reservoirs in the Colorado River system as reservoir levels continue to decline (USBR 2007b).

Colorado River Interim Guidelines for Lower Basin Shortages

Increasing demand, multiple years of drought, and dwindling reservoir supplies prompted the Secretary of the Interior in May 2005 to call upon the USBR to construct a coordinated management plan of Colorado River Basin reservoirs during times of low reservoir conditions. In response, the USBR launched a public process to develop and adopt the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* (*Interim Guidelines*). The *Interim Guidelines* identify coordinated operations of Lakes Powell and Mead, criteria for shortage and surplus declarations, and rules allowing water users in the Lower Basin to develop and store conserved water in Lake Mead. The *Interim Guidelines* seek to ensure equity in times of surplus, shared burden during times of shortage, and certainty for Colorado River Basin managers and users by explaining when, and by how much, water releases from reservoirs will be reduced to compensate for low water levels. The *Interim Guidelines* are set to expire at the end of December 2025 and a revised operating plan will be proposed for adoption in January 2026. If a new plan is not adopted, operations will revert back to the *Final Environmental Impact Statement for the Interim Surplus Guidelines*, which were effective beginning in December 2000 (USBR 2007b).

The first key management guideline promulgated in the *Interim Guidelines* contains thresholds for shortage, normal, and surplus conditions at Lake Mead.[3] The second key management guideline is the coordinated operation of Lakes Powell and Mead. The main goals of coordinated operation are to:

1. avoid Upper Basin curtailments,
2. avoid Lower Basin shortage, and
3. ensure both basins share the burden during drought years and the benefits during times of surplus.

The *Interim Guidelines* detail equalization elevations and corresponding operational tiers that dictate the annual release for the upcoming water year from Glen Canyon Dam to Lake Mead (Figure 4). Each month, the USBR releases operational 24-Month Studies that forecast the amount of water expected to be stored in the reservoirs for the following water year based on projected inflows. The 24-Month Study released every August is of special importance because it projects reservoir storage levels for January 1 for the following water year (the accounting for the water year is October 1-September 30). This projection dictates the relevant operational tier and the consequent release guidelines to ensure that Lake Powell and Lake Mead reservoir levels are equal (Figure 4). Each month the USBR alters releases from Glen Canyon Dam that are representative of that month's projected reservoir inflow. The goal is for Lakes Powell and Mead to be equal at the end of each water year.

[3] The Lake Mead Drought Thresholds are out of the scope of this analysis, but are detailed in *The Bathtub Ring: Implications of Low Water Levels in Lake Mead on Water Supply, Hydropower, Recreation and the Environment* (Jiang et al. 2015).

Lake Powell Operational Tiers (subject to April adjustments or mid-year review modifications)		
Lake Powell Elevation (feet)	**Lake Powell Operational Tier**	**Lake Powell Active Storage** (maf)
3,700		**24.32**
	Equalization Tier equalize, avoid spills or release 8.23 maf	
3,636 – 3,666 (see table below)		**15.54 – 19.29** (2008 – 2026)
	Upper Elevation Balancing Tier release 8.23 maf; if Lake Mead < 1,075 feet, balance contents with a min/max release of 7.0 and 9.0 maf	
3,575		**9.52**
	Mid-Elevation Release Tier release 7.48 maf; if Lake Mead < 1,025 feet, release 8.23 maf	
3,525		**5.93**
	Lower Elevation Balancing Tier balance contents with a min/max release of 7.0 and 9.5 maf	
3,370		**0**

Figure 4. Lake Powell Operational Tiers in the *Interim Guidelines* that establish the Glen Canyon Dam water releases necessary to achieve coordinated management of Lakes Powell and Mead (USBR 2007b).

Table 1 represents the target water elevation for each water year that will create equalization between Powell and Mead. These target elevations are used to determine the operating tier for Lake Mead during the upcoming water year. The levels increase each year to allow for additional storage at Lake Powell for Upper Basin use and development (USBR 2007b). Releases promulgated under the *Interim Guidelines* must also adhere to the requirements dictated in the *Colorado River Basin Project Act*, the *Glen Canyon Dam Final Environmental Impact Statement* and the *Glen Canyon Operating Criteria* (USBR 2007b). The current operating tier (water year 2016) at Lake Powell is the Upper Elevation Tier, which calls for an initial release volume of 8.23 MAF (USBR 2016a).

Table 1. Lake Powell's yearly upper level targets promulgated in the *Interim Guidelines* (USBR 2007b).

Lake Powell Equalization Elevation Table	
Water Year	**Elevation** (feet)
2008	3,636
2009	3,639
2010	3,642
2011	3,643
2012	3,645
2013	3,646
2014	3,648
2015	3,649
2016	3,651
2017	3,652
2018	3,654
2019	3,655
2020	3,657
2021	3,659
2022	3,660
2023	3,662
2024	3,663
2025	3,664
2026	3,666

Lakes Powell and Mead are operated in concert through the *Interim Guidelines*: "If the Lower Basin reduces its use of Colorado River water, less water needs to be released from Lake Mead, and under the *Interim Guidelines*, Lake Powell releases will average less," (Colorado River District n.d.). For this reason the seven basin states and the USBR regard drought contingency planning as a system-wide endeavor.

Water Supply

Introduction

Upper Basin tributaries, such as the Gunnison, Dolores, and Green, flow into the main stem of the Colorado before entering Lake Powell in Southern Utah. To the east, the San Juan River joins Lake Powell at what's referred to as the "San Juan Arm". Along the way, water users throughout the Upper Basin divert and use Colorado River water for a variety of purposes. Some water is used non-consumptively and eventually rejoins the system as return flow to the Colorado River; examples of non-consumptive uses in the basin are household, municipal, or agricultural uses, where once the water is used, it flows back into surface or groundwater and can be withdrawn again by other users downstream. On the contrary, some water in the Colorado River Basin is used consumptively and is removed from the system. Examples of consumptive use in the Colorado River Basin are evapotranspiration and transbasin diversions where the water is unable to cycle back into the Colorado River system. Once in Lake Powell, the stored water helps Upper Basin states fulfill compact obligations to the Lower Basin, generate hydroelectric power, and create recreational opportunities. Currently, the water level at Lake Powell is approximately 3,591 feet, about 108 feet below full capacity (as of April 20, 2016 USBR 2015b). Figure **5** portrays Lake Powell's historic water elevations since Glen Canyon Dam began impounding water in March 1963 relative to the reservoir's maximum active storage level (USBR 2015c).

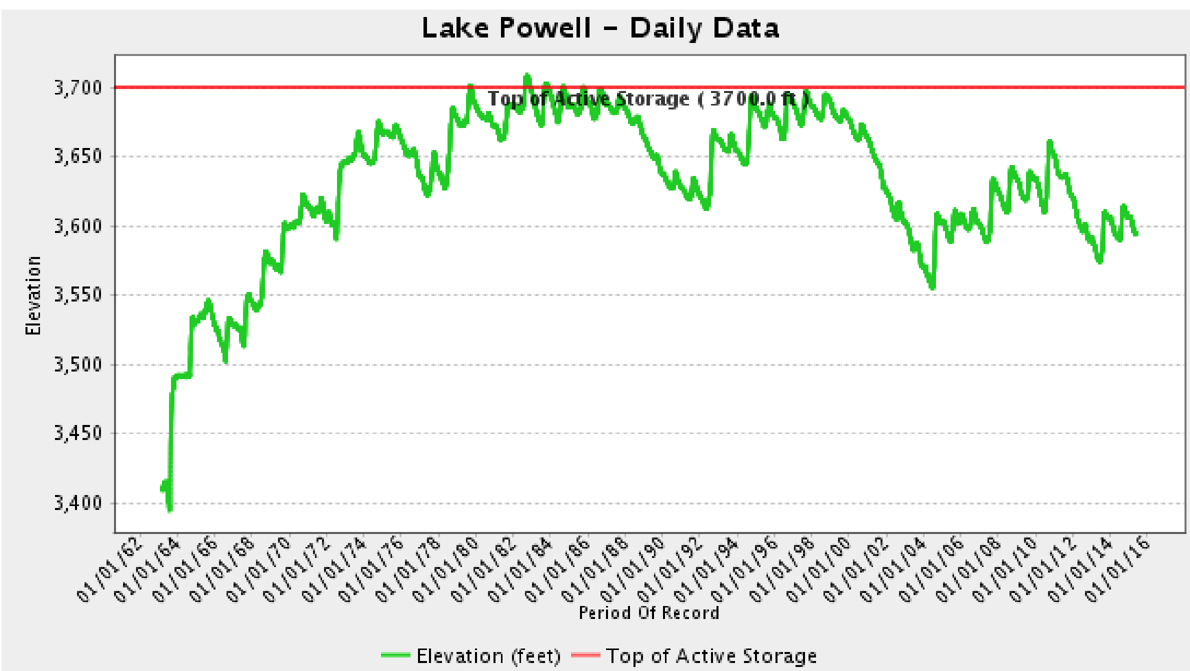


Figure 5. Historic daily reservoir elevations at Lake Powell from 1963-2016 (USBR 2015c).

While the *1922 Compact* roughly allocated the river evenly between the Upper and Lower Basins, the Upper Basin has not fully developed their apportionment. The Lower Basin states, however, use close to their decreed entitlement due to traditionally higher demands posed by a region with higher irrigation needs for agricultural production and bigger urban centers such as Las Vegas, Phoenix, Tucson, Los Angeles, and San Diego (Hecox et al. 2012). If Glen Canyon Dam delivers 8.23 MAF and intervening tributaries (or side inflows) add about 800 thousand acre feet (KAF), the average shortfall per year is about 1.2 MAF (Central Arizona Project 2015), resulting in what's known as the "structural deficit" (Given Basic apportionments in the Lower Basin, the allotment to Mexico, and an 8.23 MAF release from Lake Powell, Lake Mead storage declines:). Combined with the unallocated evaporation losses from Mead, Mead will continue to suffer declines if no action is taken. Due to the reservoir balancing rules defined by the *2007 Interim Guidelines*, and depending on the current month's inflows, when Lake Mead drops, so will Lake Powell. In recent years, inflows to Lake Powell have been generally less than released outflows, causing Powell's water level to drop.

Given Basic apportionments in the Lower Basin, the allotment to Mexico, and an 8.23 MAF release from Lake Powell, Lake Mead storage declines:

Table 2. Water budget at Lake Mead describing the structural deficit (Fleck 2014).

Inflow (release from Powell + side inflows)	9.0 MAF
Outflow (AZ, CA, NV, and Mexico delivery + downstream regulation and gains/losses)	- 9.6 MAF
Mead evaporation loss	-0.6 MAF
Balance	-1.2 MAF
*Data based on long-term averages	

Declining levels at Lake Powell directly impact Upper Basin water users through delivery obligations to the Lower Basin. In order to ensure enough water is in Lake Powell, USBR and the seven basin states are engaged in drought contingency planning. An element of these plans that will directly impact Upper Basin water supplies is "drought operations," which involve additional water releases from Colorado River Storage Project dams upstream from Lake Powell. It is important to maintain hydropower production at Glen Canyon Dam while simultaneously working to prevent water levels at Powell from becoming so high that dam operations transition to a different operational tier pursuant to the *Interim Guidelines* that consequently "bumps up" releases from Powell to Mead (Colorado River District n.d.). A shift to a higher operational tier would mean that more water would be released to Lake Mead

Three separate but interrelated factors influence water shortage challenges in the Upper Basin. First, hydrologic factors, such as climate change impacts to natural flows from the headwaters of the Colorado River, limit locally available water supply in Upper Basin states as well as inflow to Lake Powell. Second, social factors contribute to increased demand of the Colorado River such as population increases and shifts in sectorial water use. Lastly, the Law of the River promises more water to rights holders than has actually ever been available (Kenney et al. 2011). Given a fixed obligation to the Lower Basin, Upper Basin states essentially have the lowest priority under the *1922 Compact* and are effectively limited to the amount of water available after obligations to the Lower Basin have been met (Culp et al. 2015). All three of these factors challenge the ability of the Colorado River to equitability meet the water needs of the Upper Basin as well as those of users downstream

Methods

The main objective of the *Water Supply* section is to describe the factors contributing to the Upper Basin's vulnerability to water shortages. We performed a literature review and consulted with experts to address:

1. hydrologic factors affecting water availability;
2. historical water demand trends;
3. recent water demand by sector to highlight state specific concerns;
4. future water demand forecasts; and
5. legal factors creating management uncertainty.

The hydrologic factors section incorporates regional climate studies as well as studies focusing specifically on the Colorado River Basin. Historical and future projections of water demands are synthesized from the USBR's *Basin Study* while recent water demand data sets are sourced from the most current water use assessment studies that are available from each state.

Hydrologic Factors

Ninety percent of the Colorado River's flow originates as headwaters in Colorado, Utah, and Wyoming as snowmelt runoff (Jacobs 2011). Since 2000, the Colorado River Basin has experienced a long-term drought where the years between 2000 and 2015 were the driest 16 years in the past 100 years (OWDI n.d.). Persistent drought conditions and climate variability could continue to impact future runoff and water supplies in the Upper Basin as well as flows draining into Lake Powell. This section evaluates regional climate studies, as well as studies analyzing the Colorado River Basin more specifically, to understand how physical factors contribute to water supply vulnerabilities in the Upper Basin.

Regional climate studies also help illustrate how climate change can affect water supplies in the Colorado River Basin. Figure 6 below shows a map from the Environmental Protection Agency's *Climate Change Indicators in the United States* (2014) comparing average Southwestern temperatures from 2000-2013 to long-term averages (temperature recordkeeping for the region began in 1895) . All areas in the Southwest have experienced higher-than-average temperatures than what's considered normal (EPA 2014).

Figure 7 below depicts the annual values of drought severity in the Southwest since the 1890's and shows that the last ten years have experienced consistent "drier-than-average conditions". This estimate is based off the Palmer Drought Severity Index that considers precipitation and temperature fluctuations. An important conclusion drawn from this analysis is that the most persistent Southwestern droughts have occurred in the last ten years (EPA 2014).

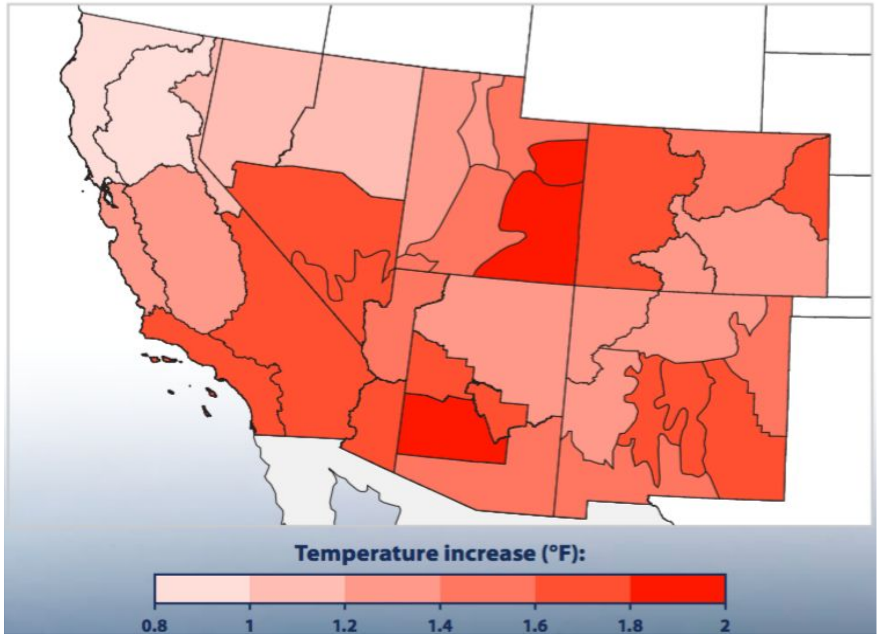


Figure 6. Average temperature increases above normal in the Southwestern United States, 2000-2013 versus long-term average (EPA 2014).

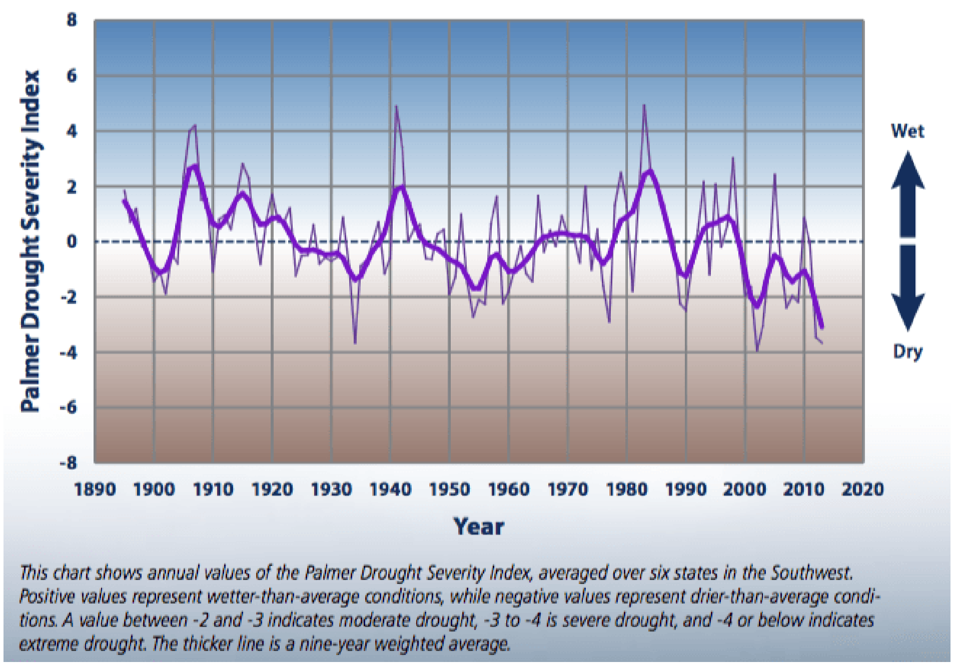


Figure 7. Drought severity in the Southwestern United States 1895-2013 (EPA 2014).

The Third National Climate Assessment predicts that regardless of whether future global greenhouse gas emissions are reduced or continue to rise, the Southwest will experience an increase in temperature (Garfin et al. 2014) (Figure 8). The study estimates that over the last five decades the Southwest has experienced decreases in spring snowfall and earlier runoff events that result in earlier contributions to surface water flows, thereby decreasing dependability and consistency of surface water supplies for the remainder of the year.

Figure **9** shows a decrease in the amount of water held within future Southwestern snowpack if global emissions continue to increase (Garfin et al. 2014).

The National Research Council in 2007 issued a report evaluating climate and hydrology of the Colorado River Basin. An analysis of temperature data throughout the basin concluded that the basin has experienced the most warming out of any other region in the United States, and that “warmer conditions across the region are likely to contribute to reductions in snowpack, earlier peaks in spring snowmelt, higher rates of evapotranspiration, reduced late spring and summer flows, and reductions in annual runoff and streamflow” (NRC 2007). Furthermore, a recent study by Woodhouse et al. examined the temperature, winter precipitation and streamflow for the years 1906 to 2012 and found that temperatures during spring runoff greatly influence streamflow levels, exacerbating the effects of what otherwise would be modest precipitation deficit (2016).

Future temperatures throughout the Colorado River Basin are predicted to increase between 2-2.5°C ± 1°C while changes in precipitation could range between −4 percent ± 12 percent to −2.5 percent ± 6 percent by mid-twenty-first century depending on the level of future greenhouse gas emissions. Decreased streamflows (five percent to 35 percent) projected for Lee’s Ferry (the point of division between the Upper and Lower Basins) are likely due to increased temperatures in the region and changes in precipitation (a five percent decline in precipitation will yield a 10 to 15 percent decline in streamflow). The coupling of the basin's natural susceptibility to prolonged dry periods with climate change related reductions in stream flow could lead to some of the lowest streamflows on record (Vano et al. 2014).

Changes in winter precipitation and temperature patterns in the headwaters of the Upper Basin have far reaching implications for water supplies in states throughout the Southwest, which rely on the Colorado River to meet their water needs. Because the Upper Basin states do not directly withdraw from Lake Powell, water shortages affecting rivers and streams in local communities are of the greatest concern. In fact, Upper Basin states and areas outside the hydrologic basin that use Colorado River water have already experienced periodic shortages (USBR 2015a).

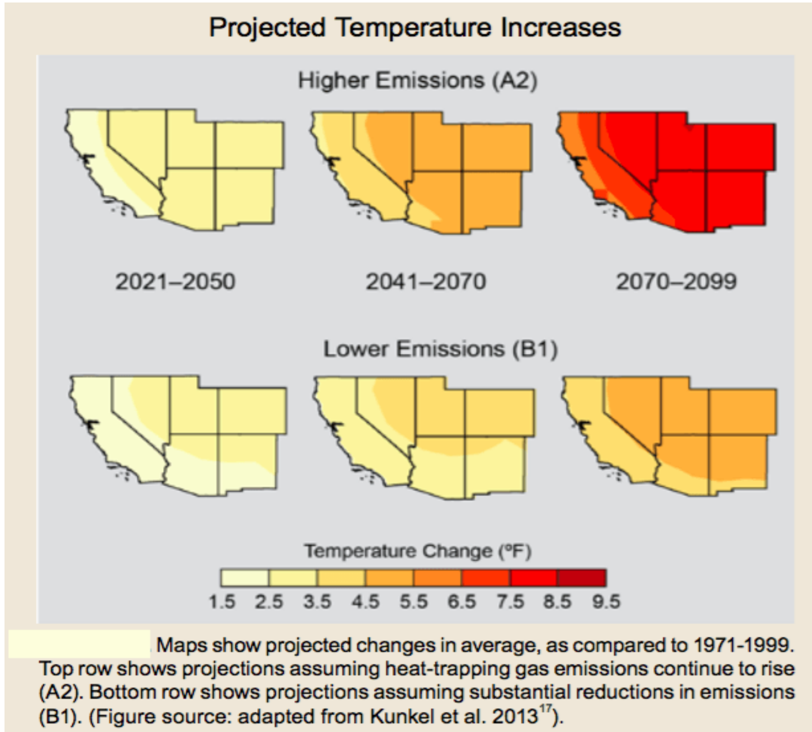


Figure 8. Projected temperature increases in the Southwestern United States (Garfin et al. 2014).

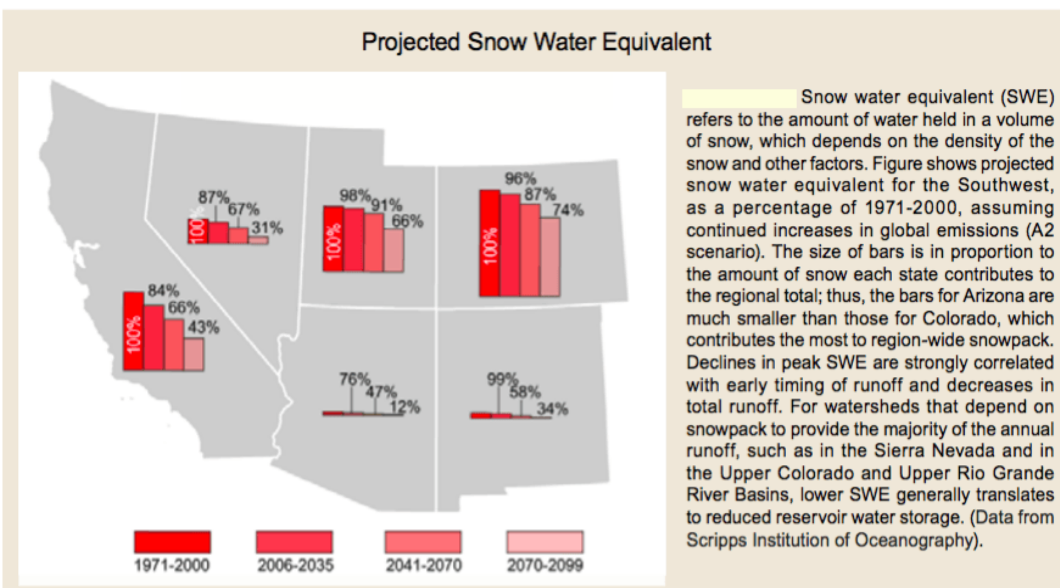


Figure 9. Projected snow water equivalent in the Western United States (Garfin et al. 2014).

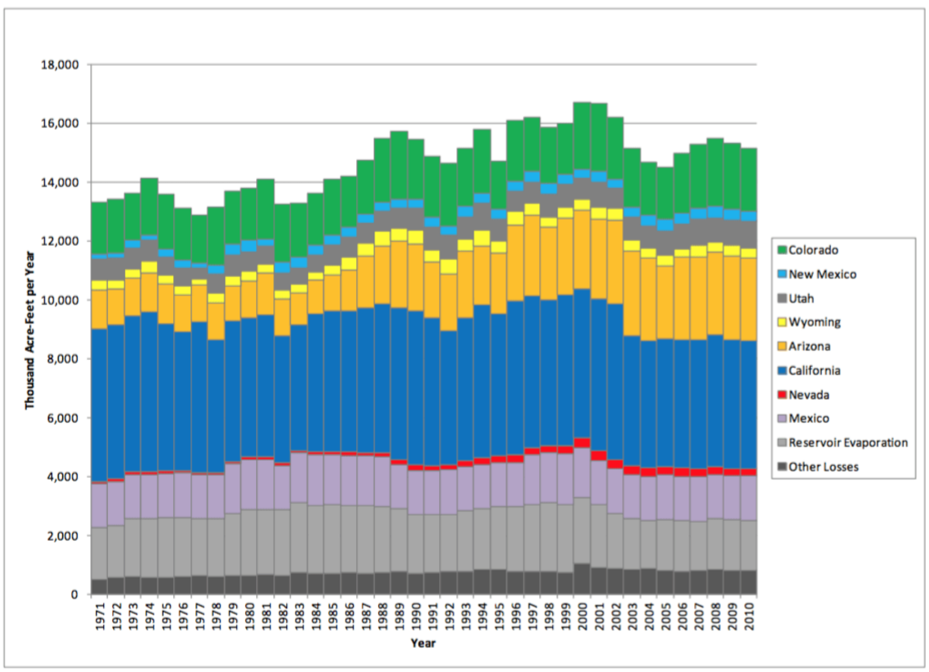
Upper Basin Water Use

Upper Colorado River Basin water supplies provide water for agricultural, municipal, industrial, recreational, and environmental purposes in Colorado, Wyoming, Utah, and New Mexico. In addition to hydrologic and legal factors, specific water demands in each of the Upper Basin states create water supply vulnerabilities. The following section will outline historical water demand in the Upper Basin, provide recent water demand profiles for each state, and conclude by outlining the USBR's forecasts for Upper Basin water demand in 2060.

Historical Water Demands

Estimates of historical water demand help us understand key trends in water use over time. *The Basin Study* depicts Colorado River water consumptive use and loss broken down by each Colorado River Basin state, Mexico, evaporation loss, and other losses between 1971 and 2010 (Figure 10). The highest total consumptive uses and losses in the Upper Basin are attributed to Colorado (USBR 2012e).

Historical Colorado River Water Consumptive Use[1] and Loss by State, Mexico, Reservoir Evaporation[2], and Other Losses[3], 1971–2010



[1] Excluding consumptive use in Lower Basin tributaries.

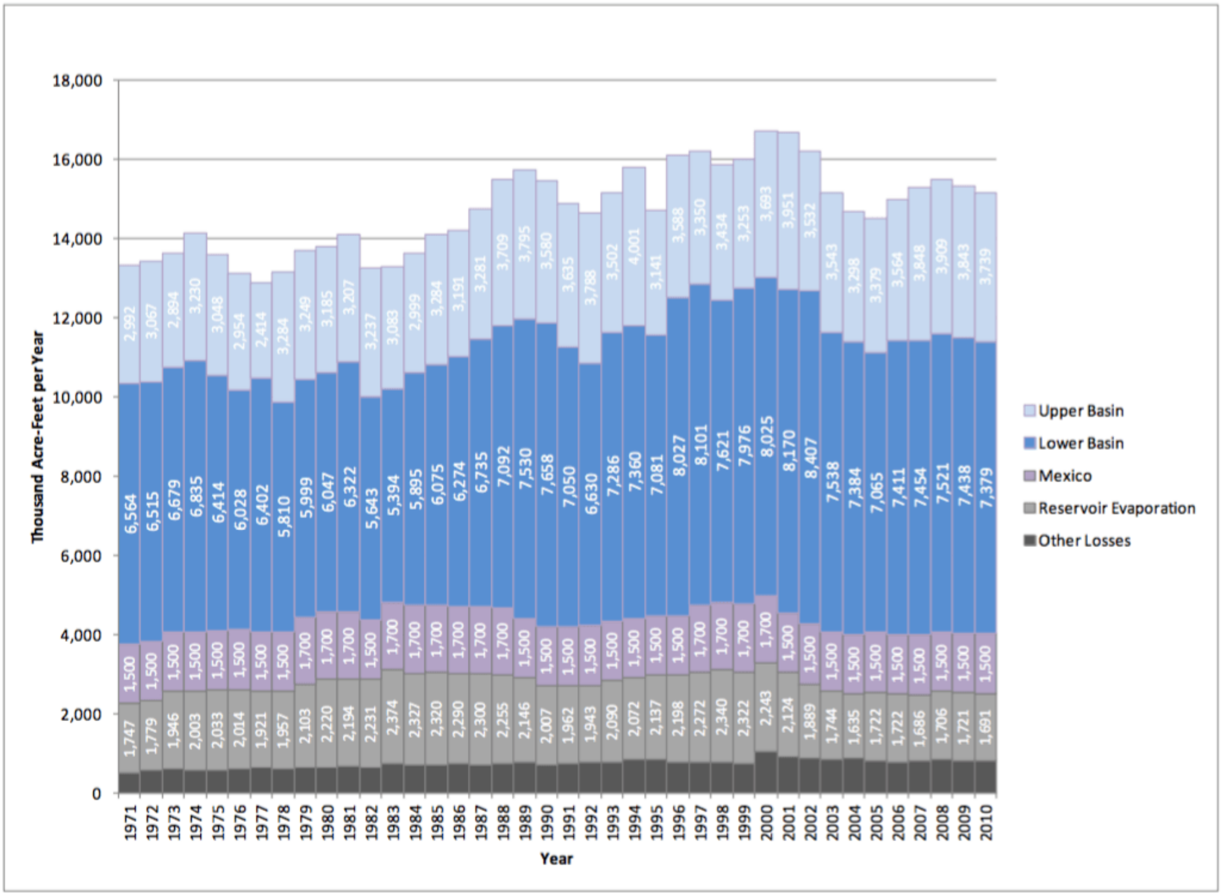
[2] Reservoir evaporation losses are accounted differently in the Upper and Lower Basin. In the Upper Basin, reservoir evaporation losses are accounted as part of each state's total uses. In the Lower Basin, reservoir evaporation losses are accounted separately from each state's uses. Reservoir evaporation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

[3] Phreatophyte and operational inefficiency losses.

Figure 10. Historical Colorado River water consumptive use and loss by state, Mexico, reservoir evaporation, and other losses, 1971-2010 (USBR 2012e).

Figure 11 from *The Basin Study* represents the same data, but represents it in such a way that compares the consumptive uses and losses between the Upper and Lower Basins. It can be concluded that the Lower Basin has consistently had higher consumptive uses and loss in comparison to the Upper Basin between 1971 and 2010 (USBR 2012e).

Historical Colorado River Water Consumptive Use[1] and Loss by Basin, Mexico, Reservoir Evaporation[2], 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.

Figure 11. Historical Colorado River water consumptive use and loss by state, Mexico, reservoir evaporation, and other losses, 1971-2010 (USBR 2012e).

It is important to note that a significant portion of consumptive uses and losses throughout the Colorado River Basin is attributed to reservoir evaporation (Figure 10 and Figure 11). Figure 12 below, representing large reservoirs in the basin, shows that average evaporative losses between 1971 and 2010 are about 2 MAF/YR and 1.8 MAF/YR between 2000 and 2010. Declining evaporative losses can be attributed to lower average reservoir storage (USBR 2012e). The Upper Basin portion of this figure includes Morrow Point, Blue Mesa, Flaming Gorge, and Lake Powell.

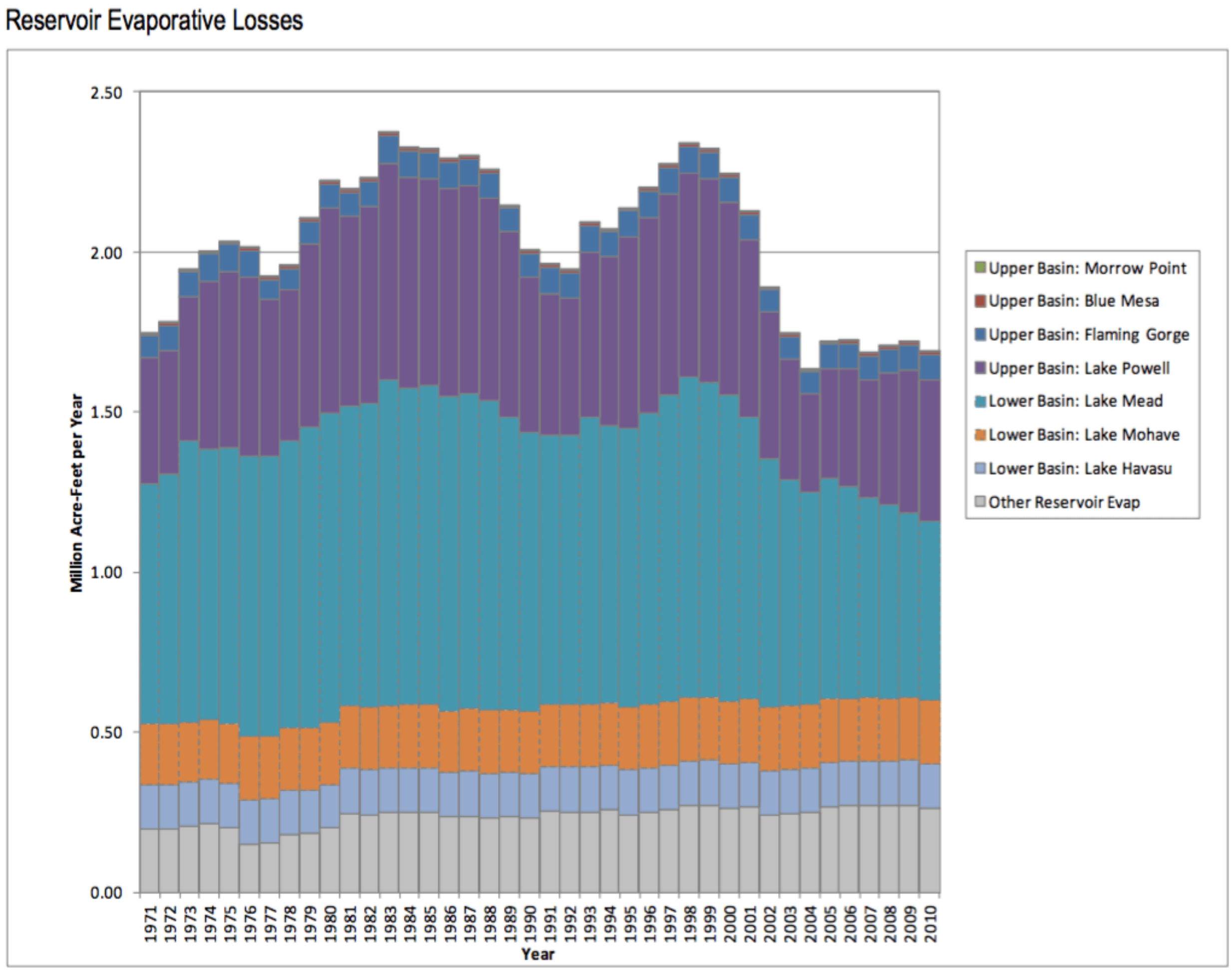


Figure 12. Reservoir evaporative losses (USBR 2012e).

Figure 13 through Figure 16 below provide timelines (1971-2010) of consumptive Colorado River water use in Colorado, Wyoming, Utah, and New Mexico by four sectors: agriculture, municipal and industrial (M&I), energy, and minerals (USBR 2012f). These graphs show agriculture as the largest water user in the Upper Basin during that time frame (USBR 2012f).

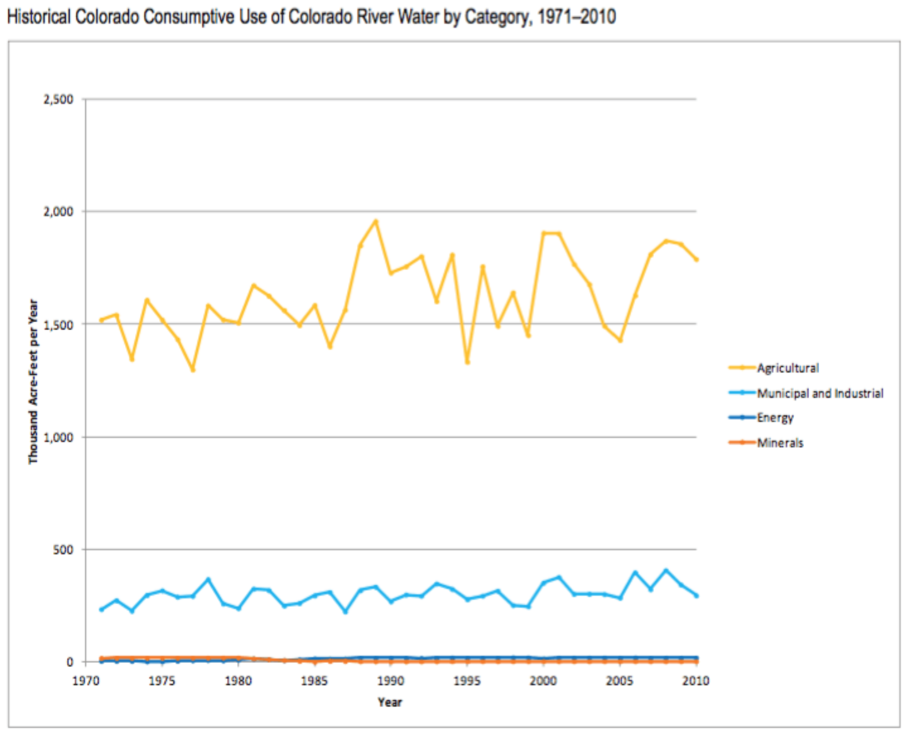


Figure 13. Historical Colorado consumptive use of Colorado River water by sector (USBR 2012f).

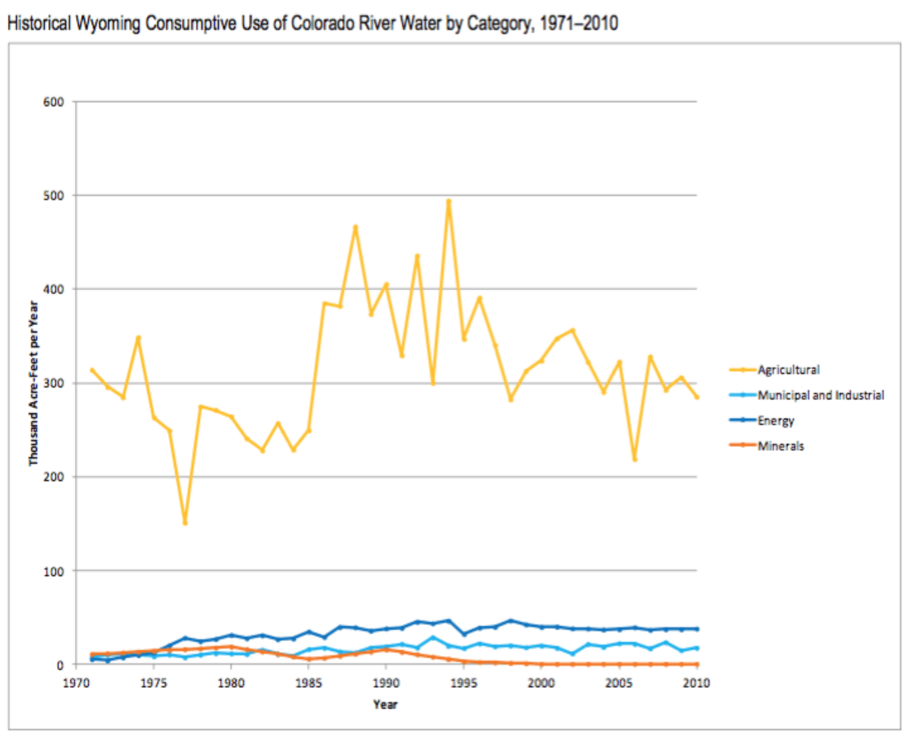


Figure 14. Historical Wyoming consumptive use of Colorado River water by sector (USBR 2012f).

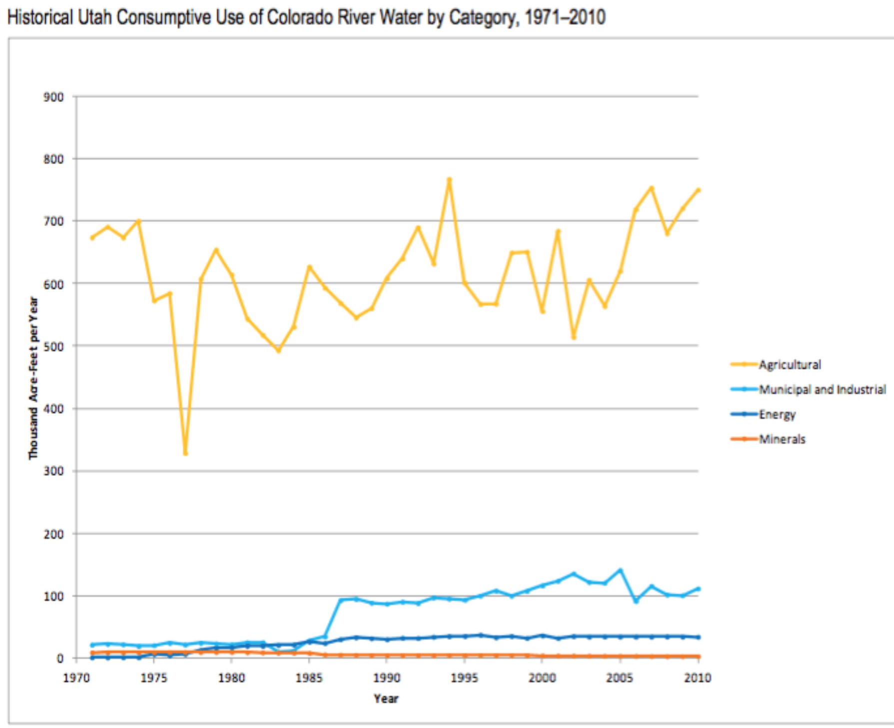
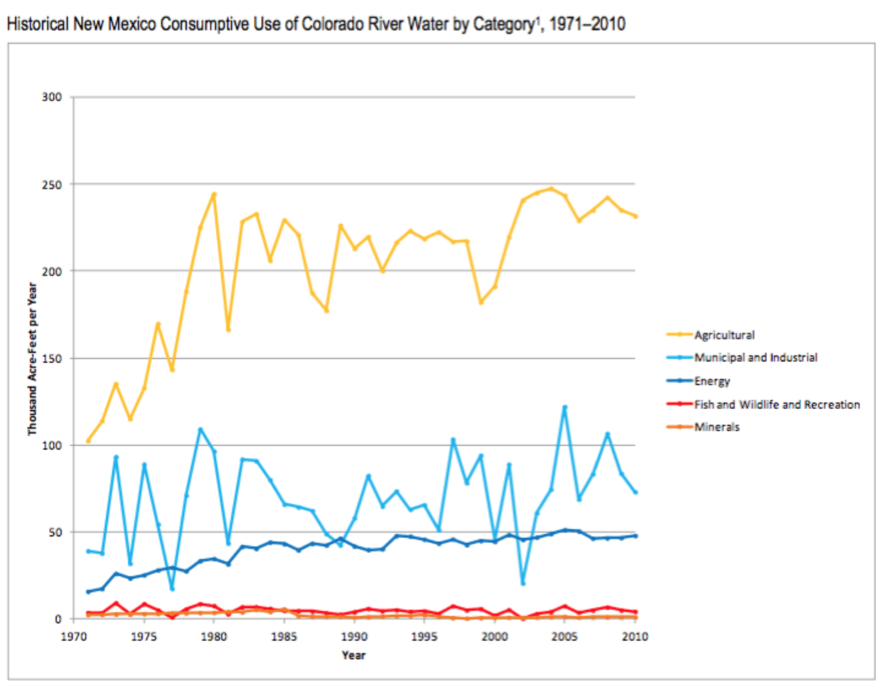


Figure 15. Historical Utah consumptive use of Colorado River water by sector (USBR 2012f).



[1] San Juan-Chama project diversions are determined annually based on bypass flow requirements and maximum in-year and decadal diversions. Variations from year to year are due to flow limitations and not changes in demand.

Figure 16. Historical New Mexico consumptive use of Colorado River water by sector (USBR 2012f).

The Basin Study reports that in all four Upper Basin states, consumptive use of Colorado River water has increased (Colorado: 29 percent, Wyoming: 59 percent, Utah: 29 percent, and New Mexico: 122 percent) between 1971 and 2010 (USBR 2012f). While consumptive use distribution across sectors has remained fairly constant in Colorado, the other three Upper Basin states have witnessed slight shifts in recent years (USBR 2012f):

- Wyoming: increases in agriculture, energy, and M&I uses; decreases in mineral use.
- Utah: increases in M&I and energy uses; decreases in agriculture use.
- New Mexico: increases in M&I, agriculture, and energy uses.

More than two dozen American Indian Tribes live on reservation lands that have water rights to the Colorado River Basin (Cozzetto et al. 2013) amounting to more than 2.9 MAF (CRWUA N.d.c). Five tribes, the Jicarilla Apache Nation, Navajo Nation, Southern Ute Indian Tribe, Ute Indian Tribe of the Uintah and Ouray Reservation, and the Ute Mountain Ute Tribe, have quantified water rights in the Upper Basin (Table 3); but water rights remain unsettled in Utah and New Mexico for both the Navajo Nation and Ute Mountain Ute Tribe (USBR 2012e, Nania n.d.). Tribal water rights are held in federal trust by the United States government, who must ensure rights granted to tribes when their reservations were created (USBR 2012e). Water allocated to tribes in the Colorado River Basin counts against the apportionment of the state where the reservation is located. Unsettled tribal water rights in the Colorado River Basin are substantial. For instance, the pending settlement between the Navajo Nation and the state of Utah would provide the Nation with 314,851 AF/YR of Colorado River Basin water (Nania n.d.).

Table 3. Upper Colorado River Basin American Indian Tribes with quantified rights to Colorado River water (USBR 2012e).

Tribe	Location
Jicarilla Apache Nation	New Mexico
Navajo Nation	Arizona, New Mexico, and Utah
Southern Ute Indian Tribe	Colorado
Ute Indian Tribe of the Uintah and Ouray Reservation	Utah
Ute Mountain Ute Tribe	Colorado, New Mexico, and Utah

State Profiles

Colorado

The main stem of the Colorado River emerges from the Rocky Mountains of Colorado and approximately 75 percent of the water in the entire Colorado River Basin originates from the state (Colorado Water Conservation Board 2015a). The Colorado River Basin in Colorado includes the Yampa, White, Gunnison, Dolores, San Juan, and the Colorado River subbasins on the Western Slope of Colorado; water is also exported to the South Platte and Arkansas subbasins in the Front Range of Colorado (Figure 17).[4]

[4] The Yampa and White sub-basins, as well as the Dolores and San Juan subbasins, are often grouped together for water supply analyses; the first may be referred to the Yampa-White Basin and the latter referred to as the Southwest Basin.

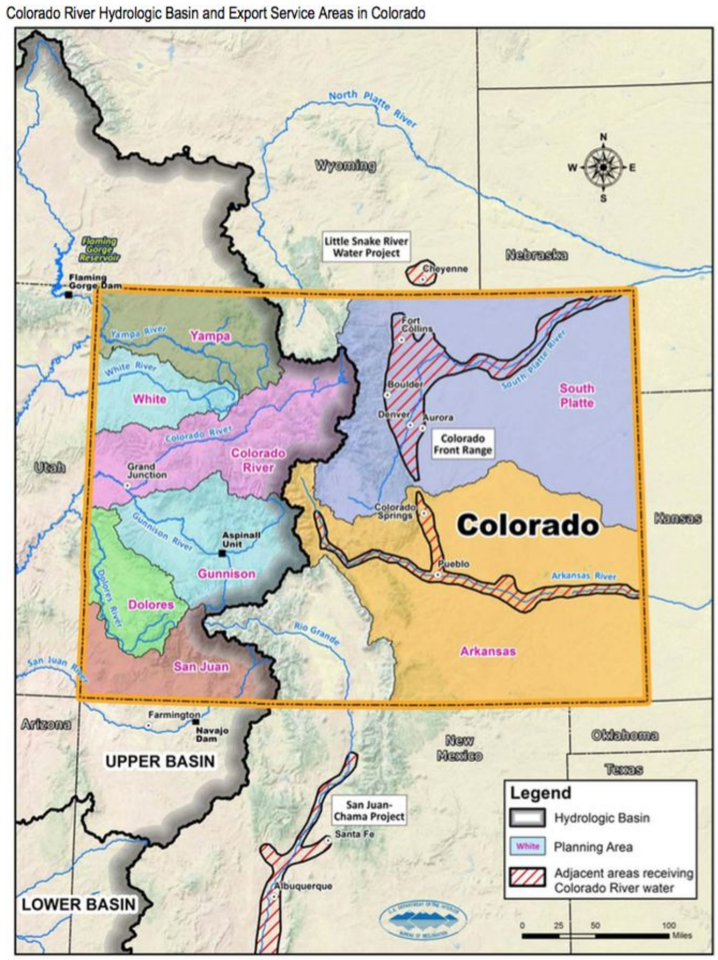


Figure 17. Map of the Colorado River Basin in Colorado (USBR 2012g).

Colorado's water management structure is unique in that there are seven water courts in each of the state's main watersheds that confirm water rights (Colorado Water Conservation Board 2015b). The Colorado Division of Water Resources (also called the State Engineer's Office), within the Department of Natural Resources, is responsible for administering water rights in Colorado and has field offices in each of the seven subbasins. Commissioners housed in these field offices monitor water rights administration by gauging diversions, complete studies for water management plans, and administer "calls on the river" to guarantee that senior water right holders receive their full amount of water during shortages (Colorado Water Conservation Board 2015a).

Under the *Upper Colorado River Basin Compact*, Colorado is allocated 51.75 percent of the Upper Basin's portion of Colorado River Water (US Congress 80). This translates to between 3.9 MAF/YR under the formal *1922 Compact* hydrologic apportionment of 7.5 MAF, and 3.1 MAF/YR under a hydrologic forecast of 6.0 MAF. In 2010, estimates indicated that Colorado consumptively used between 2.4 MAF/YR to 2.6 MAF/YR. The Statewide Water Supply Initiative estimated that "about 80 percent [of the renewable water] is on the West Slope and 20 percent is on the East Slope. However, about 80 percent of Colorado's population is on the East Slope and 20 percent is on the West Slope and most of Colorado's irrigated agricultural lands are on the East Slope" (Figure 18) (Colorado Water Conservation Board 2010). In 2008, the population living in the Colorado River Basin area of Colorado was 562,000, while 4,438,000 people lived in areas outside of the hydrologic basin that received exported Colorado River water (Colorado Water Conservation Board 2010).

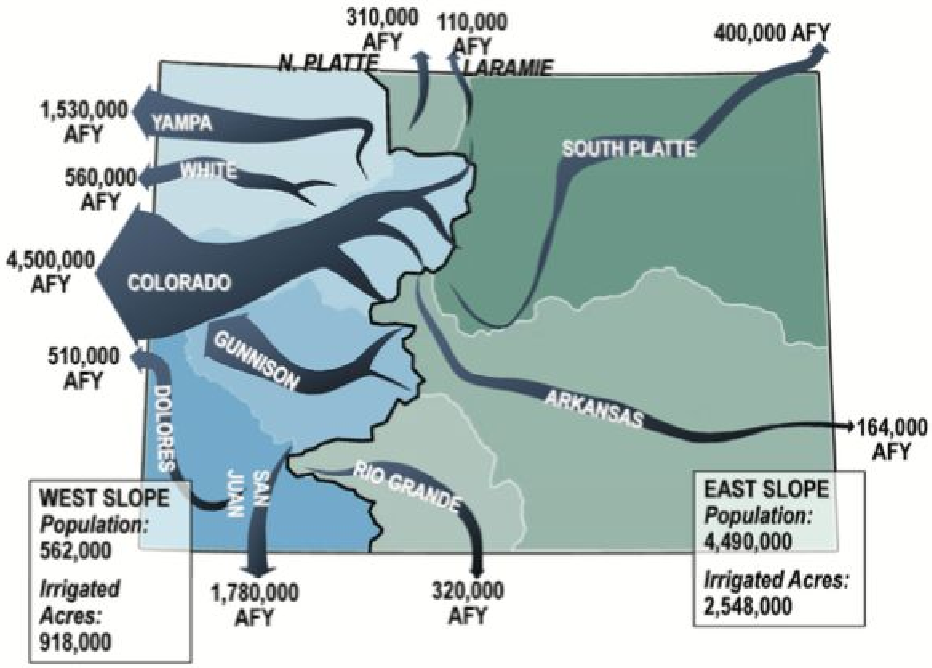


Figure 18. Colorado's population, irrigated acres, and river flows in 2010 (Colorado Water Conservation Board 2010).

The Statewide Water Supply Initiative offers the most recent comprehensive analysis of water use in the state of Colorado (2010).[5] Table 4 and Table 5 summarize the report's estimates of population and water demands in 2008. Table 4 sums estimates from the Colorado, Gunnison, Dolores, San Juan, Yampa, and White subbasins on the West Slope; and Table 5 sums estimates from the Arkansas and South Platte (including the Denver Metro area) subbasins on the East Slope. For both of these tables, the irrigation water requirement estimates describe the total amount of water that would be used if there were no limitations created by legal or physical factors. Water supply-limited consumptive use is defined as the amount of water actually used by the crop when limited by water availability. Non-irrigation demand includes consumptive uses due to livestock consumption, stockpond evaporation, and losses during water deliveries. M&I includes residential, commercial, light industrial, non-agricultural related irrigation, non-revenue water, firefighting, and households that self-supply their water and are therefore not connected to public water supply infrastructure. Lastly, self-supplied industrial includes mining, manufacturing, brewing, and food processing industries; snowmaking; thermoelectric power generation at coal and natural gas plants; and the extraction and production of natural gas, coal, uranium, and oil shale.

[5] These numbers were also used in the Colorado's Water Plan released in 2015.

Table 4. 2008 water use in the hydrologic Colorado River Basin area of Colorado (Colorado Conservation Board 2010).

Use Category	Use (AF/YR)
Agriculture	
Irrigated Acres	918,000
Irrigation Water Requirement	2,032,000
Water Supply-Limited Consumptive Use	1,553,000
Non-Irrigation Demand	175,000
Total Agriculture Water Use	3,760,000
Municipal and Industrial	117,000
Self-Supplied Industrial	36,640
Total Water Use	3,913,640

Table 5. 2008 water use in areas of Colorado that receive exported Colorado River water (Colorado Conservation Board 2010).

Use Category	Use (AF/YR)
Agriculture	
Irrigated Acres	428,000
Irrigation Water Requirement	2,491,000
Water Supply-Limited Consumptive Use	1,659,000
Non-Irrigation Demand	171,000
Total Agriculture Water Use	4,321,000
Municipal and Industrial	839,000
Self-Supplied Industrial	151,120
Total Water Use	5,311,120

It is important to note that the demands expressed in Table 5 do not exclusively impact Colorado River Basin water supplies. Portions of the water demand in these areas, the Arkansas and South Platte Basins, is satisfied by local supplies. Transmountain diversions, however, account for five percent (or 500,000 AF/YR) of the total water supply in Colorado (Colorado Water Conservation Board 2010, Colorado Water Conservation Board 2015b) and these diversions mostly move water west to east to satisfy Front Range needs.

Wyoming

The headwaters of the Green River, a major tributary to the Colorado River, are located in the Wind River Mountains in southwest Wyoming. The hydrologic portion of the Colorado River Basin in Wyoming spans 16 percent of the state (Figure 19).

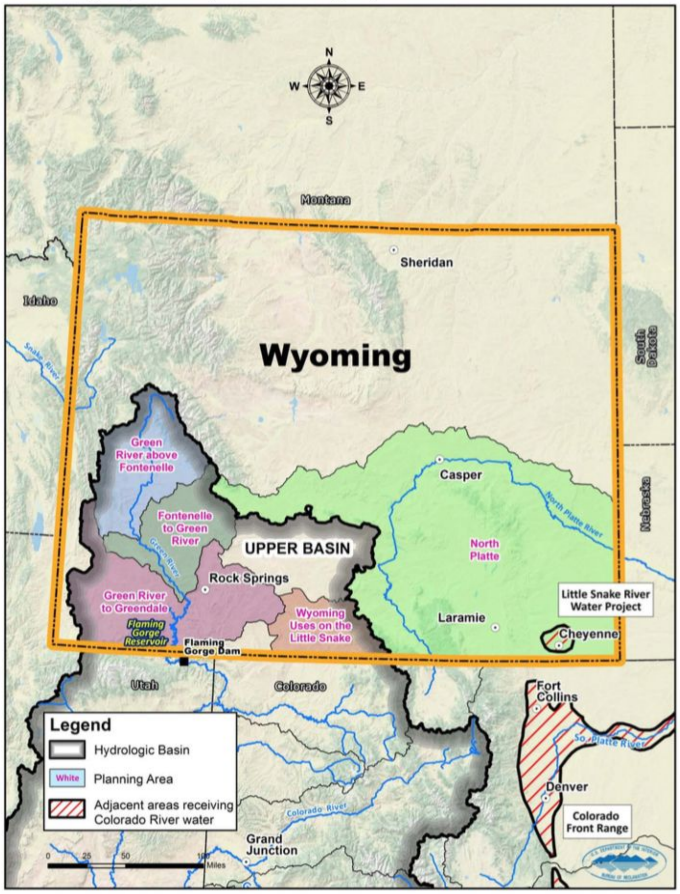


Figure 19. Map of Colorado River Basin in Wyoming (USBR 2012h).

Wyoming gives regulation and administrative power of the state's water resources to the Wyoming State Engineer's Office. The state is divided into four Water Divisions (the Green River Basin is Division 4), each of which is headed by a superintendent. Together the State Engineer and the superintendents make up the Wyoming Board of Control, which adjudicates Wyoming water rights (Wyoming State Engineer's Office n.d.a). Additionally, the Interstate Streams Division aids the State Engineer with allocation and administration needs of streams subject to interstate compacts and court decrees (Wyoming State Engineer's Office n.d.b). In 2006, the Interstate Streams division created the Colorado River Compacts Administration Program to develop, implement and operate a process to monitor the consumptive use of water in the Colorado River Basin of Wyoming.

The *Upper Colorado River Basin Compact* allocates 14 percent of the Upper Basin's portion of Colorado River Water to Wyoming (1948). Under a water supply of 6.1 MAF/YR, Wyoming's available share is 847,000 AF/YR (Carrico 2014)[6]. Estimates in 2010 indicated that Wyoming consumptively used 603,878 AF/YR of Colorado River water (WWC Engineering 2010). The 2010 Green River Basin Plan prepared for the Wyoming Water Development Commission Basin Planning Program is the most recent comprehensive analysis available describing Wyoming's use of Colorado River Basin water.[7]

[6] The formal *1922 Compact* hydrologic apportionment of 7.5 MAF yields 1,050,000 AF/YR.

[7] The Wyoming State Engineer's Office will soon release the 2016 Green River Basin Consumptive Use Report that will provide updated water use data.

Table 6 summarizes the report's estimates of water demands in the Green River Basin in 2010. In that year, 67,900 people lived in the Green River Basin of Wyoming (USCB 2010). Irrigation for agricultural purposes uses more water than any of the other economic sectors. Livestock production is the main agricultural practice in the Green River Basin. Consequently, forage crops like alfalfa and grass hay attribute between 70 and 100 percent of the crops grown in the area. Local livestock consumes most of the crops, but a small portion of these crops are exported out of the Green River Basin (WWC Engineering 2010).

The 2010 Green River Basin Plan describes municipal water users as entities served by a public water supply system, of which there are 14 cities, towns, and joint power water boards that provide water to their residents. The largest consumer of municipal water is the City of Cheyenne (Table 6), which lies outside the hydrologic boundaries of the Green River Basin. Cheyenne has water rights in the Little Snake Basin of the Green River from which the city diverts and transports water across the continental divide to the North Platte Basin to meet the growing needs of the city (Wolff and Ross 2016).

The 2010 Green River Basin Plan defines domestic water use as inclusive of rural homes outside of urban areas that use individual groundwater wells, public supply systems that convey water to rural subdivisions, and small commercial establishments such as parks and campgrounds. Table 6 shows that this sector is largely satisfied by groundwater supplies (WWC Engineering 2010).

The industrial sector includes, as defined by the 2010 Green River Basin Plan, electric power generation and soda ash production that consumes surface water; and coal mining, uranium mining, and oil and gas industries that generally consume groundwater supplies. Natural gas is Wyoming's largest export and Sublette County, located in the Green River Basin, produces the most natural gas in the state (WWC Engineering 2010).

The two remaining uses discussed in the 2010 Green River Basin Plan, recreation and environmental, are regarded as non-consumptive uses. Activities important to Wyoming's economy such as boating, fishing, hunting, camping, golfing, and skiing, rely on adequate water levels to maintain recreational quality. Environmental water helps to enhance instream flows, minimum pools in reservoirs, wildlife water consumption, threatened and endangered species, and wetlands.

A significant portion of water that benefits the environment does so indirectly as a byproduct of other uses and not as an instream flow water right specifically designated to the environment (WWC Engineering 2010). It is possible to designate instream flow as a beneficial use in the state of Wyoming. The Wyoming Game & Fish Department determines the stream reaches and the desired flow levels; the Wyoming State Engineer's Office reviews and issues the permit; and the Wyoming Water Development Commission holds the permit in their name for the State. There are currently over 100 instream flow permits for designated reaches in the state of Wyoming (Wolff and Ross 2016).

Table 6. 2010 water use in the hydrologic Colorado River Basin area of Wyoming (WWC Engineering 2010).

Use Category	Use (AF/YR)
Agriculture	
Irrigation Use	396,246
Stock	1,755
Total Agriculture Water Use	398,001
Municipal	
Surface Water	6,578
Groundwater	884
City of Cheyenne Diversions	15,281
Total Municipal Water Use	22,743
Domestic	
Surface Water	0
Groundwater	3,047
Total Domestic Use	3,047
Industrial	
Surface Water	56,833
Groundwater	1,954
Total Industrial Use	58,787
Recreation	Nonconsumptive
Environmental	Nonconsumptive
Total Water Use	482,578

In addition to the City of Cheyenne diversion that was mentioned earlier in this section, there are three small agricultural diversions that carry water outside of the Green River Basin and one small agricultural diversion that moves water from the North Platte basin into the Green River Basin. Importantly, there are no water imports to the Green River Basin that can be used to augment the water supply should a localized water shortage occur (Wolff and Ross 2016).

Utah

With regard to the Colorado River Basin, Utah is a state of confluences. The Green River crosses the Wyoming-Utah state line in northeastern Utah just before the Flaming Gorge Dam. Downstream the Duchesne, White and Price Rivers merge with the Green before it meets the Colorado River in southeast Utah. The San Juan River, flowing west from Colorado, joins Lake Powell in south-central Utah. The Colorado River Basin in Utah is broken down into three subbasins in the eastern portion of the state: the Uintah, West Colorado River, and the Southeast Colorado River Basins (Figure 20). The southwest corner of Utah is in the Lower Colorado River Basin where water is diverted from the Virgin River and Kanab Creek.

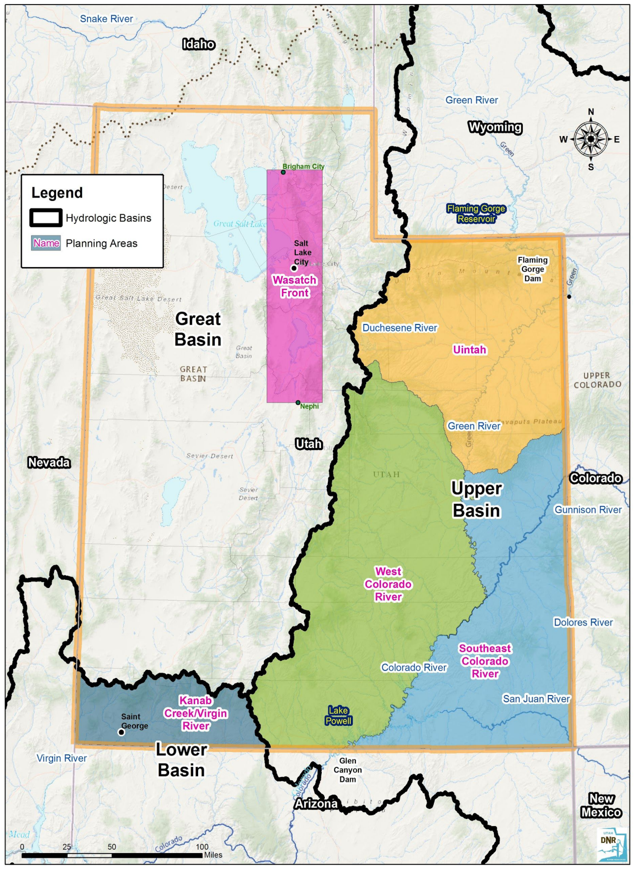


Figure 20. Map of Colorado River Basin in Utah (Millis 2016).

The Utah Division of Water Rights is housed under Utah's State Government within the Department of Natural Resources. Led by the State Engineer, the Utah Division of Water Rights administers the state's water appropriations and oversees the distribution of the resource. Additionally, the Utah Division of Water Resources deals with regional and state-level water planning (USBR 2012i).

The *Upper Colorado River Basin Compact* allocates 23 percent of the Upper Basin's portion of Colorado River Water to Utah (US Congress 80), which translates to approximately 1.4 MAF/YR under a hydrologic forecast of 6,090,000 AF/YR (Millis 2016)[8]. Currently the state of Utah is using approximately 1 MAF/YR of this allocation (Millis 2016). Similar to Colorado and Wyoming, the major population centers in Utah are located outside of the Colorado River Basin (State of Utah Division of Water Resource 2001). For instance, the Governor's Office of Management and Budget estimate that currently 2.1 million people, or 75 percent of the entire state, reside along the Wasatch Front (Figure 20) (Utah Governor's Office of Management & Budget n.d.).

Between the years 1989 and 2014, an average amount of approximately 840 KAF of water was diverted out of the hydrologic Upper Basin area of Utah (Table 7). The largest consumer of water is agriculture (601 KAF). Agricultural use includes water for pasturing, grazing, and watering of livestock and the cropping, cultivation, and harvesting of plants. Municipal use refers to residential, commercial and institutional

[8] The formal *1922 Compact* hydrologic apportionment of 7.5 MAF yields 1,700,000 AF/YR.

water use, but excludes uses by large industrial operations. Water used for residential purposes and irrigation of residential vegetation is accounted for in the domestic use category. The power sector incorporates water used to generate hydroelectric and thermoelectric power. Industrial use refers to water associated with manufacturing and commercial businesses. Finally, imports include water diverted into a river system from another hydrologic basin by a transbasin diversion; exports serve the opposite purpose. Therefore, net export/import is calculated by subtracting imported flow from exported flow to establish a net flow (if the value is positive, there is a net export. A negative value indicates a net imported flow). Currently, 170 KAF is exported out of the system (Millis 2016).

Table 7. Average water diverted in the hydrologic Upper Colorado River Basin area of Utah between 1989 and 2014 (Millis 2016).

Use Category	Diversion (AF/YR)
Agriculture	601,000
Municipal/Domestic	32,000
Power/Industrial	40,000
Net Export/Import	170,000
Total Water Diverted	843,000

The Central Utah Project, authorized by the *Colorado River Storage Project Act of 1956*, conveys water from the Uintah Basin to the Wasatch Front (Figure 20) and has the ability to deliver approximately 251,750 AF/YR. **Table 8** below shows how this water is used by sector. The environmental sector includes protection and maintenance of riparian ecosystems for the primary purpose of sport fishing in the Uinta Basin (Central Utah Completion Act Office n.d.a). The Central Utah Project is yet to be fully completed due to continuously changing political climates, funding availability, and environmental concerns that alter the design and functioning of the project (Central Utah Completion Act Office n.d.b). Uses of Utah's remaining allocation of the Colorado River include two American Indian Tribes reserved water right settlements, and future municipal, industrial, energy development and agricultural water uses (Millis 2016).

Table 8. Water provided by Central Utah Project by sector (Central Utah Completion Act Office n.d.).

Use Category	Use (AF/YR)
Agriculture	112,600
Municipal and Industrial	94,750
Environmental	44,400
Total Water Use	251,750

Additionally, in 2006 the Utah State Legislature passed the *Lake Powell Pipeline Development Act* authorizing the Utah Board of Water Resource to construct the Lake Powell Pipeline. The intention is for the pipeline to extend over 139 miles and transport up to 86,000 AF of water from Lake Powell to Washington and Kane Counties in southwest Utah as part of the state's *Upper Colorado River Basin Compact* allocation. Recent cost estimates from last November 2015 anticipate that the pipeline will require between $1.1 billion and $1.8 billion in funding. The final price tag will become more clear as additional information becomes available, including the route that is deemed favorable by the pending Environmental Impact Statement (Utah Division of Water Resources n.d.). In January 2016 a state legislative committee voted in favor of a bill that would funnel $35 million from a transportation investment fund to finance the Lake Powell Pipeline. In the meantime, the federal government is reviewing an application submitted by the Utah Division of Water Resources and will deliver a decision within two to three years (Tory 2016).

The ability of Utah water users reliant on Colorado River water to switch to supplemental sources varies throughout the state. The Colorado River is the primary water source in many areas within the state. For areas in Utah located outside of the hydrologic Colorado River Basin, imported Colorado River water is viewed as a supplemental water source to their available in-basin supplies and is important to meeting local needs (Millis 2016).

New Mexico

The northwest portion of New Mexico lies within the Colorado River Basin. The San Juan River enters New Mexico south of the Colorado state line before it enters Navajo Reservoir. Downstream, the Animas and La Plata Rivers merge with the San Juan before exiting New Mexico near the Four Corners where it eventually meets the main stem of the Colorado River in Lake Powell. The area over which the Colorado River Basin spans New Mexico is considered the San Juan River Basin. The San Juan River Basin[9] is also shared with Colorado, Utah, and Arizona (Figure 21).[10]

[9] The San Juan River Basin in New Mexico is often referred to as the Upper Colorado River Basin in New Mexico (Longsworth et al. 2010)

[10] It is important to note that Northwest and Southwest Basin pictured in Figure 23 are included in the Lower Basin analysis and are therefore not within the scope of this report.

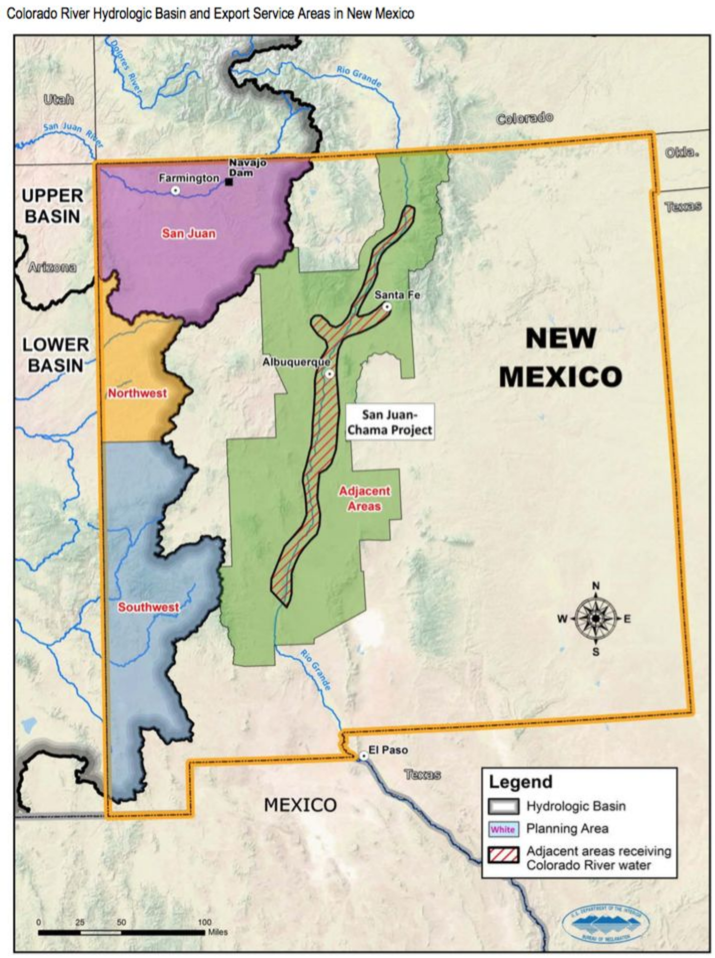


Figure 21. Map of Colorado River Basin in New Mexico (USBR 2012j).

The Office of the State Engineer is given authority over administering the state's water rights as well as measurement and distribution (NMOSE n.d.b). An additional role of the State Engineer is to serve as the Secretary to the Interstate Stream Commission, which is the agency responsible for overseeing interstate river systems, engaging in interstate settlement negotiations, and ensuring interstate compliance. Accompanying the State Engineer, eight unsalaried commissioners are appointed by the Governor to serve on the commission. Staff working for the commissioners perform stream measurement studies to monitor and develop water supplies in New Mexico "for planning, conservation, protection and development of public waters," (NMOSE n.d.c).

The *Upper Colorado River Basin Compact* allocates 11.25 percent of the Upper Basin's portion of Colorado River Water to New Mexico (UCRB Compact), a consumptive use amount of no less than 642,380 AF/YR based on a hydrologic forecast of 5.7 MAF (NMOSE 2016)[11]. The most recent comprehensive assessment of water use in the region is the New Mexico Water Use by Categories issued in 2010 by the Office of the State Engineer. (Longsworth et al. 2010). These numbers are being used in the *2016 San Juan Regional Plan* that is currently in draft phase. In 2010, New Mexico diverted approximately 876,200 AF/YR within

11 The formal *1922 Compact* hydrologic apportionment of 7.5 MAF yields 843,750 AF/YR.

the San Juan River Basin. During the same year, approximately 149,431 people (seven percent of the of the state's population) lived in McKinley, Rio Arriba, Sandoval, and San Juan counties that are situated within the basin (NMOSE 2016).

Table 9 below describes the total diversions by sector in the San Juan River Basin in 2010. A diversion is defined as the "the quantity of metered water taken from a surface or groundwater source" (Longsworth et al. 2010). Table 9 shows that the largest consumer of Colorado River Basin water in New Mexico is irrigation of crops in farms, ranches, and wildlife refuges. Irrigation needs are mainly served by surface water. The other agriculture related water use in this region is livestock at 4,400 AF, which can include water for animal consumption, facility needs, and on-location meat and dairy processing (NMOSE 2016).

The public water supply/domestic category, diverting 27,700 AF/YR in 2010, includes municipal water systems that distribute water to residential, commercial and industrial water consumers. Industrial users that do not fall under the jurisdiction of a public water system are accounted for in the industrial/commercial category such as the processing of raw materials, manufacturing, and construction. This category diverted 400 AF/YR of water in 2010. The power sector diverted 51,300 AF/YR of water 2010, which includes water for power generation and coal mining operations. Water used to extract oil, natural gas, gravel, water and metal is included in the mining category, which diverted 1,600 AF/YR in 2010. The reservoir evaporation category at 29,900 AF/YR in 2010 was calculated by measuring the amount of water evaporated in the San Juan River Basin's three largest reservoirs: Navajo Reservoir, Farmington Lake, and Morgan Lake.

Lastly, a significant portion of total diversions in the San Juan River Basin is attributed to exports out of the basin. The most significant of the two exports discussed in the *2016 San Juan Regional Plan* is the San Juan-Chama Project that diverts and exports water in the San Juan River from Colorado to the Rio Grande Basin in New Mexico. The San Juan-Chama Project's long term average annual diversion is 105,200 AF/YR. Coupled with a 600 AF/YR groundwater diversion by the City of Gallup from the San Juan River for municipal needs, exports a total of 105,800 AF/YR (NMOSE 2016).

Table 9. Total diversions in the San Juan Basin Water Planning Region in 2010 (NMOSE 2016).

Use Category	Diversion (AF/YR)
Public Water Supply/Domestic (Self-supplied)	27,700
Irrigated Agriculture	655,100
Livestock (Self-supplied)	4,400
Total Agriculture Water Use	659,500
Industrial/Commercial (Self-supplied)	400
Mining (self-supplied)	1,600
Power (Self-supplied)	51,300
Reservoir Evaporation	29,900
Exports	105,800
Total water diverted	876,200

It is nearly impossible for New Mexico water users who consume Colorado River Basin water to switch to supplemental sources is nearly impossible (Flanigan and Green 2016). Most groundwater resources throughout the region are saline and are not economically practicable to develop (NMOSE 2016).

Future Water Demands

Understanding how water demands in the Upper Colorado River Basin may change in the future is critical to assessing the potential vulnerability the region may face with respect to declining water levels. This report summarizes *The Basin Study* assessments of future water demand specifically for the Upper Basin states (USBR 2012a). While *The Basin Study* evaluated various growth scenarios, this report uses Scenario A, the current, business-as-usual growth trend. Each state in the Colorado River Basin provided data based on their own specific water planning and assessment processes to aid *The Basin Study* in completing a comprehensive demand analysis. For consistency purposes, Table 10 below provides definitions of each demand category used in *The Basin Study*. Table 11 describes *The Basin Study's* projected change in water use by sector for Colorado, Wyoming, Utah, and New Mexico. These forecasts were made in 2012 and consider projected changes between 2015 and 2060.

Table 10. Definition of demand categories and their associated parameters (USBR 2012e).

Demand Category	Definition	Parameters
Agriculture	Water used to meet irrigation requirements of agricultural crops, maintain stock ponds, and sustain livestock	Irrigated acreage, irrigation efficiency
Municipal and Industrial	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	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

Table 11. Change in projected use between 2015-2060 (USBR 2012g, 2012h, 2012i, 2012j).

Category	Colorado (The Basin Study Appendix C2)	Wyoming (The Basin Study Appendix C5)	Utah (The Basin Study Appendix C4)	New Mexico (The Basin Study Appendix C3)
Population	Increase 5.7 million to 9.9 million	Increase 310,000 to 410,000	Increase 2.4 million to 4.9 million	Increase 1.5 million to 2.6 million
Change in per capita water use	Decrease 9% due to more efficient water use by the growing municipal population	Increase 3% because the increase in municipal population across the entire CRB in WY is predicted to be less efficient	Decrease 14% due to more efficient water use by the growing municipal population	Decrease 11% due to more efficient water use by the growing municipal population
M&I Demand	Increase 455 KAF to 732 KAF The majority of this increase (between 60-75%) is due to population growth in the South Platte basin.	Increase 30 KAF to 67 KAF	Increase 236 KAF to 324 KAF	Increase 138-141 KAF to 230 KAF
Agriculture Demand	No change (1,875 KAF)	Increase 398 KAF to 406 KAF	Increase 457 KAF to 493 KAF	No change (111 KAF)
Irrigated acres	Decrease 2.17 millions of acres to 2.13 millions of acres due to increased urbanization	Remain relatively constant (95,000 KAF to 94,000 KAF)	Decrease 860,000 acres to 800,000 acres	No change (140,000 acres)
Change in per acre water delivery	0% decrease	1% increase	3% decrease	0% increase

Category	Colorado (The Basin Study Appendix C2)	Wyoming(The Basin Study Appendix C5)	Utah(The Basin Study Appendix C4)	New Mexico(The Basin Study Appendix C3)
Energy Demand	Increase 30 KAF to 118 KAF Due to increasing need for energy sources from coal, solar, and oil shale. These increases root mostly from energy demands in the Colorado River and White basins. (These reductions in irrigated acreage are offset to some extent by increases in water delivery per acre as a result of more intense cultivation or full irrigation of remaining acreage)	Increase 42-52 KAF to 65 KAF. Due to increasing need for electricity generated by coal and solar	Increase 47 KAF to 60 KAF Due to growing need for electricity generation	Increase 40.0 KAF to 41.5 KAF Due to increasing need for electricity generated by coal and solar
Mineral Demand	Increase 32 KAF to 60 KAF The mineral extraction industry in all basins will increase (except in the Dolores where demands are small and the South Platte and Arkansas basins where demands are not identified)	Increase 20-34 KAF to 59 KAF This increase, primarily due to soda ask production, is expected to increase in the Fontenelle and Green River areas	0 No projections	0 There is no reported mineral extraction in New Mexico that uses Colorado River water
Fish, Wildlife, and Recreation	0 Water for fish, wildlife, and recreation is not considered consumptive.	Increase 2 KAF to 10 KAF	0 Water for fish, wildlife, and recreation is not considered consumptive	0 Water for fish, wildlife, and recreation is not considered consumptive

Category	Colorado (The Basin Study Appendix C2)	Wyoming (The Basin Study Appendix C5)	Utah (The Basin Study Appendix C4)	New Mexico (The Basin Study Appendix C3)
Tribal Demand	0 Tribal water needs are considered in the other categories, at the request of the Southern Ute Indian and Ute Mountain Ute tribes. (The tribal reserved water rights are the senior rights in the San Juan basin in Colorado; therefore, in times when full basin demands cannot be met, the first water diverted in the basin is essentially for tribal water right diversions.)	0 There are no federally recognized tribes in Wyoming with rights to Colorado River water	Increase 170-272 KAF to 259 KAF	Increase 303-309 KAF to 367 KAF
Total Colorado River Demand	Increase 2,391 KAF to 2,784 KAF	Increase 511 KAF to 606 KAF	Increase 911-1,012 KAF to 1,154 KAF	Increase 598 KAF to 606 KAF

Some important conclusions can be drawn from this analysis:

- Overall water use in the Upper Basin states is expected to increase.
- Population is likely to increase in each state.
- M&I and energy sectors are also expected to increase in each state.
- While Utah's irrigated acres and per acre water deliveries are expected to decrease over time, the state will still likely see an increase in agricultural demand due to an increase in applied water use.
- Colorado, Utah, and New Mexico expect to see a decrease in per capita water use by 2060 due to more efficient water use by municipal populations.

Legal Factors

As mentioned earlier in this report, the Upper Basin has an obligation under the *1922 Colorado River Compact* to make available 75 MAF in any 10 year running average of Colorado River water to the Lower Basin (NRC 2007) and in some years an additional 1.5 MAF/YR to Mexico (*Mexican Water Treaty and Protocol* 1944). The *Upper Colorado River Basin Compact of 1948* dictates how this apportionment is allocated between the Upper Basin states (each state is given a percentage of available Colorado River water), which is elaborated upon in the above state profiles. Each Upper Basin state has the authority to allocate their individual shares of Colorado River water (Hecox et al. 2012). Failure of the Upper Basin to deliver the required amount of water to the Lower Basin, however, could result in a compact call, with Upper Basin junior water rights holders required to temporarily forego water use and diversions. Specifying which states are curtailed in the event of a compact call, and by how much, remains contentious.

The primary legal issue of contention is conflicting legal terminology in the *1922 Compact* that defines how water is shared between the Upper and Lower Basins. One interpretation is that the phrase "obligation to deliver 75 MAF every ten years" used in Article III(a) requires the Upper Basin to deliver the full apportionment to the Lower Basin before satisfying Upper Basin needs. The second interpretation concerns the phrase "an obligation not to deplete" the flow of the river below 75 MAF in any 10 year running average in Article III(d). A USBR report defines this phrase as reductions resulting from "manmade improvements", effectively stating that the Upper Basin is not required to bear the full burden of shortages as long as the reduced streamflow is not the direct consequence of human-built infrastructure. Debate remains over the prevailing interpretation based on the actual text of the document and the intent of the legislators when creating the *1922 Compact* (Colorado River Governance Initiative 2012a).

The *Upper Colorado River Basin Compact of 1948* provides only slight certainty as to how a compact call would work; water levels in the Colorado River Basin, to date, have never dropped so low to trigger such a requirement. Due to differences between how each Upper Basin state manages their water right systems and disagreement about how curtailment rules work in the event of a compact call, curtailments could be legally complicated. In the event of a compact call, pre-compact water rights would not be curtailed due to the Doctrine of Prior Appropriations under which each Upper Basin state operates. However, "there are technical and administrative differences among the states," that leave operational questions unanswered about how a compact call would look on the ground (Kuhn 2012).

Lastly, much uncertainty remains as to the exact proportion of Mexico's 1.5 MAF/YR treaty entitlement that is required of the Upper and Lower Basins. While there is consensus that an obligation to Mexico exists, how much falls to each basin remains a legally contested issue that pits the Upper Basin states against those in the Lower Basin. The current majority position is that each basin must provide half of

Mexico's entitlement; requiring each basin to deliver 0.75 MAF/YR out of their annual allocation (Colorado River Governance Initiative 2012b).

There are important legal differences between the Upper and Lower Basin that implicate associated risks and vulnerabilities to the regions in the event of water shortages:

1. The *1922 Compact* states*, "*The States of the Upper Division will not cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75 MAF for any period of 10 consecutive years," (US Congress 67) effectively placing the Lower Basin states at higher priority compared to the Upper Basin. This creates vulnerability for the Upper Basin should water levels decline because these states will ultimately "bear the primary risk of reductions in basin yield in the future -- whether those reductions result from drought, climate change, or other critical landscape-scale changes that are impacting water yields" (Culp et al. 2015). It's important to note, however, that under Article VIII, the *1922 Compact* makes the distinction that Present Perfected Rights are "unimpaired" by curtailments (US Congress 67).

2. The Lower Basin is not subject to the same compact delivery obligations affecting the Upper Basin. The USBR under the *Interim Guidelines* established Lake Mead storage thresholds that trigger shortages to water deliveries in the Lower Basin. Due to coordinated operations described in the *Interim Guidelines*, however, localized shortages in one basin may alter operational guidelines in the other.

3. As beneficiaries of an upstream reservoir, Lower Basin water users are required to have a contract with USBR that describes accounting records for use on the main stem of the Colorado River below and in Lake Mead. These are grouped together in the Lower Colorado River Water Delivery Contracts Entitlement Listing. These contracts help describe the types of sectors from which each water rights holder comes as well as their priority date (Jiang et al. 2015). Documentation of this kind is not available for the Upper Basin. Instead, water in the Upper Basin is not generally diverted under contracts, but through state water rights (or decrees) (Kuhn 2016). Each State Engineer is responsible for water rights accounting, making it difficult to comprehensively analyze, for the entire Upper Basin, the pre- and post-compact water rights, the sectors from which they come, and the proportion of allocated water rights currently in use. This level of uncertainty creates substantial risk for the Upper Basin should water managers begin curtailment.

Conclusion

Water originating in the headwaters of the Upper Colorado River Basin passes through Colorado, Wyoming, Utah and New Mexico before merging upstream from Lake Powell. Stored water helps Upper Basin states fulfill annual compact deliveries to the Lower Basin, generate hydroelectric power, and create recreational opportunities. Above this point, however, this water is used to meet the needs of agriculture, municipalities, industry, recreation and the environment. Declining water levels due to hydrologic factors, high water demand, and legal ambiguity create risk for these Upper Basin water users. To fully understand the impacts of operating Lake Powell at low levels, we assessed:

- hydrologic factors affecting water availability;
- historical water demand trends;
- recent water demand by sector to highlight state specific concerns;
- future water demand forecasts;
- legal factors creating management uncertainty.

Each state has their own set of vulnerabilities when it comes to declining water levels; however, a few broad conclusions can be drawn:

- Regional and localized models show increases in regional temperature, reductions in snowpack, and reductions in annual runoff and streamflow.
- Discrepancies exist between the location of large population centers and where Colorado River supplies are natural located.
- Many users reliant on Colorado River water have limited access to substitutable water sources in the event of localized shortages.
- Overall water use in the Upper Basin is expected to increase.
- Population in the Upper Basin is expected to grow.
- M&I and energy sectors are expected to increasingly use more water in the future.

The Upper and Lower Basins differ in large part to varying legal factors that are fraught with much ambiguity. Debates over the intentions of *1922 Compact* remain today and contribute to great uncertainty as to how compact curtailments would be implemented in the event of substantial water shortages. One piece of the contention is over whether the Upper Basin is in fact junior to the Lower Basin. This becomes increasingly complicated when considering the priority system of water rights in each individual state, which of the junior users would be curtailed first and by how much, and how this would all play out across the entire Upper Basin.

Concurrently, the Lower Basin is not subject to the same compact delivery obligation affecting the Upper Basin and is instead subject to Lake Mead shortage thresholds dictated by the *Interim Guidelines.* These thresholds define when the Lower Basin will experience a shortage and the size of that shortage. This is not the case upstream. While the Upper Basin and Lake Powell are operationally and legally linked to Lake Mead through the coordinated operations outlined in the *Interim Guidelines*, the operational tiers (Figure 4) affecting Lake Powell do not directly trigger quantifiable curtailments in the Upper Basin. Upper Basin vulnerability to declining reservoir levels at Powell are instead incremental, with localized shortages more directly influenced by on-going hydrologic and social trends that are illustrated in the above state profiles.

Hydropower

Introduction

Glen Canyon Dam is the second largest hydroelectric power producing facility in the Colorado River Basin after Hoover Dam (Figure 22). It is located in northern Arizona, near the City of Page, in Coconino County. The dam is 710 feet tall and spans 1,560 feet from wall to wall across Glen Canyon (USBR 2009b). The dam was congressionally authorized in 1956 by the *Colorado River Storage Project Act* and construction was completed in 1963, creating Lake Powell (USBR 2008a). Due to the massive size of the reservoir, it took 17 years for its full capacity of over 26 MAF to be reached, making it the second largest man-made reservoir in the United States (Friends of Lake Powell n.d) (again, second only to Lake Mead, above Hoover Dam). Lake Powell stretches 186 miles behind Glen Canyon Dam and has 1,960 miles of shoreline dispersed throughout its 96 canyons.

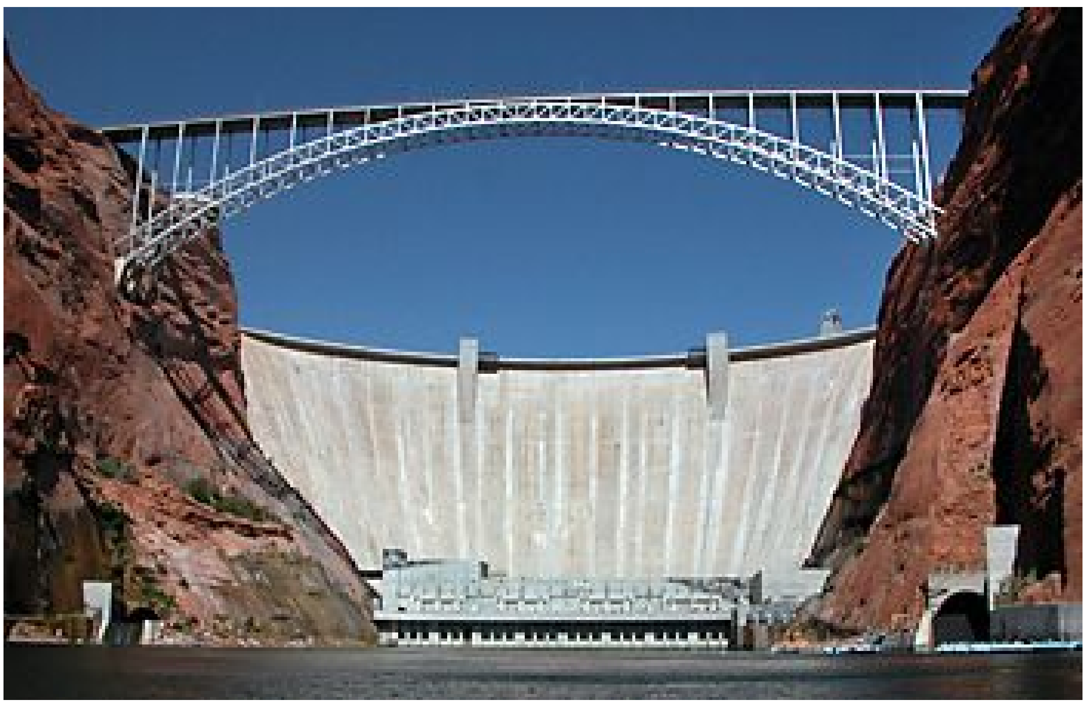


Figure 22. Photograph of Glen Canyon Dam and Power Plant (USBR 2009).

Despite the magnitude of Lake Powell, it remains vulnerable to a changing environment and management priorities. Recent analyses show that drying trends in the Southwest will continue to manifest as lower cold-season precipitation and increased evapotranspiration. These factors working in tandem will lower soil moisture and reduce overall water availability within the Colorado Basin (Cook et al. 2015). Water is also lost from the system via evaporation and seepage into the porous sandstone (Myers 2013). In addition to these hydrological factors there are several management challenges that may constrain Glen Canyon Dam's ability to produce hydropower. The coordinated action of Glen Canyon Dam and Hoover Dam, driven by the *Interim Guidelines,* and environmental constraints imposed by the 1996 Record of Decision (ROD) on the Operation of Glen Canyon Dam add to the challenge of keeping Lake Powell full.

The overarching goal of this section is to better understand the operational and financial implications of reduced reservoir levels on hydropower generation at Glen Canyon Dam. A detailed knowledge of dam operations, hydropower generation, and hydropower marketing is essential in order to investigate this question. Because dam operations and hydroelectric power marketing are managed by different entities and are subject to a variety of regulations, there are many variables that could influence hydropower generation and its associated cost in the event of drought. While much of this information is known and conveyed in different places, few resources exist that bring together all of these components with an explanation of the system as a whole.

Additionally, few studies have sought to quantify the financial impact that could occur as reservoir levels decrease in Lake Powell. A 2004 analysis estimated that if Glen Canyon were to stop producing power entirely, it would cost $180 million dollars to meet contractual energy obligations (Ostler 2004). However, the complete elimination of power generation at Glen Canyon is unlikely and estimates at various reservoir levels before deadpool would provide information regarding more likely scenarios.

The 2007 Environmental Impact Study (EIS) for the *Interim Guidelines* provides an in depth look at likely changes in power production associated with the alternatives being considered at the time, however a similar analysis post implementation of the *Interim Guidelines* does not exist. Additionally, while the EIS provides information associated with the alternatives, it does not provide information regarding energy production associated with discrete reservoir elevations. Our final objective is to quantify the additional cost of power at discrete elevation intervals as reservoir levels decline.

Background Information

Glen Canyon Hydropower Technical Specifications

The Glen Canyon Power Plant began generating power in 1964, and by 1966, all eight of the dam's generators were operational (USBR 2008a). Each generator has a capacity of 165 MW for a total operational capacity of 1,320 MW which produces an average of five million MWh annually, serving the needs of over 5.8 million power customers (USBR 2014a). It would take an estimated 2.5 million tons of coal or 11 million barrels of oil each year to produce the same amount of power generated on a yearly basis at Glen Canyon Dam (based upon an approximate conversion rate of 580 kilowatt-hours per barrel of oil and 1,822 kilowatt-hours per ton of coal) (USBR 2008). Additionally, replacing Glen Canyon Dam's power with natural gas or coal would result in the release of over four billion and eight billion pounds of CO_2, respectively, into the atmosphere (CREDA 2015).

Water can be released from the dam in three ways: through the power plant, through river outlet works, or bypassed through spillways (Figure 23). Spillway releases only occur during instances of critical high water to avoid overtopping the dam. Although the combined capacity of spillway releases, river outlet works, and power plant release facilities is 256,000 cfs, the maximum combined release from Glen Canyon Dam under current operating criteria should not surpass 25,000 cfs, as outlined in the 1996 Glen Canyon ROD (USBR 1995a). Exceptions to this limit are made for operating emergencies, habitat maintenance flows and high flow experiments.

When water is released through the power plant the kinetic energy of the falling water can be harnessed and converted to mechanical energy via a turbine (WVIC 2015). At Glen Canyon Dam, water stored in Lake Powell is directed through an intake structure towards eight penstocks, which directs water towards eight turbines (Figure 23) (USBR 2009). As the water pushes against the turbine blades, the generators, which are connected to the turbines by a shaft, also spin, creating electrical energy. Seven of the eight generators were upgraded to their present capacity of 165 MW between 1984 and 1987 and the eighth and final upgrade was made in 1997 (USBR 2007a).

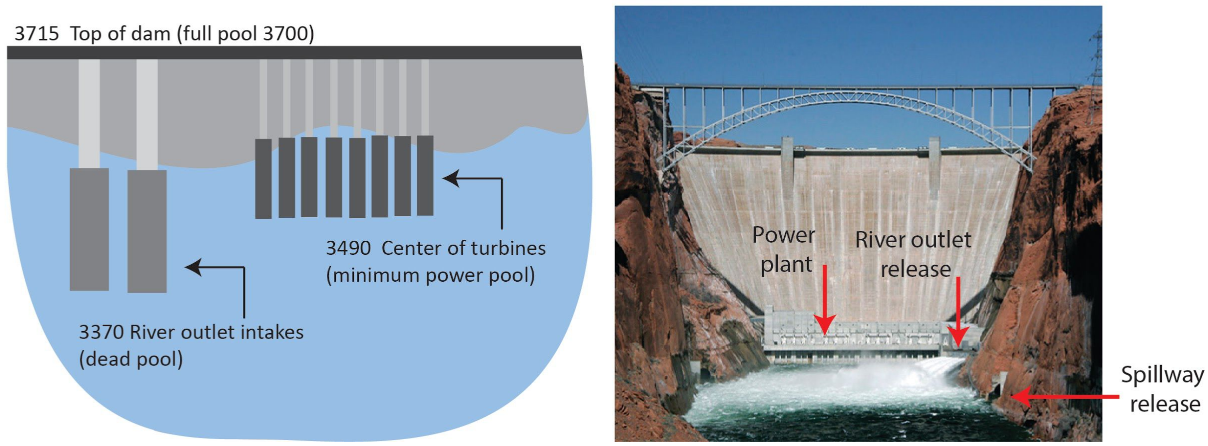


Figure 23. Diagram of Glen Canyon Dam identifying the three methods for water releases (power plant, river outlet works, and the spillway) (Image at right from USBR 2016a).

The eight turbines have the ability to discharge 31,500 CFS, but as mentioned earlier, releases above 25,000 CFS are typically not allowed due to environmental constraints identified in the 1996 EIS. Higher releases are allowed for emergency or extreme hydrologic conditions. These operating constraints, as well as limits on the rate of increasing flow, are in place to prevent rapid fluctuations downstream. Thus, the Glen Canyon Power Plant is limited to an operational capacity of 1,000 MW, when the reservoir is full (USBR 2007c). If additional releases are needed beyond the capacity of the turbines, the river outlet works are utilized. The elevation of water when the reservoir is full is 3,700 feet. This is known as the full pool elevation. The eight penstocks, which divert water towards the power generating turbines, are located at a centerline elevation of 3,470 feet and are 15 feet in diameter (Figure 23).

The USBR has set the minimum power operation level (minimum power pool) at 3,490 feet to avoid vortex problems on the surface of the reservoir (water at the surface swirling as it is pulled into the penstocks below), and to avoid cavitation problems[12] with the generating turbines (Ostler 2004). Below this elevation, releases from the dam can be made through the river bypass tubes and water will not be drawn into the penstock and power production will cease (1995a). Discharge through the turbines is the preferred method of water release because electricity, and its associated economic value are produced through this process (Ostler 2004). Recent reservoir elevations at Lake Powell have hovered around 3,591 feet above sea level (as of April 20, 2016), about 43 percent of capacity, or about 6.6 MAF of usable power pool (USBR 2016b).

Colorado River Storage Project

Glen Canyon Dam was authorized and constructed pursuant to the *Colorado River Storage Project Act of 1956*, which congress passed to allow for the development of water resources in the Upper Basin (US

[12] Cavitation is the formation of bubbles in fluid flowing through a turbine, which generate pressure waves at high frequencies and may damage the turbines (Germann 2014).

Congress 84). The four main water storage units developed as part of the Colorado River Storage Project, or CRSP, store water for consumptive use, provide for flood control and have hydroelectric power producing capabilities. Glen Canyon Dam is the largest of the four and is the keystone unit for controlling water releases from the Upper Basin to the Lower Basin. Flaming Gorge Dam in northeast Utah is located on the Green River and has a power generating capacity of 150 MW (USBR 2014b). Navajo Dam is located on the San Juan River in northwestern New Mexico. Although not initially constructed as a hydroelectric power plant, capacity was added to the unit in 1985 by the City of Farmington and today has a capacity of 32 MW (USBR 2008b). Finally, the Wayne N. Aspinall Unit, located in western Colorado on the Gunnison River, is comprised of three individual dams; Blue Mesa Dam, Morrow Point Dam, and Crystal Dam. Those three dams have a combined power capacity of 283 MW (USBR 2008c). Figure 24 provides a map of all CRSP projects. Glen Canyon Dam and its eight generators represent 70 to 80 percent of the total CRSP capacity.[13]

[13] In addition to the four units initially authorized there are twenty-two participating projects, authorized by subsequent legislation. Only sixteen of these participating projects are complete, and the remaining are deemed infeasible. These participating projects supply an additional 554,000 AF of water for irrigation and serve the needs of an additional 1.2 million people (USBR 2016).

Figure 24. Map of initial four CRSP units (in red) and additional participating projects (USBR 2016).

Marketing Hydropower

Methods

Along the Colorado River, dams are operated and power is marketed according to legislative requirements and institutional protocols. While some key concepts are transferable across systems, many are not. In order to determine how power from Glen Canyon Dam is marketed we first considered the factors that govern power marketing as a whole within the region. To do this, we utilized a variety of technical papers, agency websites, historical perspectives, and correspondence with managers in charge of marketing operations. While this provided a broad overview, many questions about how Glen Canyon Dam fits within the regional power framework remained. Many details specific to Glen Canyon are not readily available via online sources and so we elicited the assistance of several agency personnel. Through a series of phone conferences, we obtained information regarding the specific manner in which power from Glen Canyon Dam is marketed to the public. Below we present the information we gathered from online and agency documents. This is followed by a description specific to Glen Canyon Dam based on information from our series of conference calls with Western Area Power Administration personnel.

Western Area Power Administration

Many large dams throughout the Southwest, including the CRSP system, are operated and maintained by the USBR. In 1977, the *Department of Energy Organization Act* created the Western Area Power Administration (known as Western) and transferred the responsibility of power marketing and the operation of the transmission systems from the USBR to Western. Western consolidates CRSP power with the power generated from two other hydroelectric projects (the Collbran Project in Colorado and the Rio Grande Project in New Mexico and Texas) and bundles it into a combined energy product known collectively as the Salt Lake City Area Integrated Projects, often identified as SLCA/IP (USBR 2008d). These power generating projects make up the SLCA/IP marketing area, which provided power for the SLCA/IP service areas (Figure 25). Currently, 143 customers receive power from SLCA/IP including numerous municipalities, irrigation districts, and American Indian Tribes (Western n.d.a). A full list of customers is provided in Appendix A.

Figure 25. Map of SLCA/IP marketing area, shown in blue (Western n.d.b).

Western supplies both firm and non-firm power to a variety of wholesale customers who provide retail electrical services to customers throughout the West. Firm power is energy that Western guarantees will be available to customers 24 hours a day according to contract agreements, while non-firm power is sold with the understanding that it is not guaranteed and the customer must be able to meet its own load (customer demand) in the case that it cannot be provided by Western (Western 2012).

Hydropower production in the region follows fluctuating electrical demand to the extent water releases and environmental restrictions allow, through a practice known as load following. This means that power generation adapts to the demand, which is determined by the amount of electricity being utilized at a given time. One of the primary benefits of hydroelectric power is that generation can be adjusted quickly and efficiently by varying the amount of water being released through the generator turbines (USBR 1995b). This makes hydropower a good source for providing peaking power while the larger, less-flexible coal, natural gas and nuclear resources provide baseload power (USBR 2008f). Baseload is the constant and steady electrical power demand that is relatively stable over the course of the year. Depending on operating restrictions, additional power can be generated from Glen Canyon Dam at a very rapid rate to address daily peak demand. When demand is greater, such as during the afternoon on a hot day, hydropower generation can ramp up quickly to meet that additional load. Western schedules hourly releases in response to monthly water volumes and to meet contractual obligations for the delivery of electrical power (GCDAMP 2013).

Western's mission is to market the federal hydropower and resources in accordance with the law and at the lowest possible rate consistent with sound business practices. When generating and delivering power from Glen Canyon Dam, Western and the USBR must follow multiple criteria set by a variety of laws and operating requirements, which may vary from project to project. CRSP power must first be used to meet project needs, known as project-use power. Project-use power includes the energy required to pump water at federal irrigation projects as defined by the *Federal Power Act*. Project-use power cannot be diminished by sales to other customers and congressional action is required to authorize additional purposes for project-use power. Once project-use obligations have been met, Western may then provide power to preference customers.

The *Reclamation Act of 1939* requires that certain users have priority in accessing federal power. These preference customers include state and federal agencies, water and irrigation districts, municipalities, public utility districts, American Indian Tribes, and rural electrical cooperatives. Western must sell this power to preference customers at the lowest possible rate while also generating enough revenue to cover its repayment obligations, which include the project's capital cost plus interest, irrigation assistance (beyond the ability of irrigators to pay), operation and maintenance costs, salinity control costs, as well funding for certain environmental programs (Western, 2012). Western conducts power repayment studies in order to determine the power rate for preference customers that will allow Western to meet their annual revenue requirement (USBR 1995b). Once obligations to preference customers are met, Western may then sell any remaining power to for-profit utilities on a non-firm basis at market rates (CREDA 2006).

Based on the above regulations, Western develops specific power marketing plans for all projects that specify how and when power will be sold. Additionally, the marketing plan specifies contract terms, the types of electrical services offered and the amount of services offered (Western 2012). Since Western's ability to generate enough electricity to meet its contractual obligations can be hindered by decreased hydrology during periods of drought, marketing plans may also outline Western's obligations to provide supplemental power from other non-hydroelectric sources.

CRSP Power

CRSP contracts have a 20-year term and the current contracts extend until September 30th, 2024 (Western n.d.d). The power generated by CRSP units is marketed to 143 preference customers at a guaranteed contracted rate of delivery or "CROD." The CROD is the maximum energy and capacity that customers are entitled to receive from the CRSP generating units. These long term contracts can be changed with a five-year notice to customers. This energy delivery is essentially the total allotment that can be distributed to customers. The CROD allotments are a best case scenario and unlikely to be met by hydropower generation alone (Western 2016).

In 1996 the Glen Canyon ROD established the contract concept of Sustainable Hydropower, or “SHP”. The SHP is Western’s actual energy obligation to its customers for the 2004 to 2024 timeframe. SHP is less than the full CROD because it takes into account limitations such as water availability. Western guarantees CRSP customers the amount of power determined by SHP; however, year to year variation in hydrology and environmental limitations often create conditions where hydropower from the CRSP system cannot meet SHP. CROD and SHP obligations vary slightly by month and are shown below in Figure 26.

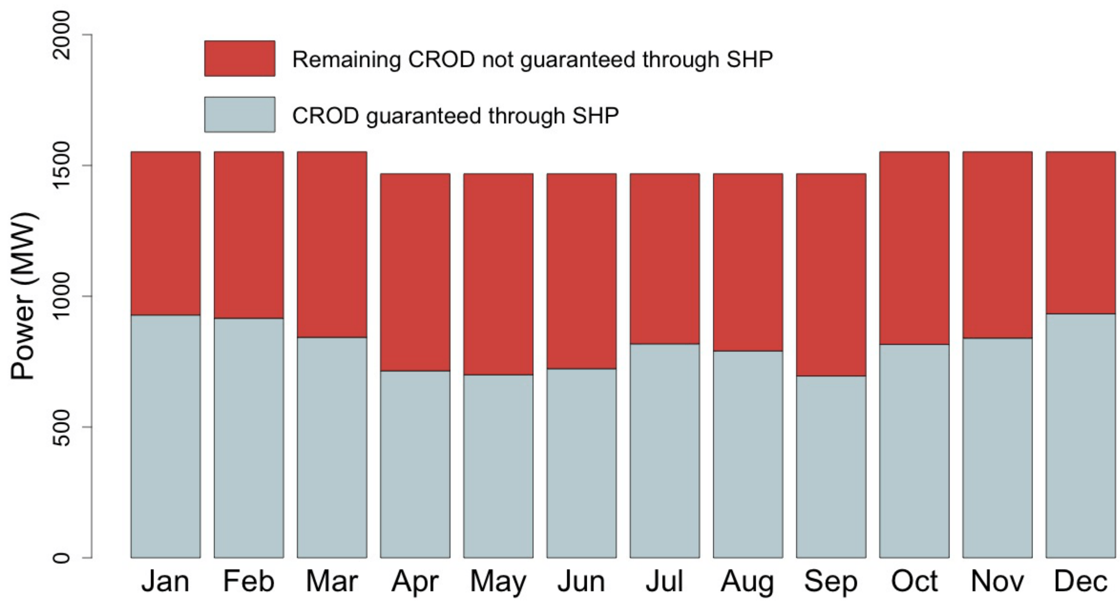


Figure 26. Monthly CROD and SHP obligations for CRSP. Data obtained from Western.

In the case that CRSP units are not able to generate the energy necessary to satisfy the SHP obligation, additional energy must be delivered by way of firming purchases. The amount of hydropower generated combined with firming purchases makes up the total SHP that Western is obligated to provide its customers (Western 2016). The cost of firming purchases is passed on to the customers. In some cases, when hydrologic conditions allow, additional hydropower (AHP) is made available to customers on top of SHP. The left side of Figure 27 below illustrates the relationship between CROD, SHP, AHP, and firming purchases and Table 12 provides definitions for each acronym.

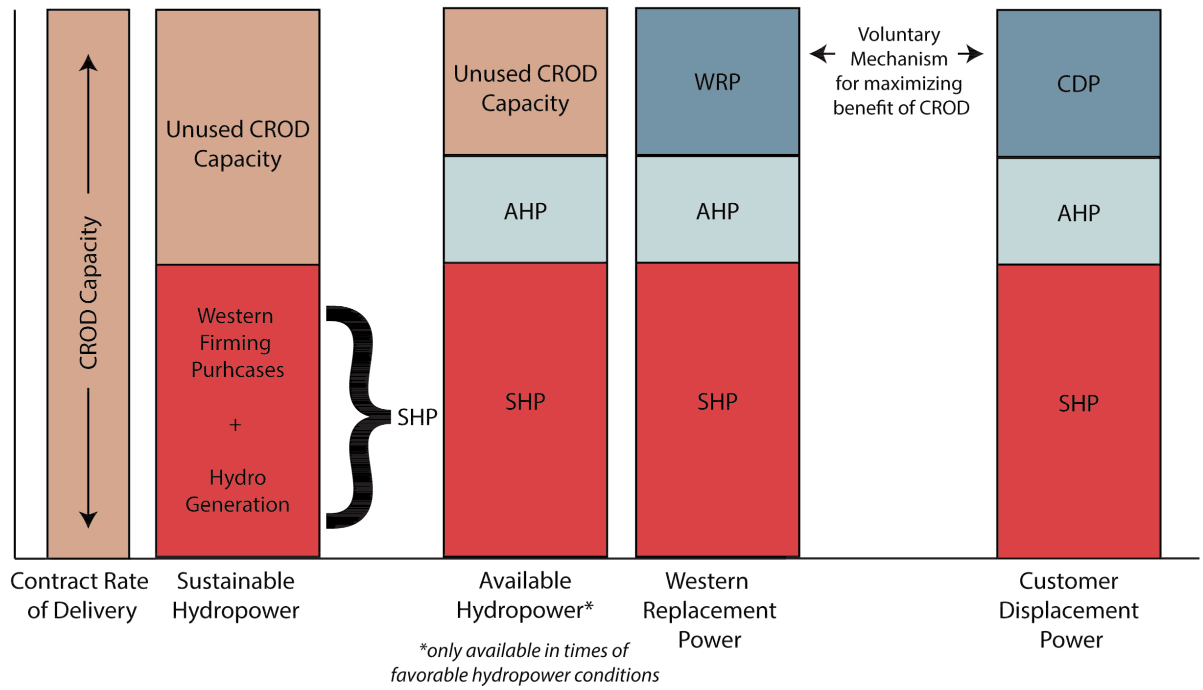


Figure 27. Diagram depicting key CRSP concepts. Information for figure obtained from Western 2016.

Firming Purchases are made by Western on the wholesale electricity market. The cost of these firming purchases is passed through to Western's customers. One major difference between power distribution at Glen Canyon and Hoover Dams is that at Hoover Dam individual customers must seek out their own firming purchases; at Glen Canyon, Western makes these purchases on behalf of the customer up to their contractual SHP requirement. These firming purchases have been a common occurrence in recent years when water availability in the reservoirs has been restricted by natural hydrologic conditions or due to experimental flows (Western 2016). For example, in fiscal year 2003, the CRSP management center purchased approximately 2.4 million MWh of firming energy to meet delivery requirements, representing 35 percent of total energy requirements at a cost of approximately $90 million (Warren, 2004). In 2004, a similar estimate was made predicting CRSP firming purchases for 2007 to be $80 million (Ostler 2004).

In order to meet the CROD, CRSP customers may purchase Western Replacement Power (WRP) or Customer Displacement Power (CDP). WRP represents additional purchases made by Western on the wholesale market on the customer's behalf. If a customer chooses CDP it is required to purchase or generate its own additional power supply but may utilize CRSP transmission up to its CROD entitlement (WRP and CDP are shown on the right side of Figure 27 and defined in Table 12).

WRP is most often used by smaller customers who do not have their own in-house means of sourcing replacement power. Western may be able to access power and deliver it to these customers at a better cost than if a small customer were to attempt to access that power on its own. In some cases, Western is able to aggregate the requests of several of its customers to utilize economies of scale in the wholesale market, as opposed to the customers accessing power individually. Larger customers may choose to use CDP because they can either increase their own production or have access to markets on their own (Western 2016).

Table 12. Definitions of CRSP acronyms. Information obtained from Western 2016.

CROD	Contract Rate of Delivery	The original CRSP contract obligation concept, CROD is the maximum capacity that customers are entitled to receive, is the basis for capacity payment and transmission rights today, and can be changed only with five years notice to customers.
SHP	Sustainable Hydropower	Established after the 1996 Glen Canyon EIS record of decision, SHP is the CRSP capacity and energy obligation concept for the 2004-2024 term, and can be changed only with five years notice to customers.
AHP	Available Hydropower	Additional hydropower made available to customers on top of SHP. Only available during times of favorable hydrologic conditions.
Firming Purchases	–	Firming purchases are the additional energy needed by WAPA to meet SHP obligations
WRP	Western Replacement Power	WRP is the mechanism that a customer can use to seek additional generation from Western, up to its CROD entitlement.
CDP	Customer Displacement Power	CDP is an option that allows a customer to seek the use of CRSP transmission to deliver its own non-CRSP generation, up to its CROD entitlement.

Quantitative Analysis of Cost Changes

Objectives and Challenges

Our final objective is to quantify the potential change in the cost of power associated with reduced reservoir levels in Lake Powell. The consolidation of power from Glen Canyon into the integrated SLCA/IP energy product presents challenges to this analysis. First, of the 143 entities who purchase SLCA/IP power, it is impossible to determine which receive power that is actually generated at Glen Canyon Dam. While some may be more likely to receive Glen Canyon power, the amount and occurrence of this fluctuates in real time. Another complication that makes it difficult to calculate the cost to individual contracting entities is that once SHP has been met, customers have the option of choosing WRP or CDP to reach their full CROD allocation. These options involve the purchase or generation of additional power via a multitude of different avenues. Additionally, even entities that choose CDP options benefit from utilizing Western transmission up to their CROD allocation. We were unable to find information regarding which of Western's SLCA/IP customers choose to pursue WRP versus CDP.

Due to these complication, we chose to consider the change in the cost of power as a whole, instead of the cost to the individual customer. However, we were still faced with the challenge of disaggregating the cost of Glen Canyon power from the entirety of SLCA/IP power. As mentioned earlier, the rate Western charges for power generated by SLCA/IP units is determined by the revenue requirement (which is calculated by the power repayment study). While it has been stated with confidence that Glen Canyon Dam makes up 70 to 80 percent of SLCA/IP power, it is not necessarily true that Glen Canyon Dam makes up 70 to 80 percent of the revenue requirement. Further, the revenue created through power generation at a particular unit is not necessarily used to repay costs of that specific unit within the SLCA/IP (Western 2016).

Based on the information above, setting a rate for Glen Canyon power based on this 70-80 percent estimate would not be an accurate representation and we chose not to attempt to estimate the cost of power originating solely from Glen Canyon Dam. However, given the fact that it is well documented that Glen Canyon makes up 70 to 80 percent of SLCA/IP SHP we can calculate the amount of firming purchases and the associated cost required to meet SHP as hydropower generation fluctuates based on reservoir conditions. Therefore, our analysis compares the potential cost increase of firming purchases as hydropower generation decreases due to declining reservoir levels.

Methods

Many factors, especially water releases and seasonal hydrology, determine the amount and timing of power that can actually be generated in a given year at Glen Canyon Dam. By determining the amount of hydropower available at given elevations we can determine the quantity of firming purchases required to meet Western's SHP obligation. By applying a firming purchase rate we can then determine the final cost of firming purchases at various elevations (see Figure 28 for model diagram).

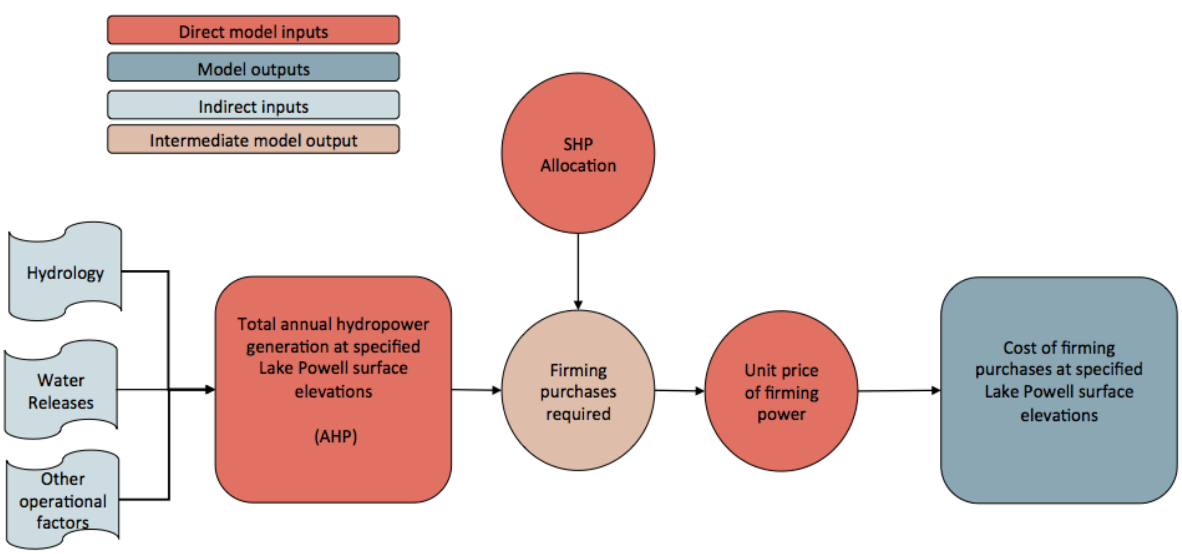


Figure 28. Conceptual diagram of model used to calculate cost of firming purchases needed to meet SHP obligations.

The change in the cost of firming purchases is examined at the elevations listed in Table 13. These numbers were chosen based on operational tiers outlined in the *Interim Guidelines* with the intention of utilizing elevations that will be relevant to managers.

Table 13. Elevation for analysis and significance

Elevation (feet)	Significance
3525	Transition from lower elevation balancing tier to mid
3575	Transition from mid elevation balancing tier to upper
3625	Within upper elevation balancing tier
3675	Within equalization tier

The model relies on two simple calculations. First, the total amount of firming purchases required is calculated as:

$$GC_{SHP} - HP_e = FP_t$$

Where;

$$GC_{SHP} = \text{Glen Canyon's contribution to SLCA/IP sustainable hydropower allocation}$$

$$HP_e = \text{available hydropower at elevation } e$$

$$FP_t = \text{Total amount of firming purchases required}$$

Finally, the total cost of total firming purchases can be determined by:

$$FP_t \text{ X } FP_r = FP_c$$

Where;

$$FP_r = \text{Rate of firming purchases}$$

$$FP_c = \text{Total cost of firming purchases}$$

This model does not consider the potential benefit of producing surplus hydropower generation over the SHP obligation, which may be possible under favorable hydrologic conditions. In some cases when surplus hydropower is generated it can be sold to customers. This is typically not done with small amounts of power due to the cost of administration. The last time this occurred was in 2011 (Western 2016).

Model Components

Hydropower (HP_e)

There are many factors that determine how much power can be generated at a hydroelectric power plant. While reservoir elevation is a crucial component, other factors also play an important role. The USBR has developed the Colorado River Simulation System (CRSS) which simulates reservoir conditions using a variety of inputs such as various environmental factors (like inflow and evaporation), reservoir conditions, and water releases, all of which impact the amount of hydropower able to be generated. The CRSS software uses this information to project the future state of various outputs, such as reservoir elevations, dam releases, the amount of water flowing through any particular point of the stream, and hydropower generation. Essentially, CRSS describes how water is released through the turbines and the subsequent generation of power under a variety of possible conditions (USBR 2012d).

Using CRSS model data, two scenarios were developed with the help of USBR staff for each key elevation in order to account for the importance of climatic conditions and dam operations on hydropower generation. The two scenarios provide bounds for the extremes in climatic conditions within the basin and dam operations. The scenarios model monthly hydropower generation and reservoir elevations over the course one full water year[14]. Multiple years of outputs were generated from a variety of varied conditions (including water releases). We sought out elevations for the month of January[15] that were close to our four elevations (3675, 3625, 3575, and 3525). January was used because of the manner in which CRSS operates and because volume predictions for January dictate the relevant operational tier and release volume. For each of these elevations we selected two full years of data. These runs represent the maximum and minimum amount of power that could be generated at each elevation.

We used this approach to account for the variability in hydropower generation. At any given elevation a variety of factors will determine how much power can be generated (as described above) and our goal was to account for this variability, although we do not attempt to quantify or assign cause to the variability. Monthly generation values were determined for one full water year and are shown below in Table 14.

[14] A water year is defined as October 1 to September 31.

[15] We used October through December of one year and January through August of the next, in order to obtain a full water year in chronological months.

Table 14. Monthly maximum and minimum generation values for each key elevation. Values are in MWh. Table created based on data generated by USBR from CRSS.)

	3525 ft		3575 ft		3625 ft		3675 ft	
	Min	Max	Min	Max	Min	Max	Min	Max
October	168,188	166,527	238,026	184,442	265,939	262,919	290,345	988,042
November	172,915	171,892	236,716	193,487	264,246	262,439	289,718	587,618
December	204,295	204,045	311,533	232,748	348,965	348,203	384,465	271,062
January	215,465	298,552	285,422	328,154	345,541	346,338	382,944	452,424
February	195,358	224,448	211,857	244,904	257,449	280,436	286,822	571,794
March	171,140	222,207	210,878	244,735	256,148	280,862	286,528	490,179
April	157,100	220,814	175,615	246,603	254,740	261,808	286,465	464,912
May	156,646	276,694	211,161	255,772	253,253	291,382	288,141	466,310
June	197,056	336,867	212,287	290,549	272,005	372,590	313,573	980,670
July	303,600	427,403	281,268	385,268	350,650	474,841	407,945	1,013,337
August	281,855	461,641	277,990	402,453	364,600	498,117	427,728	806,791
September	135,400	357,929	206,455	278,758	252,409	379,813	297,550	675,614
Annual	2,359,018	3,369,019	2,859,208	3,287,873	3,485,945	4,059,748	3,942,224	7,768,753

Sustainable hydropower (GC_{SHP})

Sustainable hydropower, which is determined for the 2004 to 2024 contract period was obtained from Western. These values pertain to the entire SLCA/IP system. On average Glen Canyon makes up between 70 and 80 percent of this value. To incorporate sensitivity we ran the model utilizing 70, 72.5, 75, 77.5, and 80 percent of the total SHP. Total SHP values and the middle value of 75 percent of SHP are shown below for each month.

Table 15. Total SLCA/IP SHP energy allocation and the proportion likely to be generated by Glen Canyon Dam (shown here as 75 percent of total and calculated at 70, 72.5, 75, 77.5, and 80 percent in the model). Values are in MWh. (Data provided by Western.)

	SLCA/IP SHP Energy Allocation (MWh)	Glen Canyon Contribution (MWh) (Calculated at 75%)
October	447,173	335,380
November	446,635	334,976
December	495,044	371,283
January	503,142	377,356
February	446,960	335,220
March	471,247	353,435
April	411,826	308,869
May	425,869	319,402
June	444,032	333,024
July	482,353	361,764
August	485,701	364,276
September	426,699	320,025
Annual	5,486,679	4,115,009

Firming purchase rate (FP_r)

Western publishes firming purchase prices online for both peak and non-peak power (Western n.d.c). Since Westerns firming purchases are generally made at peaking rates we calculated a ten-year average of peak rates (2004/05 - 2014/15 water years) and used that as our base rate for firming purchases. All dollar values are adjusted for inflation into 2015 dollars. Because prices on the wholesale market fluctuate based on a variety of factors and are very difficult to predict we chose to incorporate sensitivity into the model by calculating the standard deviation for each month during the ten-year period. We then calculate the percent change from the average required to cover one standard deviation from the mean. While not all monthly values fell within one standard deviation of the mean, most did. The variance is likely due to the sensitivity of the energy market over time. As shown in Table 16 the maximum percentage change to one standard deviation is just under +/- 40 percent. In order to incorporate the range of data over the ten-year period into the model we varied the prices of firming purchases by -40, -20, 0, +20, and +40 percent. This method means that rather than predicting specific costs of firming power at our defined elevations we instead provide a range of possible costs. Increasing the range to 40 percent creates a wider range of possible cost predictions, however, it does not change the average.

Table 16. Ten-year average cost of firming purchases for the 2004/05 - 2014/15 water year time period. All costs were adjusted into 2015 dollars. (Raw data obtained from Western n.d.c)

	Average cost ($/MWH) (2015$)	Standard deviation	Range needed to incorporate +/- 1 standard deviation
October	49.59	16.87	34%
November	49.44	15.75	32%
December	52.96	20.01	38%
January	58.29	17.53	30%
February	60.17	18.19	30%
March	54.51	17.51	32%
April	53.29	19.83	37%
May	54.31	18.83	35%
June	56.84	20.18	35%
July	68.28	23.92	35%
August	62.68	17.40	28%
September	53.50	16.20	30%

Results

For each scenario, we ran 25 model iterations to incorporate the fluctuation in the percent of SLCA/IP power that is produced by Glen Canyon Dam (70, 72.5, 75, 77.5 and 80 percent) and variations in firming power prices (-40, -20, 0, +20, +40). These 25 iterations were used to provide ranges of potential costs for maximum and minimum generation at each of the four elevations.

Again, it should be noted that the range of values calculated in this model represent the potential cost of firming purchases needed to meet Western's SHP obligation. It does not include the prices of power actually produced at the dam. Additionally, to fulfill full CROD allocations customers will have additional costs associated with WRP or CDP. Last, these numbers only represent months where firming purchases were required to meet SHP. Months where hydropower generation was above SHP are not included, since it is unknown whether that power would be sold and the rate at which it would be sold. Table 17 below, shows the number of months where firming purchases were required for each elevation in the case that Glen Canyon power makes up 70, 72.5, 75, 77.5 and 80 percent of total SLCA/IP power. As shown, firming purchases were required during the majority of months for each scenario except maximum generation at maximum (3675) elevation.

Table 17. Number of months requiring firming purchases for each of the elevations. Shown for both maximum and minimum generation scenarios assuming Glen Canyon contributes varying amounts of SHP between 70 and 80 percent).

		Percent of SHP made up by Glen Canyon Dam				
Generation	Elevation (ft)	**70%**	**72.5%**	**75%**	**77.5%**	**80%**
Max	**3675**	1	1	1	1	1
	3625	7	8	8	8	8
	3575	10	10	10	10	11
	3525	8	8	8	9	9
Min	**3675**	6	6	7	8	8
	3625	9	10	11	12	12
	3575	12	12	12	12	12
	3525	12	12	12	12	12

Figure 29 shows the annual amount of hydropower generated in both maximum and minimum generation scenarios at all four elevations. Firming purchases are greater at lower elevations and under minimum generation scenarios. In this figure, the amount of firming purchases required at Glen Canyon Dam is calculated to meet 75 percent of total SLCA/IP SHP. Under the minimum generation scenario firming purchases make up to 43 percent of total SHP (Table 18).

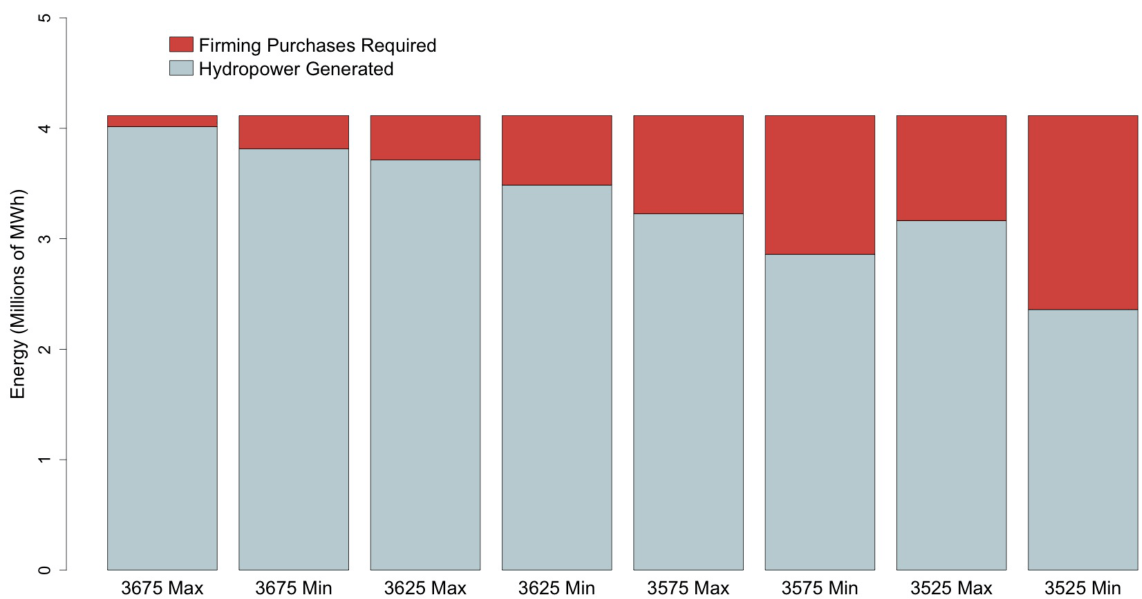


Figure 29. Annual amount of hydropower generation for maximum and minimum generation scenarios at all four elevations, assuming Glen Canyon contributes the average amount of 75 percent of SLCA/IP's SHP.

Table 18. Percent of SHP comprised of firming purchases for maximum and minimum hydropower scenarios at all four elevations assuming Glen Canyon contributes the average amount of 75 percent of SLCA/IP's SHP.

Elevation (ft)	Maximum	Minimum
3675	2%	7%
3625	10%	15%
3575	22%	31%
3525	23%	43%

Figure 30 and Figure 31 depict the full range of potential costs associated with each elevation for maximum (Figure 30) and minimum (Figure 31) scenarios. Ranges exhibit more overlap at maximum generation than at minimum. The large ranges are likely a result of sensitivity factored into both the percent of total SLCA/IP power being generated at Glen Canyon (70, 72.5, 75, 77.5, and 80 percent) and the sensitivity incorporated into the cost of firming purchases (-40, -20, 0, +20, +40), in order to incorporate one standard deviation around the mean). Ranges are much wider at lower elevations, likely due to the fact that more purchases are being made in these scenarios, resulting in more variability due to the -40 to 40 range.

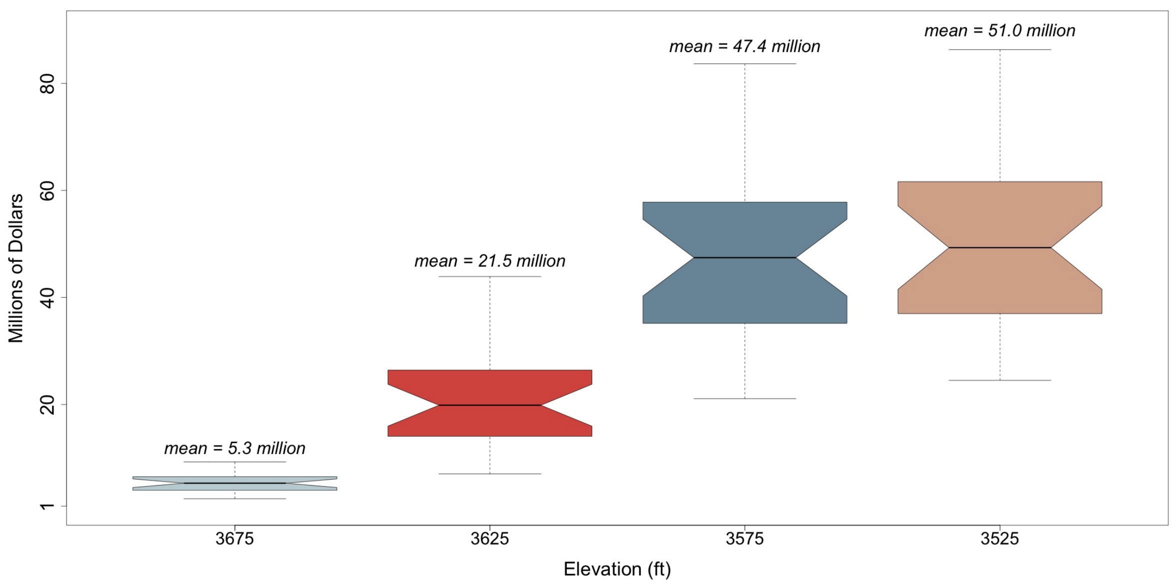


Figure 30. Distribution of predicted firming purchase costs based on 25 model iterations for each of the four elevations assuming maximum generation scenarios.

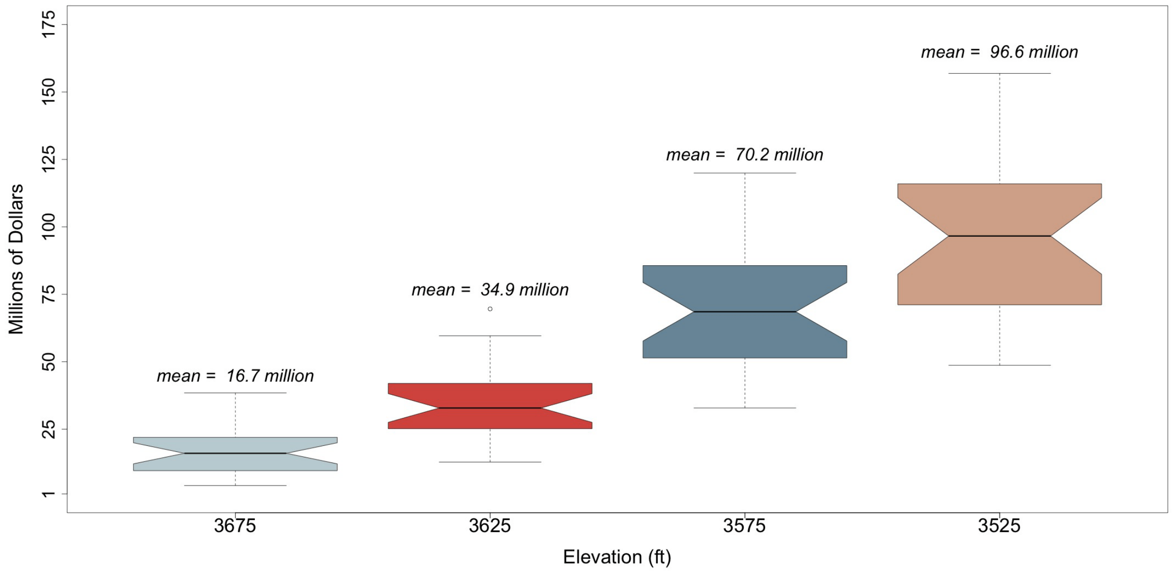


Figure 31. Distribution of predicted firming purchase costs based on 25 model iterations for each of the four elevations assuming minimum generation scenarios.

Finally, mean values for each of the maximum and minimum hydropower scenarios at all four elevations are shown below (Figure 32). As can be seen, under maximum hydropower scenarios the cost of firming purchases levels off more quickly than in the minimum hydropower scenario suggesting that decreased elevations have a great impact when compounded with other factors that result in less hydropower generation.

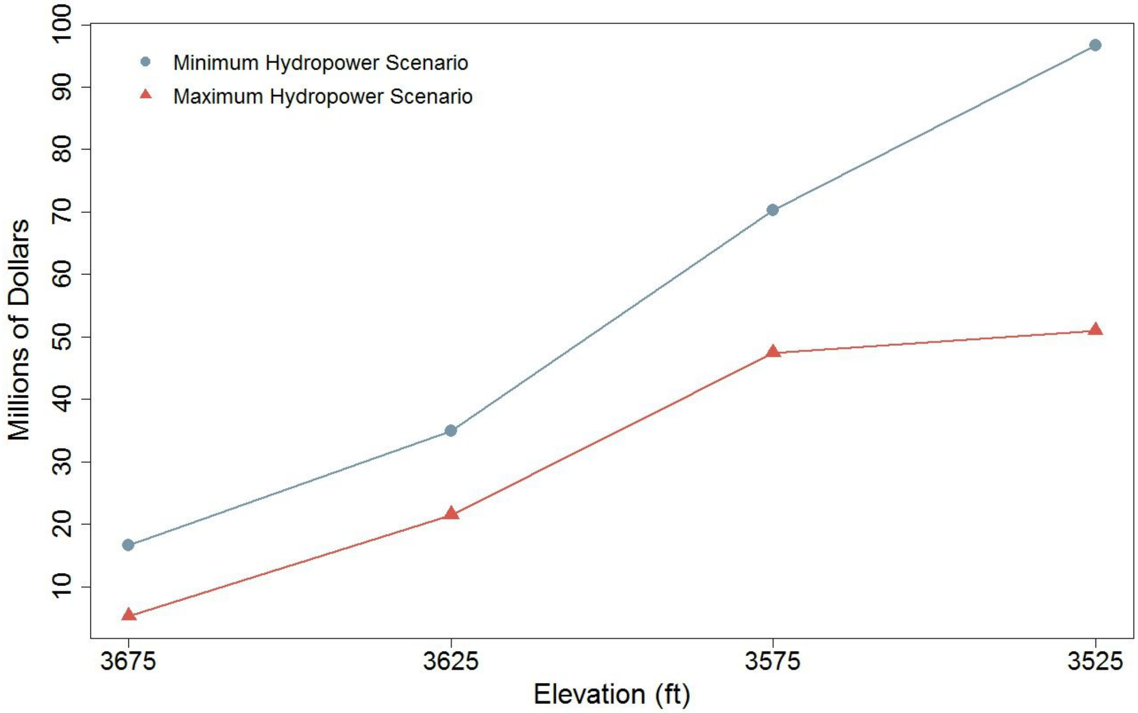


Figure 32. Mean cost of firming purchases for maximum and minimum scenarios at all four elevations.

Discussion

The model we developed predicts potential ranges for the cost of firming purchases at key elevations designated by the *Interim Guidelines*. Western makes these purchases for their customers in order to fulfill SHP as per their contractual obligations. The cost of firming purchases is additional to the cost of the power that is generated by the Glen Canyon hydroelectric power plant. Western's hydropower sales must make up the revenue requirement, and so when less power is produced, the power rate may increase to ensure that obligatory costs are covered. The total cost of hydropower, therefore, stays the same, regardless of how much power is purchased. One implication of this is that if power generation decreases dramatically, the federal power rate become more expensive than the wholesale market price. In this case, the additional cost is passed on to the customer, who is obligated to continue purchasing their full SHP allocation for the 20-year term of their contract. However, this model does not take into account the rate of hydropower sales and so does not incorporate this aspect of total cost.

Power from Glen Canyon Dam is marketed as a part of the greater SLCA/IP system. Although Glen Canyon typically makes up 75 percent of SLCA/IP power, this number does vary. Operating dams in the Upper Basin as a system, rather than individually, is beneficial because production at one dam may be ramped up when generation at another dam is low. Before going to the wholesale market, Western considers this possibility. We were unable to directly incorporate this into our model. Instead, we ran the model utilizing different proportions of total SLCA/IP SHP (from 70 to 80 percent). We want to emphasize that the numbers predicted by our model do not incorporate other units in the SLCA/IP system besides Glen Canyon Dam.

Although other models predicting the cost of firming purchases at low elevations do not exist, in 2003 when Lake Powell's elevation was approximately 3600 feet, firming purchases for the CRSP system were reportedly 90 million dollars due in part to high wholesale electricity prices that year (Warren 2004). Given that our estimates are for Glen Canyon alone, our range of estimates for 3625 and 3575 feet are reasonable compared to this value.

One downfall of the sensitivity incorporated into this model is the wide range of values our model predicts. One way to reduce this range would be to generate better estimates for the cost of firming purchases. However, the volatility of the wholesale energy market makes this difficult. We used the ten year averages with a range that covered one standard deviation of this average. Another method that could reduce variability would be simply to use the most recent values.

The wider range of predicted values at lower elevations, as shown in Figure 30 and Figure 31, suggests that when reservoirs are low, manipulating dam operations, such as increasing water releases, could increase power generation. However, the same conditions that have created low reservoirs are likely to prevent such operational changes. For example, when there is less water in the reservoir there is less water available for release through the turbines. Restrictions such as this limit the flexibility of hydropower and occur because dam operators must balance water supply needs with power generation.

Conclusions

The Western Area Power Administration markets power from numerous dams in both the Upper and Lower Basins of the Colorado River. Despite this, power may be marketed differently throughout the region. Glen Canyon Dam is operated as part of the larger CRSP project and power generated from Glen Canyon Dam and CRSP is marketed by Western as the SLCA/IP. Other dams in the region, such as Hoover Dam, are operated under separate legal, contractual and repayment obligations. This difference made it difficult to replicate methods utilized in T*he Bathtub Ring* (Jiang et al. 2015), which predicted the total cost of power at varying reservoir elevations for contractors' purchasing power from Hoover Dam. Because of these differences in power marketing across systems, we determined a substantial component of this section should be devoted to explaining power marketing at Glen Canyon Dam and the greater SLCA/IP system. As managers contemplate how to adjust to increasing variation and uncertainty about reservoir levels, it is essential to understand the many benefits derived from natural resources such as hydropower. It is essential for water managers in the Upper Basin to understand how power is marketed from multi-purpose federal projects in order to assess how declining reservoirs may impact the basin as a whole.

Despite the differences between Glen Canyon and Hoover Dams, we sought to quantify the potential change in costs associated with decreased reservoir elevations in Lake Powell in a similar manner to Jiang et al 2015 for Lake Mead. There were two primary differences in our approach. First, due to the aggregation of Glen Canyon power into the larger SLCA/IP energy product, we were unable to calculate a rate for power specifically at Glen Canyon Dam. However, we were still able to calculate the cost of firming purchases under different reservoir scenarios. The second major difference between our study and Jiang et al 2015, is that we did not consider the cost to the individual customer. This was due to the large number of customers that purchase SLCA/IP power and the inability to determine which customers receive power specifically from Glen Canyon Dam. Additionally, once each customer has received full SHP it can choose between purchasing more power through Western (WRP) or obtain power on their own (CDP) to meet their full allocation. These choices are difficult to quantify and vary based on specific conditions at the time of purchase.

Further studies could attempt to more closely mimic *The Bathtub Ring* by incorporating data from all SLCA/IP units. This would allow for the calculation of costs to the individual contractor and the rate of hydropower for SLCA/IP customers. It would take considerable time to obtain information regarding how much power each of the 143 customers receives from SLCA/IP units. Due to the choice between WDP and CDP, the ability to calculate the cost of power up to full CROD allocations is unclear. Further conversations with Western personnel would be required for this to be assessed.

Our estimates quantify the cost of firming purchases under different reservoir scenarios. Our results indicate that an elevation change of 150 feet (from 3675 to 3525) could result in a tenfold increase in the cost of firming purchases under maximum generation scenarios and a fivefold increase under minimum generation scenarios. As indicated in Figure 29 and Table 18 our results also show that in the average scenario where Glen Canyon Dam comprises 75 percent of SLCA/IP power firming purchases could make up between two and forty percent of total SHP (Table FIMR). The increased cost of firming purchases would be additional to the cost of hydropower produced at the dam. Although not included in our estimates, the cost of hydropower would also increase as reservoirs decline due to Western's repayment obligations.

Regardless of generation scenarios, which are controlled by a variety of operational and environmental factors, the impact of drought on reservoirs will result in increases to the cost of power in the Upper Basin. If reservoir elevations continue to decline the benefits of hydropower will also decline. Hydropower will become more expensive and firming purchases will become more frequent. The most extreme implication of this is that it could become cost prohibitive to purchase hydropower from Glen Canyon Dam and alternative energy sources, besides the wholesale market, would need to be identified. While this is an extreme scenario and unlikely in the near future, the slow decline of reservoir levels are cause for concern. Future policies may need to be reassessed and changed to fit new environmental norms.

Recreation

Introduction

Since the creation of the Glen Canyon National Recreation Area (GCNRA) in 1972, Lake Powell has become a renowned destination for domestic and international recreationists. More than two million yearly visitors come to enjoy the expansive shoreline (NPS 2013), where there are abundant opportunities to boat, fish, hike, and camp. The lake's popularity helps rank the GCNRA as having the longest average "stay" of any attraction in the National Park system (4.5 days), while also offering convenient access to other cultural and natural landmarks in the region, such as the Rainbow Bridge and Grand Staircase-Escalante National Monuments (Friends of Lake Powell n.d.).

Lake Powell tourism and recreation are cornerstones of the regional economy. A broad spectrum of businesses caters to visitors in nearby Page, Arizona, the largest commercial hub in the region. The local Chamber of Commerce lists among its members over eighty businesses that meet sports, recreation, travel and transportation needs alone, in addition to 21 storefronts and 59 food and dining establishments (PLPCC n.d.). According to the National Park Service (NPS), nearly 2.3 million GCNRA visitors spent over $190 million in neighboring communities and supported almost 3,000 local jobs in 2012 alone (NPS 2014a).

While the recreation economy and its importance to the region are relatively well understood, no known analyses have modeled how it may be impacted by future low lake levels. Therefore, to inform a more holistic assessment of drought impacts to various lake-dependent sectors, we ask two primary questions:

1. How might recreational visitation change?
2. What are the impacts of low reservoir elevations on popular lake access points?

Recreation on and around Lake Powell contributes essential visitor dollars to nearby communities like Page, and drives the daily and long-term operational decisions of the Glen Canyon National Recreation Area. This section seeks to illuminate how changes in lake elevation may impact the magnitude of future Lake Powell recreational use.

Methods

Lake Powell Elevation and Recreational Visitation Correlation

As in The Bathtub Ring's analysis of Lake Mead, our primary method for assessing changes to recreational visitation is a statistical analysis that correlates mean monthly Lake Powell volume and monthly recreational visitor use, and uses linear regression to predict future visitation at four lake elevation scenarios. The linear model utilized in this analysis was developed in the study, *Modeling the influence of water levels on recreational use at lakes Mead and Powell* (Neher et al. 2013), which correlates lake storage volume to observed recreational use between 1996-2011.

Lessons from Neher et al.

The Neher et al. study found lake volume and elevation to be interchangeable, highly collinear data points, rendering them nearly identical for modeling purposes. For consistency with the 2013 report, we performed calculations in volumetric units (acre-feet, or AF) and converted to elevation as needed.

Neher et al. also found that scatterplots of historical Lake Powell visitation and storage volume demonstrate a horizontal banding pattern (as shown in Figure 33), that differentiates winter

(November-March), shoulder (April, May, September and October) and summer months (June-August). This trend indicates that the importance of volume as a predictor of visitation varies depending on the season, and is likely attributable to Lake Powell's high altitude, cold water temperatures, and remote location relative to similar destinations (such as Lake Mead), causing summer month visitation to be more sensitive to lake volume.

Additional variables that were tested by the 2013 study and found to be non-significant included a fuel price index and an indicator variable for the influence of the "great recession."

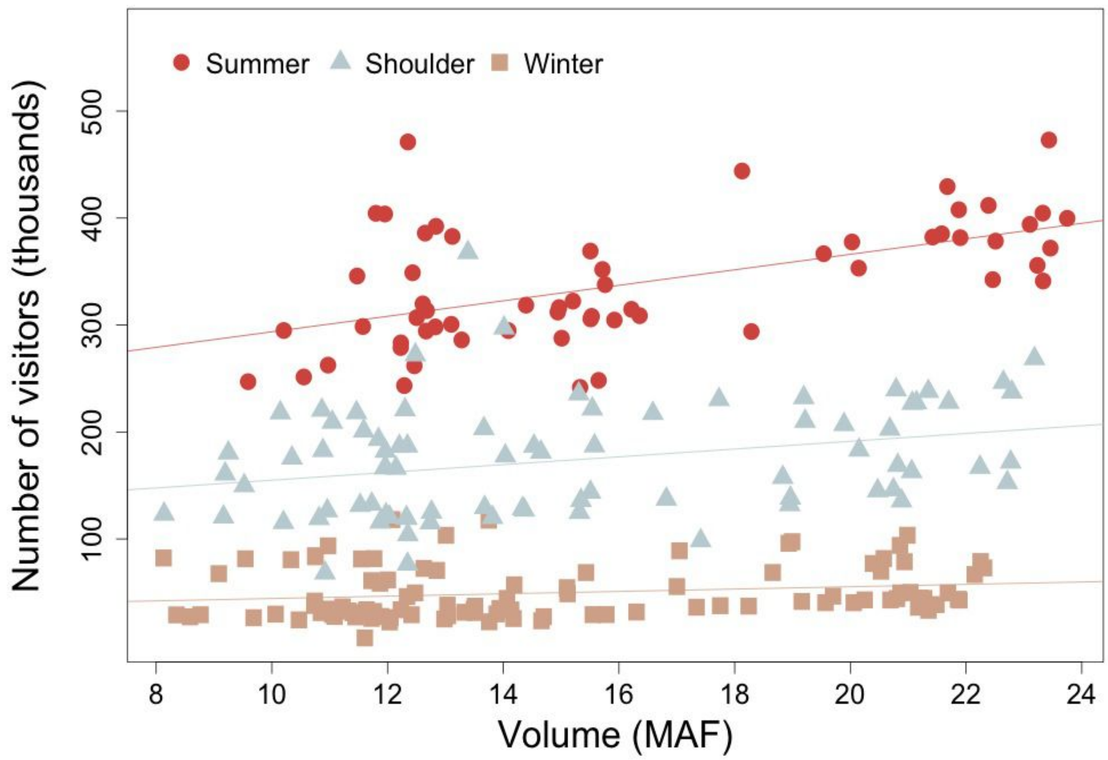


Figure 33. A seasonal horizontal banding pattern is evident in a scatterplot of Lake Powell water volume and corresponding visitation.

Data

To extend the Neher et al. dataset through January 2016, monthly mean live storage[16] volume was procured from the USBR Monthly Summary Reports for water operations (USBR 2016c). Visitor use data was obtained from the National Park Service Monthly Public Use Report for the Glen Canyon National Recreation Area and disaggregated by location to include only shoreline Lake Powell data points (NPS 2014b). Non-recreational visitors were excluded from the model (including through-traffic, subsistence users, and government personnel and employees) (NPS 2004).

[16] The total reservoir capacity minus the dead pool capacity. This metric was used for consistency with the Neher et al. dataset.

Calculations

We revised the 2013 Neher et al. model using the extended dataset. In keeping with the 2013 model, categorical indicator variables were used for the months of March-November. Interaction terms were used for summer and shoulder season months because of seasonal variability in the degree to which volume predicts visitation. The resulting regression analysis and equation were then used to predict visitation for each month in the dataset timeframe (January 1996-January 2016).

Then, to test the fit of the model, we used paired t-tests to compare actual monthly visitation to the model's predicted visitation for those same months.

Finally, recreational visitation was predicted at four lake level scenarios to represent future drought conditions (at 3675, 3625, 3575, and 3525 feet of elevation). These were employed for consistency with this report's hydropower analysis; although they have no particular significance to recreational activities, they provide useful benchmarks for modeling the decline of lake levels. The scenarios were sourced from the USBR maximum hydropower generation scenarios, which provide monthly elevation values for a hypothetical water year[17] (Figure 34). Each monthly elevation was converted to a volume live capacity equivalent using USBR conversion tables (conversions are presented below in Table 19) (USBR 2007d). These volumes were then used within the revised Neher et al. model equation to produce a predicted monthly visitation number. Those monthly predictions were combined to produce an annual total.

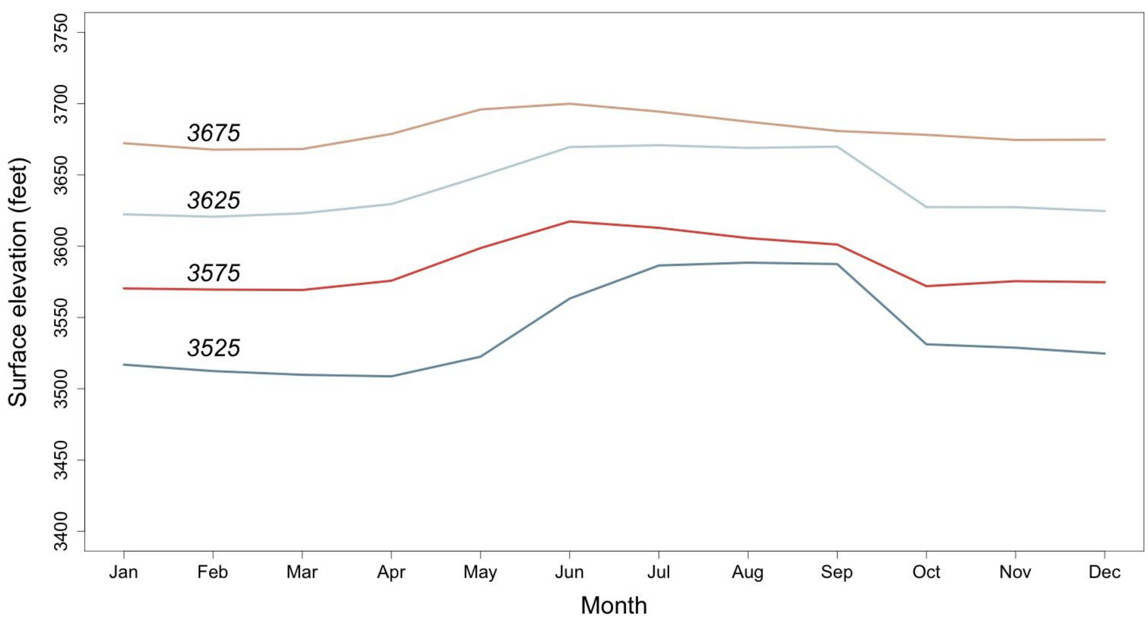


Figure 34. Lake Powell elevation scenarios from January through December. Each scenario reflects seasonal hydrological fluctuations within a water year.

[17] As noted in the hydropower section of this report, data was acquired for one full water year (October - September) beginning in January. (October through December of one year and January through August of the next.) This was done because of the manner in which the CRSS software operates and the fact that volume predictions for January dictate the relevant operational tier and release volumes.

Table 19. Elevation converted to a volume live capacity equivalent (USBR 2007d).

Elevation (ft)	Volume Live Capacity (AF)
3675	20,539,038
3525	14,300,458
3575	9,517,254
3525	5,926,576

Key Public Access Points and Lake Powell Elevation

In addition to modeling visitation numbers in correlation with lake volume, this report reviews popular boat ramps used by water recreationists as well as the Castle Rock Cut.

Declining lake levels will impact each access point differently, depending on the geological features of their location. Each has an absolute minimum water elevation below which it cannot be practicably or safely utilized, which we assess in comparison to our four elevation scenarios. Marinas are excluded because they do not have absolute minimum water elevations; they are capable of regular adjustment as water levels fluctuate, although extreme elevation shifts (5 feet or greater) require multiple, time-intensive adjustments. The GCNRA facilities division provided background information and current data on each access point.

Results

Key findings from the recreation analysis include:

1. Recreational visitation to Lake Powell is predicted to decline from 2.2 million at 3675 feet to 1.7 million at 3525 feet, a 26 percent reduction (Table 20 and Figure 35).

2. No official access points are projected to be operable below 3525 feet without the investment of resources to extend boat ramps and deepen the Castle Rock Cut (Table 23).

These results suggest that low lake levels could reduce recreational visitation at Lake Powell by over a quarter, an impact that would have serious economic repercussions for the local Page economy.

Table 20. Predicted yearly Lake Powell visitation for each elevation scenario.

Elevation (ft)	Predicted Visitation (Max Scenario)
3675	2,237,545
3625	2,052,313
3575	1,791,418
3525	1,652,730

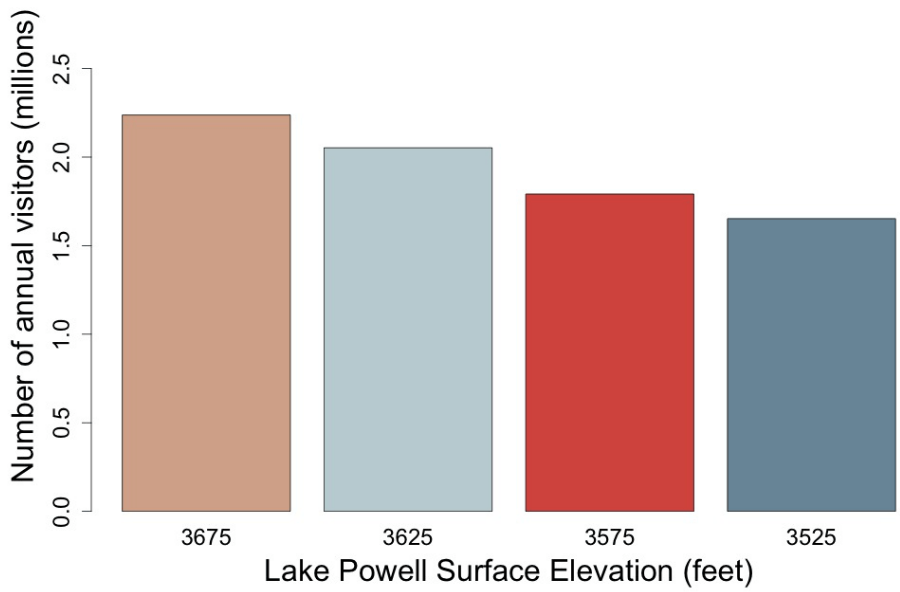


Figure 35. Predicted yearly Lake Powell visitation for each elevation scenario.

Discussion

Lake Powell Elevation and Recreational Visitation Correlation

A summary of the extended Neher et al. regression model is summarized in Table 21. Annual Lake Powell visitation predictions were made using this model and four elevation scenarios. Projected recreational use does not drop below 1.7 million visitors per year even when Lake Powell is at 3525 feet.

Table 21. Lake Powell estimated recreational visitation model using data from January 1996 through January 2016, adapted from Neher et al. (2013). R-squared is 94.6% with a sample size of 241.

Variable	Coefficients	Standard Error	t value	P-value
Intercept	15,446	11,092	1.4	0.17
Lake Volume	0.0012	0.0007	1.8	0.082
March	53,841	7,585	7.1	0.0
April	71,740	17,133	4.2	0.0
May	153,124	17,380	8.8	0.0
June	203,227	19,138	10.6	0.0
July	227,603	19,390	11.7	0.0
August	192,925	19,146	10.1	0.0
September	138,330	17,814	7.8	0.0
October	56,670	17,738	3.2	0.002
November	27,092	7,587	3.6	0.0
Summer Visits	0.0059	0.0011	5.2	0.0
Shoulder Visits	0.0023	0.0011	2.2	0.03

Observed historical visitation compared to model-predicted visitation during 1996-2016 is presented in Figure 36. Although the lines appear to diverge from 2011 to 2016, the difference was not found to be statistically significant.

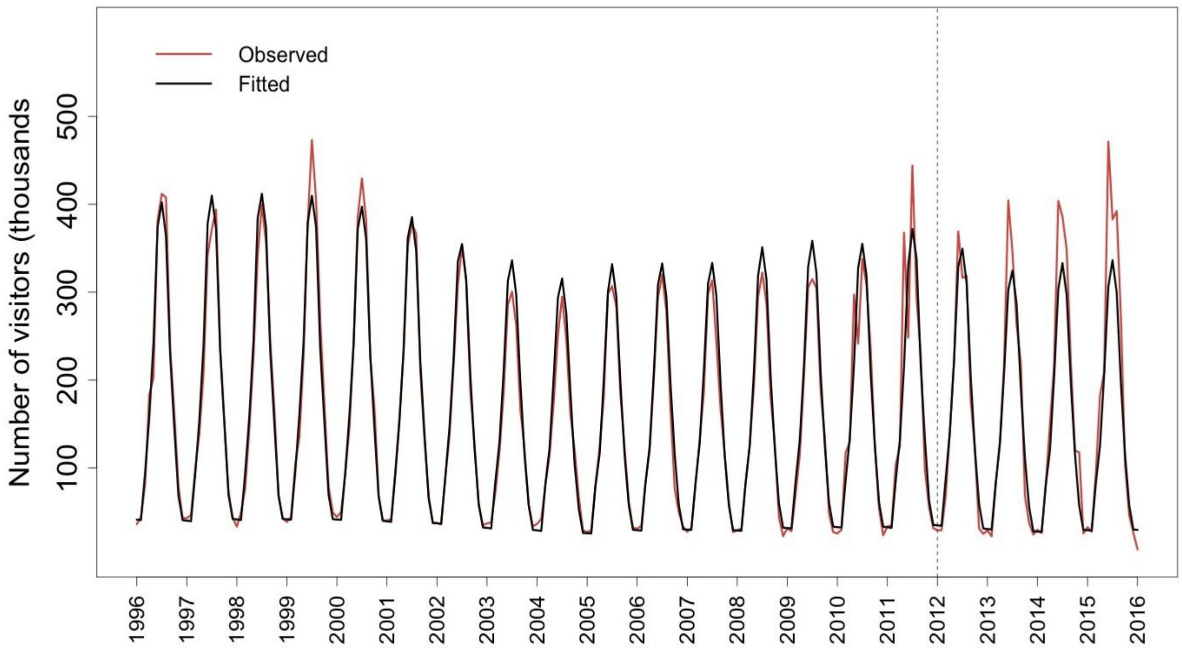


Figure 36. Observed and predicted visitation at Lake Powell during study timeframe. The revised Neher et al. model correlated Lake Powell volume to visitation from January 1996 - December 2011 (left of black dash line). The model was extended through January 2016 with additional visitation and lake volume data (right of dash line).

To test the fit of the extended Neher et al. model, paired t-tests were used to compare actual visitation with model-predicted visitation for the 1996-2016 timeframe. Tests conducted separately for 1996-2011, 2012-2016, and 1996-2016 all produce high p-values and suggest no significant difference between the mean values of model predictions and historical observations (see Table 22).

Table 22. Results of paired t-tests conducted to compare the difference between the means of observed (actual) visitation and model-predicted visitation.

	1996-2011	2012-2016	1996-2016
P-Values	0.991	0.997	0.994

Key Access Points and Lake Powell Elevation

The natural fluctuations between wet and dry cycles on the Colorado River produce highly variable conditions for the managers of Lake Powell access points, and drought conditions only amplify those trends. As more beach is exposed, it becomes necessary to move recreational facilities such as marinas and courtesy docks (see Figure 37 map), extend boat ramps, and relocate signs and navigational water aids – a yearly process known as "chasing water." Certain boat ramps are particularly vulnerable to reaching their absolute minimum water elevations due to the unique conditions of their locations along the reservoir:

- Antelope Point ramp and Antelope Point Public ramp are positioned along a narrow channel, and the length of their concrete ends where a cliff begins. Both must close for safety purposes when lake levels are within 10 vertical feet of the ledge.
- Bullfrog Main launch ramp ends where the bottom of the lake flattens out, thus, additional extensions of the ramp are not effective in lowering its elevation.
- Hite boat ramp cannot be extended because of movement of the Colorado River channel due to declining water levels and silt aggradation.

In Table 23, the absolute minimum elevations for Lake Powell boat ramps and the Castle Rock Cut are compared to our four elevation scenarios. While each point is accessible at 3675 feet, four out of nine are not usable at 3575 feet, and none at 3525 feet. The lowest elevation that can be accommodated is 3551.5 feet, at the Wahweap Main boat ramp.

Table 23. Accessibility of Lake Powell boat ramps and the Castle Rock Cut (Cook 2016), and their operability at each of the four elevation scenarios.

Boat Ramps and Passageways	Absolute Minimum Elevation	3675 ft	3625 ft	3575 ft	3525 ft
Wahweap Main	3551.5	Yes	Yes	Yes	No
Wahweap Stateline	3558.5	Yes	Yes	Yes	No
Antelope Point (Public)	3585.5	Yes	Yes	No	No
Antelope Point	3586	Yes	Yes	No	No
Castle Rock Cut-off	3580	Yes	Yes	No	No
Bullfrog Main	3575	Yes	Yes	Yes	No
Bullfrog North	3557	Yes	Yes	Yes	No
Halls Crossing	3555	Yes	Yes	Yes	No
Hite	3645	Yes	No	No	No

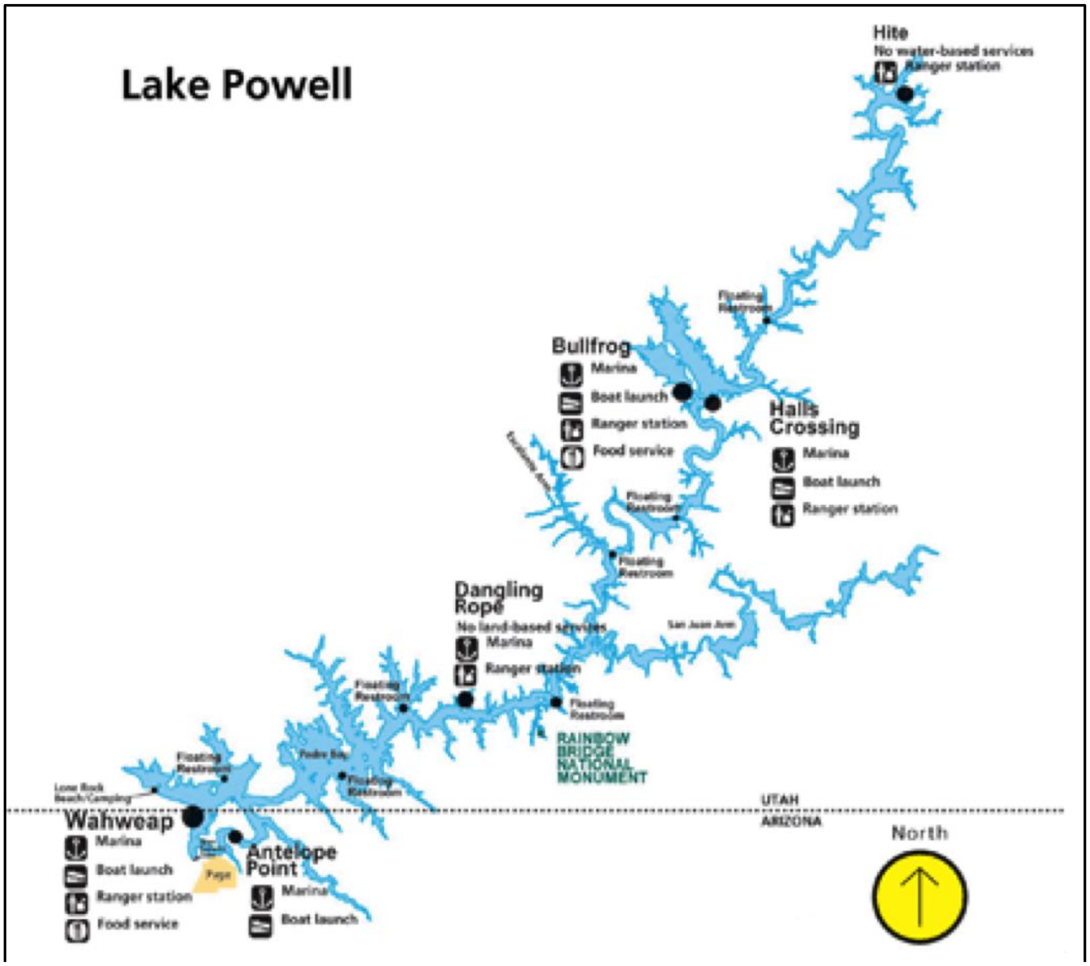


Figure 37. Map of Lake Powell recreation access points (NPS 2015).

Castle Rock Cut

After the completion of Glen Canyon Dam in 1963, Lake Powell became accessible to visitors for the first time in 1972 with the creation of the Glen Canyon National Recreation Area. As the lake filled, not reaching its full pool elevation (3700 feet) until 1980, a short-cut from Wahweap Bay to Warm Creek Bay was excavated between Castle Rock and Antelope Island by Lake Powell concessionaire, Art Greene. This passage connects the popular Wahweap Bay with up-lake locations, allowing boaters to bypass the narrow Colorado River channel (Figure 38), a route that extends travel time by at least forty-five minutes and requires the use of additional fuel.

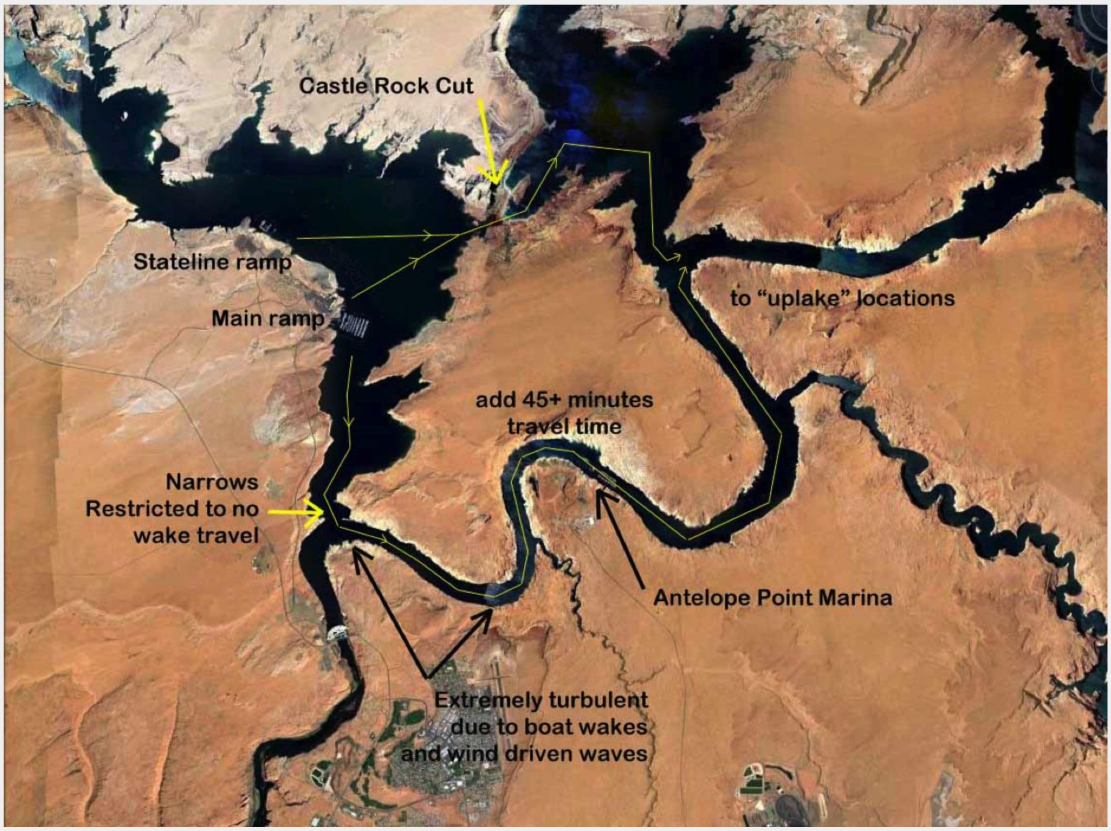


Figure 38. Wahweap Bay (left) and Castle Rock Cut (Elleard 2016).

Castle Rock Cut's first excavation in the 1970's lowered the cut's depth to an elevation of 3620 feet. Declining lake levels have since required four additional excavations in 1994 (3615 feet), 2008 (3607 feet - after five years without access), 2013 (3600 feet) and 2014 (3580 feet) (Elleard 2016).

Due to its proximity to Page and the relative depth of the Wahweap ramp, Wahweap Bay is a popular put-in for boaters. Because the Cut becomes impassable well in advance of facilities in the Bay, this causes widespread inconvenience to boaters and the GCNRA employees who must navigate the lake. Additionally, in two of the four elevation scenarios we explored, both Antelope Point ramps and the Cut are unusable. When this occurs, boaters do not have the option to save travel time by putting in at Antelope, which is located mid-way up the river channel, rather than Wahweap.

Without further investments, the route provided by Castle Rock Cut would be rendered impassable at two of the four elevation scenarios explored in our report.

Model Limitations

The predictions of the extended Neher et al. model are premised on the climatic, economic and social conditions that drove volume and visitation in the January 1996-January 2016 timeframe. Thus, future trends that may impact Lake Powell recreation cannot be foreseen and accounted for in our modeling.

Additionally, NPS visitation data does not distinguish between water-based and land-based recreation. Low lake levels could be presumed to impact these usages differently, a nuance that is not captured in the Neher et al. model. For instance, lower lake elevation may negatively impact boating, but increase interest in hiking as shorelines change and side canyons are exposed. Further research that disaggregates recreationist data and analyzes trends in predominant uses (land versus water-based) would enhance our understanding of Lake Powell visitation and its vulnerability to drought.

The value of additional research is demonstrated by Figure 39, a line graph of historical lake volume compared to actual observed visitation from 1996-2016. Beginning in 2011, visitation remains high relative to the lake's volume and previous years. While this relationship is observable, the high p-values from our t-tests confirm that it is not impacting our model's predictive usefulness. However, this trend reinforces observations from GCNRA representatives that the demography of Lake Powell visitors has shifted within the past five years, most notably through an influx of international visitors during shoulder and summer months, whose recreational habits are dominantly land-based.

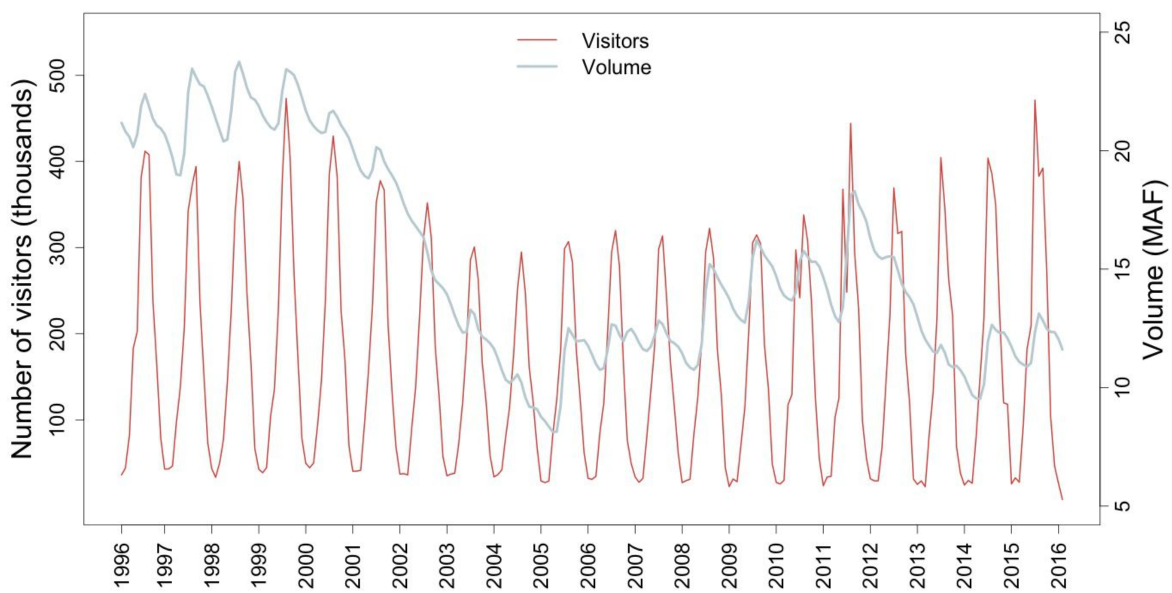


Figure 39. Lake Powell volume and recreational visitation, January 1996-January 2016. Between 2011 and 2016, historical visitation remains high despite declines in lake volume.

Conclusion

The recreational opportunities offered by Lake Powell are essential to attracting the more than two million visitors to Glen Canyon National Recreation Area each year. This activity is crucial to the local economy, supporting over 80 local businesses and attracting over $190 million visitor dollars in 2012 alone (NPS 2014a).

The extended Neher et al. model predicts a reduction in recreational visitation as lake levels decline, estimating 500,000 fewer visitors between elevations 3675 and 3525 feet. Popular lake activities like house-boating, guided boat trips, and fishing all require shoreline facilities whose accessibility will be impaired during drought conditions. Should the elevation drop below 3525 feet, all Lake Powell boat ramps and the Castle Rock Cut will be unusable in their present conditions.

However, visitation within the past five years has remained high despite low lake volume, suggesting that recreational trends may be increasingly driven by new factors not represented in the Neher et al. model. Further research may illuminate these factors, particularly an investigation of changes to types of recreation, and an analysis of whether international visitation is driving those shifts.

Environmental Considerations

Introduction

Development of hydropower and water storage projects like Glen Canyon Dam make the Colorado River one of the most engineered river systems in the country. Addressing impacts from this development on the environment and native species requires managers to consider new ways to balance the needs of water users while also promoting beneficial environmental conditions downstream from the dam. As the surface elevation of Lake Powell falls, the likelihood of negative environmental impacts occurring in the downstream reaches and riparian areas of the river increases.

Current programs designed to address and improve ecological health or environmental conditions are primarily derived from federal environmental laws and regulations that emerged after large-scale water development had already fundamentally altered the flow and sediment regime of many stretches of the river. Schmidt et al. (1998) outline potential strategies for addressing this challenge as it is presented in the context of the Grand Canyon, which can easily be applied to management strategies of the Upper Basin. They provide five approaches to management that may be espoused by different groups, reflecting a spectrum of management philosophies and desired outcomes:

- **Traditional River Management:** maximize power production at times of maximum power price;
- **Management for Naturalized Ecosystems:** manage existing ecosystems including desirable non-native species;
- **Simulated Natural Ecosystems:** simulate some pre-dam ecological processes and partially restore some pre-dam resources;
- **Substantially Restored Ecosystems**: extensive restoration of pre-dam processes and management elements;
- **Fully Restored Ecosystem**: attempt complete restoration of pre-dam processes and resources.

This range of options leads to an equally broad array of impacts and effects on hydropower, revenue generation, water transfers, recreation, and ecosystem health. Each strategy includes complex tradeoffs and uncertainty that are weighed by managers in light of societal values and concerns. As if this isn't a great enough challenge, management strategies must be sufficiently adaptive to address shifting demands (like agricultural irrigation and endangered species requirements), while remaining compatible with other moving parts within the larger management system. Collaborative and proactive strategies can be implemented to balance these varied demands while meeting the needs of vulnerable ecosystems and wildlife as the likelihood of experiencing shortfalls between projected water supplies and demand in the Upper Basin remains high.

As concerns about declining reservoir levels and uncertainty about future water availability in the basin remain pressing, it is important to consider how beneficial environmental programs may be impacted, both by there simply being less water and through potentially decreased amounts of funding available to support those programs. This section outlines several key environmental programs in the Upper Basin, how they are funded and managed, and how they may be impacted by decreased water availability. These programs include sediment management strategies and how techniques such as High Flow Experiments are used to mitigate chronic sediment issues. Additional consideration is given to exploring the issues of salinity downstream from the dam, as well as the goals and status of cooperative fish recovery programs.

Funding Environmental Programs

In the 1980s, concerns about changes in the riparian areas downstream from Glen Canyon Dam led to investigations into how to operate Glen Canyon Dam with greater consideration of impacts to the surrounding ecological systems. These concerns were formalized and supported by the congressional enactment of the *1992 Grand Canyon Protection Act* (GCPA). This action lead to subsequent environmental impact statements, biological opinions, and the 1996 Glen Canyon Dam ROD, which established the Adaptive Management Program (AMP) and Work Group. A new, Long-Term Experimental and Management Plan (LTEMP) and Environmental Impact Statement (EIS) was released in December 2015, a product of the USBR and the National Park Service in cooperation with other state and federal agencies as well as Native American Tribes. The LTEMP builds on the 1992 GCPA and federal law to provides a framework for the next 20 years of management. The LTEMP determines specific options for dam operations, non-flow actions, and appropriate experimental and management actions that will meet the GCPA's requirements. It also works to minimize impacts on resources within the area impacted by dam operations, including those of importance to American Indian Tribes (NPS 2015). The overarching goal of the LTEMP is to create more certainty and predictability for power and water users while protecting environmental and cultural resources in the Colorado River ecosystem. The public comment period on the LTEMP EIS remains open at the time of publication of this document.

The original AMP created a framework for making recommendations based on scientific findings about how the river system is impacted by dam operations and allowed for programs such as high flow and experimental water releases (Ott Verburg 2010). In addition to ensuring the repayment of federal water and power investments, the revenue created by the sale of the energy produced by Glen Canyon Dam and other CRSP units provides funding for important environmental programs, approximately $20 million annually (CREDA 2008). The AMP Work Group receives an annual allotment of $9.5 million, with a major portion of their program budget coming from the Colorado River Basin Fund). The Basin Fund, which is managed by Western, holds revenues for use in a variety of environmental programs, including salinity management and species recovery plans. The Basin Fund also supports Upper Basin states in cost sharing for Salinity Control Programs ($2 million annually), and Endangered Fish Recovery Programs (approximately $7 million annually). Revenues from sales of hydroelectric power and transmission services support the Basin Fund (USBR 2008e).

The AMP uses these funds for monitoring, science based research, and for making recommendations to the Secretary of Interior on improvements in the Glen and Grand Canyons, focused on dam operations and downstream resources (GCAMP 2013). The Basin Fund also supports water quality and use studies, as well as cost sharing for salinity control and fish recovery plans. These programs are funded in no small part by the operation of the dam itself with revenue coming in from sales of capacity, energy, and transmission services (Warren 2008).

Money from the Basin Fund is also used to make firming purchases when hydropower production is low. In 2004, CRSP had an annual revenue requirement of $143 million, including operation and maintenance, purchase power, interest, and principal payments (Warren 2004). The amount of that requirement today is likely higher. If Glen Canyon Dam were not in operation, or unable to operate due to sufficiently low reservoir elevations, and the other CRSP generation units had to produce power to meet the existing demand, the power rates would likely become cost prohibitive for customers to even consider. Of course, with the Glen Canyon power plant producing roughly four times the power output as the rest of the CRSP units combined it is unlikely that the remaining units would be able to make up the entirely of Glen Canyon's power.[18] The Basin Fund is also tapped to cover things like payroll for USBR and Western, and environmental programs like the Adaptive Management Plan which partially rely on funding from power generation revenues.

It is important to note that the environmental impacts of the dam are not abated when energy productivity diminishes. Unless customer rates rise, there is simply less money generated through hydropower sales to support Basin Fund programming. Additional funding to support environmental programs like the Adaptive Management Plan is congressionally-authorized and is not impacted by changes in hydropower generation capacity.

Managing Sediment

Like all rivers, the Colorado works as a veritable conveyor belt for sands and sediment, moving eroded rock from the surrounding landscape down the river channel toward its natural conclusion at a debris fan or sandy delta (Webb et al. 1988). When these debris fans are the result of tributary inflows they create riffles, rapids, and sandbars that are essential to river health and recreational opportunities. When impediments are placed in a river channel, altering or completely blocking a river's flow, sediments tend to become trapped behind those impediments. Under natural conditions, in the case of a down tree for instance, sediments will build up and divert water around the impediment until a large enough flow is generated to flush these sediments downstream. With many rivers, a substantial portion (sometimes more than half) of the total yearly sediment transported can occur during one large event. These large events also serve to uproot and sweep away riparian vegetation.

When permanent structures like concrete dams are placed in a river channel, the ability for these natural events to flush sediments through the river system become rare, and in most cases are strictly avoided (in the case of a structural failure, for example). Water that is flowing into an impounded reservoir slows, allowing sediments to fall out of suspension and deposit on the lake bottom. Like water in the river channel, this flow of sediment is constant, and with no outlet, the sediments begin to concentrate and accumulate.

Glen Canyon is located downstream from significant sediment-contributing areas.[19] Prior to the construction of Glen Canyon Dam, sediments were pushed downstream and deposited as sand bars and beaches. With the dam in place, those sediments are deposited in Lake Powell at a rate of about 100 million tons each year. As of 1986 when the last complete reservoir survey was conducted, deposition had reduced the storage capacity of Lake Powell by over 868,000 AF, or 3.2 percent of the total storage capacity, over the course of 23 years (Ferrari 1988).[20]

Construction of Glen Canyon Dam has impacted the size and number of sandbars downstream along the river. In free flowing rivers, sandbars are deposited during periods of high discharge and become exposed when water levels recede. Stabilized and regulated flows below the dam preclude natural

[18] The energy industry transition from coal to gas, combined with cheap gas prices, make meeting the power demand more economically feasible. Hydropower generation, which can be purchased by utilities at fraction of the cost of natural gas, is still the preferred choice when it is available (Navigant Consulting 2010).

[19] Downstream of the Dam, the Paria and Little Colorado Rivers also contribute large quantities of sediment.

[20] A subsequent "multibeam" digital bathymetric surveying was conducted in Lake Powell in 2004, but drastically lower water levels, as well as budgetary and personnel constraints, limited the usefulness and interpretation of the data collected in those surveys (USBR 2006).

deposition from occurring which would otherwise serve to revitalize or "turn over" the beaches and bars.

Disrupting the natural flow regime has also had an impact on riparian vegetation. The amount of vegetation along the river has increased, providing more diverse habitat for wildlife that could not have existed before damming when downstream flows were varied and irregular. For example, studies focusing on these post-dammed riparian habitats have discovered that the black-chinned hummingbird nests only in habitats dominated by the invasive tamarisk, and not at all in habitats dominated by the native honey mesquite (Brown et al. 1992; Smith et al. 2014). As the tamarisk takes root in the lightly disturbed soil downstream from the Dam, displacing honey mesquite, habitat for this species of bird has increased.[21]

This apparent silver lining, where new species are able to thrive in the altered habitats, is one of the tradeoffs that turns out to be a benefit as the result of damming the river. Shocks to the ecologic conditions can impact the balance of food webs in these riverine and riparian systems, allowing non-native species like rainbow trout to benefit and gain an advantage over other species like the humpback chub. Predation impacts from introduced species like black bullhead catfish, rainbow and brown trout may limit native species populations (Marsh and Douglas 1997). Views on this point will surely be based on how different people or populations value a natural or native pre-dammed environment over one that exists as the result of modification via drastic human intervention. Further discussion of the impacts to fish comes later in this section, but for now it is helpful to explore how management strategies have attempted to mitigate impacts of disrupted sediment flow.

High Flow Experiments

Controlled floods, known as pulse flows or high flow experiments (HFEs) have taken place in 1996, 2004, 2008, and 2014. As of May 2012, these HFEs are outlined as an official protocol of the Glen Canyon Adaptive Management Plan (USDOI 2012). HFEs allow sand stored in the river channel to become suspended by high-volume dam releases. Portions of that sand are re-deposited in downstream reaches as sandbars and beaches, and transported downstream by river flows.

Researchers have studied these events to determine whether and to what extent conservation and retention of sand can be improved downstream of Glen Canyon Dam by mimicking the behavior and conditions of a natural river system. These efforts aim to return the ecosystem to a desired prior state while also balancing the realities and necessity of the dam and hydropower operations. Sandbars have increased in size following each controlled flood, especially when the releases are timed to follow sand inputs from downstream tributaries such as the Paria River. Though post-HFE erosion continues to be a challenge, experimental releases provide more information about how to reform and refine management strategies to encourage desired sediment distribution and retention. Although the extent of the benefits throughout the downstream reaches are not equally distributed (Rubin et al. 2002), the cumulative results suggest that sandbar declines may be reversed if controlled floods can be implemented frequently enough.

The success of rebuilding sandbars downstream of the dam will require a sustained and dynamic effort (Grams et al. 2015). The greatest amount of deposition tends to occur in segments of the river that are most enriched with sand from tributaries. Just downstream from the dam, the Paria and Little

[21] Extensive work has been done by groups like the Tamarisk Coalition and others to evaluate the impacts of Tamarisk and Russian Olive on both hydrologic systems and habitat in the Colorado River Ecosystem. See tamariskcoalition.org for a thorough assessment from 2009.

Colorado Rivers together contribute only a fraction of the pre-dam amounts of sediment that ran through the river. Sediment augmentation appraisals have been conducted by the Adaptive Management Program Technical Working Group. The working group determined that running a pipeline to transport sediment-rich slurry from Navajo Canyon in Lake Powell to below the dam is technically feasible, though plans to carry out this project are not currently in place (Randle 2010). This leaves optimizing dam operations as the primary and essential tool for achieving a goal of optimal sediment distribution outcomes in the river channel (Rubin et al. 2002).

The HFEs appear to be at least in part achieving their desired impact, even if those results prove to be short lived, but these successes come at a financial cost (Grams 2015). Power companies say that the cost of the high flow event in 2008 resulted in almost $4 million in forgone revenue (Morales 2012). The cost, or lost revenue, of each of these flow events depends on the frequency, the duration, and timing when the flows (where water bypasses power-generating, and revenue-generating, turbines) will occur. Lost hydropower generation is typically made up by purchasing replacement power from coal, gas, or other sources.

The USBR's Environmental Assessment estimated the total costs of HFEs, including energy cost and capacity cost, as ranging from $8.1 to $122.1 million over a 10-year period. HFEs are conducted only if they will not alter annual water allocation and downstream deliveries that would have otherwise been dictated by the *2007 Interim Guidelines* (USDOI 2012). A seasonally adjusted steady flow regimen, as described in the 1995 EIS, could be implemented for an increased total cost to consumers of between $1 million and $8.8 million, or between 1 and 10 cents per month for a large portion of households (Marcus 2009).

Comprehensive approaches to assessing flow requirements can continue to inform and develop restoration projects in the future. Creating a natural flow regime that mimics the natural variability, frequency, timing, duration, rate of change, and sequencing of such events has the potential to advance protection of biodiversity and maintenance of the riparian characteristics and water quality supported by the river (Arthington et al. 2006). The benefits from such approaches can be measured in ways that are beyond purely financial.[22]

[22] More extensive study of the environmental consequences of these management initiatives, is found in chapter 4 of the December 2015 "Glen Canyon Dam Long-Term Experimental and Management Plan Draft Environmental Impact Statement" prepared by Argonne National Laboratory for the NPS and the USBR. Additional information about the science and strategy of HFEs can be found on USBR websites and in scholarly papers: Dolan et al. 1974: *Man's Impact on the Colorado River in the Grand Canyo*n.

Glen Canyon Dam releases high flows of Colorado River water on the night of March 6, 2008. A high-flow experiment was undertaken to determine if water releases designed to mimic natural seasonal flooding could be used to improve a wide range of downstream resources in Glen Canyon National Recreation Area and Grand Canyon National Park. (Photograph courtesy of T. Ross Reeve, Bureau of Reclamation.)

Figure 40. Views from below Glen Canyon Dam, looking upstream (top) and from the top of Glen Canyon Dam of jet tubes during 2008 HFE (bottom). Bottom Photo: T. Ross Reeve via USBR.

Impact of lower reservoir levels

The 2012 High-flow Experimental Releases protocol establishes an experimental plan pursuant to which the USBR will conduct high flow releases through 2020. This protocol for high-flow experimental releases from Glen Canyon Dam is part of the ongoing implementation of the Glen Canyon Dam Adaptive Management Program. The exact number of HFEs that will occur is dependent on conditions, which will be determined by sediment inputs from tributaries, as well as amount of water available to be sent downstream, and a decision process carried out by Interior. The protocol states that the timing of high-flow releases will be March-April or October-November, the magnitude will be from 31,500 cfs to 45,000 cfs, and the duration will be from one hour to 96 hours, depending on how much sediment is in the system, and other resource conditions (USBR 2012k).

It is important to consider how programs like the HFE will be impacted as the Basin experiences prolonged drying conditions. As an example, over the course of the 5-day period in 2014 when the HFEs have occurred, elevation of the water in the reservoir decreased an estimated 2.5 feet (USBR 2014c).

Over the course of the year, there is no change to the Lake Powell level as a result of the HFE. This is because the water released from the reservoir during an HFE does not change the *total* amount of water that is released over the course of the water year (October through September), just the timing and intensity. Because the additional water released during an HFE is included within the total annual release volume, these releases are made up for through adjustments made to the monthly release volumes throughout the rest of the water year (USBR 2012c). Having less water available in the reservoir could challenge the frequency, effectiveness, or even possibility of carrying out of HFEs in the future.

Salinity

As the river moves from its headwaters towards the Gulf of Mexico, salinity levels increase substantially with salt concentration levels being amplified by water withdrawals, consumptive use, and persistent drought. A majority of the salts (also known as total dissolved solids, including calcium, magnesium, sodium, etc.) in the river are derived from natural sources such as saline springs or erosion from water flowing over salt formations (Pillsbury 1981). For example, natural sources account for up to 62 percent of the salt load above Hoover Dam in the Lower Basin. A significant contribution to salinity also comes from non-natural sources, primarily irrigation. Municipal and industrial withdrawals impact salinity to a lesser extent through the consumption of the water (Barnett 2015; USBR 2013).

Water that is applied to agricultural fields picks up salts from the soil and eventually flows back into the river. Some of the water applied as irrigation is consumed by plants and does not return to the river, which, along with water lost to evaporation, serves to increase the salinity concentration in a river that now has less water and more salt (USBR 2005). The increased salinity created by agricultural use not only diminishes the water quality of the river, but also has negative effects on farming. More saline irrigation water limits the types of crops that can be grown and negatively impacts crop growth.

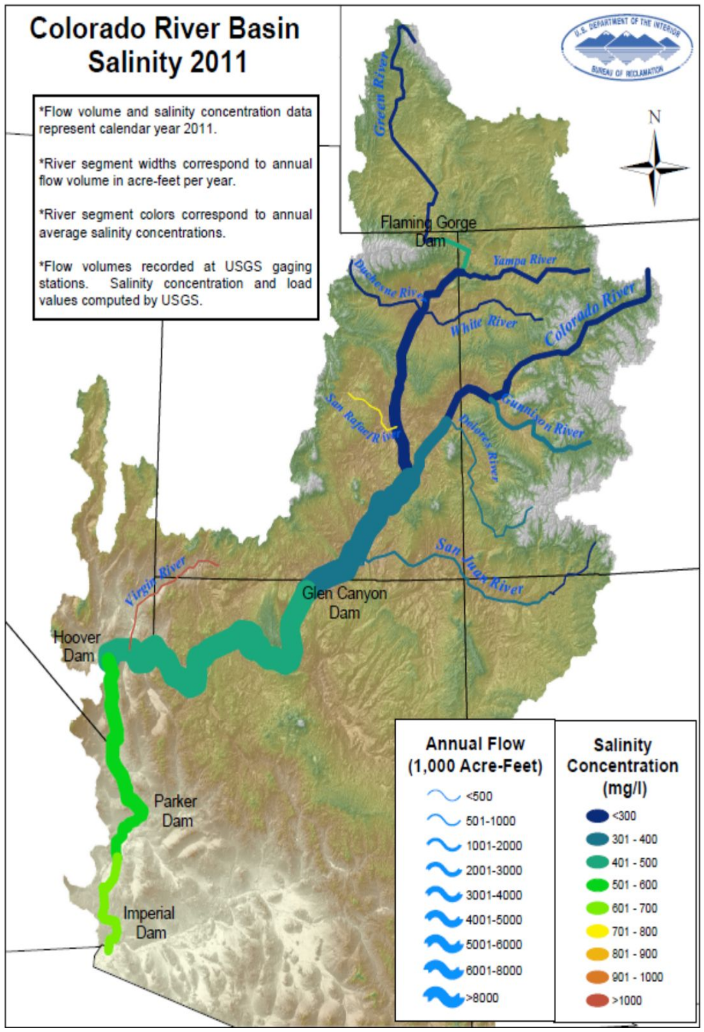


Figure 41. This figure illustrates how salinity concentrations increase moving down river. Values are based on the 2011 calendar year. (Colorado River Basin Salinity Control Forum 2014)

The *Colorado River Basin Salinity Control Act* was enacted in 1974 with the intent of preventing salts from dissolving and mixing in the river, thereby enhancing and protecting water quality. The Salinity Control Program was originally established in 1975 as an amendment to the 1974 act to more thoroughly address the requirements of the *Clean Water Act*. The amendment added language to support cost-effective measures and associated works to reduce salinity from saline springs, leaking wells, irrigation sources, industrial sources, and erosion of public and private land, while also providing for the mitigation of fish and wildlife values that are lost as a result of the measures and associated projects (Colorado River Basin Salinity Control Act 1995).

To address these issues, the Basin Fund provides $2 million in annual cost sharing to the Colorado River Basin Salinity Control Program. Federal and state programs also provide about $7 million annually that is applied toward agricultural improvements such as ditch lining or canal and piping equipment. Efforts have been made to reduce the impacts of salinity by addressing the issue at the source, which has proved more cost-effective than dealing with the detrimental impact of salinity on water quality and infrastructure. The salt load of the Colorado River has now been reduced by 1.2 to

1.3 million tons annually, but the program is required to continue to maintain the positive impacts of this effort (Barnett 2015). These partnerships continue to work with local companies and individual water users to control the salinity levels while allowing development and usage of its waters pursuant to the 1922 *Colorado River Compact*.

Modeling by USBR shows that the quantifiable damages from high salinity water are approximately $382 million per year to U.S. users, with projections that damages would rise to more than $614 million by 2035 if the Program were not to continue to be aggressively implemented (Barnett 2015). The 2012 salinity reduction report shows that the Colorado River Basin Salinity Control Program effectively mitigates the impact of over 1.295 million tons of salt per year. In order to meet the 1.85 million tons of salt per year goal and also meet the water quality standards in the Lower Basin, (below Lees Ferry, AZ) it will be necessary to fund and implement potential new measures which ensure the removal of an additional 555,000 tons by 2030 (USBR 2013).[23] The Salinity Control Program is estimated to cost between $30-$160 per ton of salt removed, while the benefits, or value of avoided damage, are $540 per ton (2015 dollar values) (USBR 2011b).[24]

Impact of lower reservoir levels

Managing salinity in the Upper Basin is essential to providing sufficient water quality as it moves downstream. The challenges outlined above will continue to contribute in various ways to increasing salinity in the river. The overall long term effects that large reservoirs like Lake Powell have on salinity are generally considered to be beneficial and to have greatly reduced the salinity peaks and annual fluctuation. In a system like this the high-concentration low-flow waters can be mixed with low concentration spring runoff, reducing the month-to-month variation in salinity below dams (Mueller et al. 1988). At Glen Canyon Dam, the pre- and post-dam peak monthly salinity has been reduced by nearly 600 mg/L, greatly improving the quality of water during the summer, fall and winter. Reservoirs like Lake Powell can selectively route less saline water while holding more saline waters during low inflow periods. The poorer quality, high-saline waters can then be slowly released after the inflows have begun to increase, which helps to prevent exceeding the salinity criteria during drought years (USBR 2005). With less water available as reservoir elevations decline, managing salinity in this way may become more difficult.

The primary damage of prolonged drought, lower in-stream flows, and higher salinity within the Colorado River main stem will be economic, with costs topping $1 billion annually (Borda 2004; Morford 2014). These greater economic costs of reacting to salinity in the future dwarf the costs of proactive investments, which have demonstrated positive ecological returns. With water demand

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[23] Biennial reports (which have been most recently published in 2005, 2009, and 2013) on the quality of water in the Colorado River Basin, including detailed information about salinity and its impacts are required by Public Laws 84-485, 87- 483, and the *Colorado River Basin Salinity Control Act* and available through the USBR.

[24] Sediment aggradation, increased salinity, impacted water temperature and dissolved oxygen (DO) are all related challenges that have been exacerbated by drought conditions. Sediments and organic matter consume oxygen as they decay, which lowers the dissolved oxygen levels on the downstream side of the dam, stressing fish populations downstream. Riffles or rapids create opportunities for re-oxygenation, but lower water availability and decreased flows may decrease the likelihood of these areas existing. While the declining reservoir levels have in some cases exposed new features that may create waterfalls or rougher water that would increase DO (Vernieu, 2005; 2010), the net impact of decreased inflows and lower reservoir levels has also decreased DO, resulting in those challenges earlier described.

trending upward, further strain will be placed on meeting water quality and salinity control requirements, particularly if natural hydrologic patterns result in decreased water availability.[25]

As reservoir levels decline, the dam's ability to generate hydropower diminishes due to decreased efficiency of water that possess lower hydraulic head[26], as well as the threat of water levels ultimately falling below "dead pool" elevation. While a portion of the funding for salinity programs also comes from Hoover Dam hydropower revenues, a change in the amount of energy produced at Glen Canyon could negatively impact the revenue gained from energy sales. This would decrease one of the sources of funding for environmental programs, funded by the Basin Fund, that work to address the challenge of managing salinity.

Fish Recovery Programs

Development of the river significantly impacted the fish habitat in the Upper Basin as well as below the dam. Alterations of seasonal flows, lower (and less variable) water temperatures, intrusion of invasive species, and the obvious physical boundaries that impede migration paths have resulted in degraded conditions for fish populations. By the early 1970s, water temperatures in Grand Canyon had dropped below the range of 16-22°C (61-72° F) needed for successful mainstem reproduction by the native warm-water fish species (Webb 1999). Reduced sediment flows and subsequent higher water clarity have significantly reduced movement by humpback chub, possibly affecting feeding and suggesting that the chub use turbid water as cover (Valdez and Ryel 1995). These changes underscore another negative effect of lowered suspended sediment in below Glen Canyon and into the Grand Canyon. The introduction of non-native sport fish which outcompete the native species for resources along with pollution and intentional poisoning for population control have also increased species stress (CRWUA N.d.a).

Two official agreements have established recovery programs that direct joint efforts and cooperation regarding water project development and the endangered fish in the Upper Basin. Program partners include the Upper Basin states, the USBR, Fish and Wildlife Service, NPS, CREDA, and NGOs. Along with these groups, the Department of Interior, Western Power, and Upper Basin American Indian Tribes have collectively implemented the recovery programs, also receiving financial support from the Basin Fund (Ott Verburg 2010).

The Upper Colorado Fish Recovery Implementation Program and the San Juan Endangered Fish Recovery Implementation Program receive a combined total of approximately $7 million annually from the Basin Fund. In the Upper Colorado the program focuses on four fish species currently listed under the *Federal Endangered Species Act* (*ESA*): bonytail chub (*Gila elegans),* Colorado pikeminnow (*Ptychocheilus lucius)*, humpback chub (*Gila cypha),* and razorback sucker (*Xyrauchen texanus)* (UCREFRP 2015). Similarly, the program in the San Juan River Basin focuses efforts on two species listed under the *ESA*, while trying to maintain other water uses within the Basin (SJRBRIP 2007).

The Upper Colorado Recovery Program was initiated in 1988, and the San Juan River Basin Recovery Plan was initiated in 1992. Both agreements are active through the year 2023. The Upper Basin states,

[25] Further information about sediment transport analysis can be found in USBR reports (Sediment Analysis for Glen Canyon Dam High Flow Experimental Protocol Environmental Assessment 2010).
[26] A Dam's ability to generate hydropower efficiently depends on the height of water behind the dam, based a measure of water pressure called "hydraulic head". Lower reservoir elevations and lower hydraulic head diminishes the ability of turbines to produce hydropower.

US Fish and Wildlife Service, water users and CRSP power customers contribute annual funding to programs each year. The total partner contributions to the Upper Colorado Program for FY 1989-2015 are just over $350 million, and total partner contributions to the San Juan Program are almost $63 million over the same time period. Power revenues represent about a quarter of total Upper Colorado Program funding, and roughly half of the total San Juan River funding (USFWS 2016).[27] Expenditures include habitat development, habitat management, in-stream flow acquisition, non-native fish management, hatchery construction and operation, endangered fish stocking, research, public information and education and program management.

Recovery programs work to provide adequate instream flow, monitor populations, and control non-native species through methods like electro-shocking (poisoning is not allowed where it would impact National Park areas, and could also hurt other species that support native fish recovery) (Loomis 2013). Humpback chub, for example, will be considered eligible for down-listing from endangered to threatened when additional self-sustaining populations form, essential habitat is legally protected, and identifiable threats are removed (UCREFRP 2015). The creation of Glen Canyon Dam rapidly changed the ecological conditions to which fish species had adapted and evolved over time. These new conditions facilitated the proliferation of non-native species at the expense of native species adapted to the natural flows of the river (Triedman 2012). Fortunately for the recovery programs, scientists confirmed the first reproduction of bonytail in the wild in the Upper Colorado River basin, representing a step in the right direction for the recovery of that species (UCREFRP 2016).

Impact of lower reservoir levels

The programs and practices in place have made positive impacts on restoring some of the ecological health necessary for the survival of threatened fish species. As a deeper understanding of the connectedness of these systems is understood, and a clearer concept of how actions upstream have complex impacts throughout the system, proactive strategies can be prioritized. The *Endangered Species Act* has provided a framework for action, and the dynamic, ever-changing nature of environmental conditions could benefit from a proactive holistic approach. Fish species that are adapted to warmer water will continue to feel pressure as releases of cold water from the reservoir are pushed downstream. Decreased water availability could continue to have detrimental impacts on populations of threatened native species, both in-stream and along the riparian corridors. As lower reservoir levels decrease the efficiency of water to generate energy at Glen Canyon Dam, revenues that support recovery programs could also decrease. However, the base funding from power revenues that is utilized to support these programs is a non-reimbursable federal expenditure. Given sufficient liquidity for the Basin Fund, there should not be an impact on rates as reservoir levels decline. Western and USBR must maintain sufficient revenues in the Basin Fund to meet the base funding obligations of these programs (USCENR 2000).

Conclusion

Construction of the dam itself created unavoidable environmental consequences that today require extensive study to understand and adequately address. The dynamic natural processes and variations of the river that flora and fauna require for survival have been without question altered by the presence of the dam. Environmental restoration programs can help alleviate some of the ecosystem impacts that have come about as a result of dam construction. The technological, political and social

[27] Fiscal Year highlight reports are issued by the U.S. Fish & Wildlife Service detailing fish recovery programs, projects and progress. See the bibliography for a link to the FY 2014-2015 highlights report, explaining specifics about the program.

challenges that these environmental programs face will be compounded as water scarcity becomes an even more pressing issue and reservoir levels remain well below full pool elevations.

Appreciating the connectivity and interdependence between the Upper and Lower Basins can inform managers in developing holistic, basin-wide management goals to address issues that impact the entire region. The challenges of sediment management and impacts of alteration of natural seasonal flows continue to create the need for expensive remediation programs that are funded at least in small part by the Basin Fund, with revenues gained from hydropower production. As reservoir levels drop, the efficiency of water to generate hydropower (the effective head) and power conversion rates of water passing through the turbines is reduced. Water at lower elevations that is “less efficient” at making power leads to lower revenues derived from power generation, and less money available to support these essential environmental programs.

Conclusion

Water supplies in Lake Powell are used to meet delivery requirements to the Lower Colorado River Basin, generate hydropower, provide recreational opportunity, and contribute to environmental health. Water deliveries in the Upper Basin are inextricably linked to water levels at Lake Powell through delivery obligations to the Lower Basin. To understand how declining water levels throughout the Colorado River Basin affect these sectors, this report complements *The Bathtub Ring* by analyzing the impacts of operating Lake Powell and Glen Canyon Dam at low water levels. The intention of this report is to spark conversation among Colorado River managers and motivate drought contingency efforts.

Upper Basin water supplies may be at risk in the future if water levels in Lake Powell reach critically low elevations. Concerns arise over increasing water demands and legal ambiguities that create uncertainty for water management should reservoir levels drop low enough to require Upper Basin curtailments. Changes in winter precipitation, temperature patterns, and timing of spring runoff impact water availability and add further complexity to management challenges. While the Upper Basin as whole share common vulnerabilities, it is important to highlight state specific concerns. The challenge is to overcome the inertia of the status quo, to curb demand in the face of growth, and to plan for contingencies that may include decreased water availability.

The current legal framework, to which the entire Colorado River Basin must adhere, promises more water than is generally available in any given year. Coupled with legal uncertainty around a potential compact call, the Upper Basin is at risk due to their junior priority to Lower Basin water users. To create more certainty, further research in this area of analysis would be a synthesis of water rights from each Upper Basin state to better understand priority dates, use by sector, and the proportion of water rights currently in use. This information would not only help planning efforts in the event of a curtailment, but also help water users understand their place in this complex, but interconnected system where one water user is linked to another.

Under the current power marketing system, declining reservoirs in Lake Powell will result in the increased cost of power for utilities that purchase power from Glen Canyon Dam. Our analysis shows that the amount of firming purchases required in order to meet Western’s Sustainable Hydropower contract obligations will increase. Although not included in our analysis, the costs of hydropower generated at Glen Canyon dam will also need to increase in order to cover rate repayment obligations. The volatility of the energy market makes it difficult to predict the exact cost associated with reservoir declines. Refining our estimates for the cost of energy on the wholesale market will help to narrow the range of predictions we make. Lastly, it was challenging to model the costs associated with power at Glen Canyon Dam alone and completing a similar analysis for the entire SLCA/IP systems will allow for the hydropower costs to be included in our estimates and is a venue for further research.

One implication of the increased power costs associated with declining reservoir levels at Lake Powell is that alternative sources of energy may need to be identified. As the quantity and frequency of firming purchases increase, the total cost of these purchases may require managers to reconsider current power marketing plans. The development of the West has relied on the benefits provided by inexpensive hydropower, however, if new environmental norms are realized in the 21st century, hydropower operations and marketing may need to be reevaluated.

Because of the correlation between the recreational visitation and storage volume of Lake Powell, low Lake elevations are projected by the extended Neher et al. model to cause a significant reduction in visitation - over 25 percent between 3675 and 3525 foot elevations. These impacts may be further exacerbated by additional considerations, such as the inoperability of shoreline access points relied upon by boaters and other water recreationists, as well as limited access to inner-lake routes such as the Castle Rock Cut. Because visitors to the Glen Canyon National Recreation Area are critical to the local Page economy, decreases in Lake Powell visitation could cause a corresponding decrease in visitor dollars spent in the region, which were measured to be $190 million in a 2012 report (NPS 2014a).

However, data analyzed in this study timeframe (1996-2016) suggest that new visitation patterns may be taking hold, demonstrating higher recreational activity in the past five years than would be inferred through reservoir volume alone. Interviews with NPS staff corroborate this observation and present an untested hypothesis that an influx of international visitors has both raised the overall visitation at Lake Powell, and shifted the types of usage towards more land-based activities. Further analysis on the demography and preferences of current Lake users could illuminate and quantify these trends further, as well as refine the Neher et al. model to account for these factors should they become significant indicators of future visitation.

Environmental impact is an unavoidable consequence of dam construction. Managers are responsible for dealing with those impacts and the policies that dictate priority for addressing concerns. Beneficial environmental outcomes rely on a shift in project priorities. Emphasizing management and implementation programs that operate in a holistic manner and allow for periodic reassessment and adjustment will be important for achieving positive environmental outcomes. Additional benefits could arise from expanded Basin-wide coordination with appreciation of the broader interconnected ecosystem and bioregion. Attending to the needs of plants and wildlife within the river system needs to be constantly balanced with the needs of people who have come to depend greatly on this water supply in a variety of ways. Environmental project funding that is tied to hydropower generation is at risk of declining as new realities of lower water availability become the norm. If reservoir levels continue to decline and the other purposes of the dam take priority over the environment, there is risk of neglect that could exacerbate existing environmental issues into the future. Balancing these demands appropriately will be no small task.

The choices that managers and policy makers make involve complex decisions that include economic effects and implications for other societal values. Multipurpose projects such as Glen Canyon Dam and Lake Powell often have conflicting goals and affect a diverse variety of stakeholders, all of which must be taken into consideration by managers when determining how to operate the system as whole. This suggests that there will be no single optimal management strategy for river or dam operations, but that different constituent groups must accept tradeoffs made during the decision process.

Drought conditions and the resulting decline in Lake Powell storage only complicate this already complex political landscape. The magnitude of the challenge should not be a discouraging factor for engagement. It is our hope that information detailed in this report will add to the existing body of knowledge and provide an additional framework for building understanding and aligning shared interests across managing entities and stakeholder groups.

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Appendix A: Full list of CRSP Customers *(Western n.d.a)*

Customer	Customer Type	State
Acoma Pueblo	Native American Tribes	NM
Aggregated Energy Services	Cooperatives	AZ
AK-Chin Indian Community	Native American Tribes	AZ
Alamo Navajo Chapter	Native American Tribes	NM
Albuquerque Operation-DOE	Federal Agencies	NM
Arizona Electric Power Cooperative	Cooperatives	AZ
Arkansas River Power Authority	Municipalities	CO
Aspen, City of	Municipalities	CO
Aztec, City of	Municipalities	NM
Basin Electric Power Cooperative	Cooperatives	ND
Black Hills Power and Light	Investor-owned Utilities	SD
Brigham City, City of	Municipalities	UT
Burbank, City of	Municipalities	CA
Cannon Air Force Base	Federal Agencies	NM
Canoncito Navajo Chapter	Native American Tribes	NM
Cargill-Alliant, LLC	Power Marketers	MN
Center, Town of	Municipalities	CO
Central Valley Electric Cooperative	Cooperatives	NM
Chandler Heights Citrus	Irrigation Districts	AZ
Cocopah Indian Tribe	Native American Tribes	AZ
Colorado River Agency-BIA	Native American Tribes	AZ
Colorado River Commission of Nevada	State Agencies	NV
Colorado River Indian Tribe	Native American Tribes	AZ
Colorado Springs Utilities	Municipalities	CO
De Cochiti Pueblo	Native American Tribes	NM
Defense Depot Ogden	Federal Agencies	UT
Delta, City of	Municipalities	CO
Deseret Generation and Transmission	Cooperatives	UT
Electrical District 2	Irrigation Districts	AZ
Electrical District 3 (APS) Pinal	Irrigation Districts	AZ
Electrical District 4	Irrigation Districts	AZ
Electrical District 5 Pinal	Irrigation Districts	AZ
Electrical District 6 Pinal (SRP)	Irrigation Districts	AZ
Electrical District 7 Maricopa County	Irrigation Districts	AZ
Farmers Electric Cooperative	Cooperatives	NM
Farmington, City of	Municipalities	NM
Fleming, Town of	Municipalities	CO
Fort Mojave Indian Tribe	Native American Tribes	AZ

Customer	Customer Type	State
Fort Morgan, City of	Municipalities	CO
Frederick, Town of	Municipalities	CO
Ft. McDowell Yavapai Nation	Native American Tribes	AZ
Gallup, City of	Municipalities	NM
Gila River Indian Community	Native American Tribes	AZ
Glenwood Springs, City of	Municipalities	CO
Grand Valley Electric Cooperative	Cooperatives	CO
Gunnison, City of	Municipalities	CO
Havasupai Tribe	Native American Tribes	AZ
Haxtun, Town of	Municipalities	CO
Heber Light and Power	Municipalities	UT
Helper, City of	Municipalities	UT
Hill Air Force Base	Federal Agencies	UT
Holloman Air Force Base	Federal Agencies	NM
Holy Cross Electric Association	Cooperatives	CO
Holyoke, City of	Municipalities	CO
Hopi Tribe	Native American Tribes	AZ
Hualapai Tribe	Native American Tribes	AZ
Intermountain Rural Electric Association	Cooperatives	CO
Isleta Pueblo	Native American Tribes	NM
Jemez Pueblo Tribe	Native American Tribes	NM
Jicarilla Apache Tribe	Native American Tribes	NM
JP Morgan Ventures Energy	Power Marketers	NY
Kirtland Air Force Base	Federal Agencies	NM
Laguna Pueblo Tribe	Native American Tribes	NM
Las Vegas Piute Tribe	Native American Tribes	NV
Lea County Electric Cooperative	Cooperatives	NM
Los Alamos County	Municipalities	NM
Luke Air Force Base	Federal Agencies	AZ
Maricopa County MWCD No. 1	Irrigation Districts	AZ
Mesa, City of	Municipalities	AZ
Mescalero Apache Tribe	Native American Tribes	NM
Morgan Stanley	Power Marketers	NY
Nambe Pueblo Tribe	Native American Tribes	NM
Navajo Agricultural Products Ind.	Native American Tribes	NM
Navajo Tribal Utility Authority	Native American Tribes	AZ
Navopache Electric Cooperative	Cooperatives	AZ
Needles, City of	Municipalities	CA
Nevada Energy	Investor-owned Utilities	NV
Oak Creek, Town of	Municipalities	CO
Ocotillo	Irrigation Districts	AZ
PacifiCorp	Investor-owned Utilities	OR

Customer	Customer Type	State
Page, City of	Municipalities	AZ
Pascua Yaqui Tribe	Native American Tribes	AZ
Piaute Indian Tribe of Utah	Native American Tribes	UT
Picuris Pueblo Tribe	Native American Tribes	NM
Platte River Power Authority	Municipalities	CO
Pojaque Pueblo	Native American Tribes	NM
Powerex	Power Marketers	CAN
Price, City of	Municipalities	UT
Public Service Company of Colorado	Investor-owned Utilities	CO
Public Service Company of New Mexico	Investor-owned Utilities	NM
Ramah Navajo Chapter	Native American Tribes	NM
Resource Management	Cooperatives	AZ
Roosevelt County Electric Cooperative	Cooperatives	NM
Roosevelt Irrigation District	Irrigation Districts	AZ
Roosevelt WC District	Irrigation Districts	AZ
Safford, City of	Municipalities	AZ
Salt River Pima-Maricopa	Native American Tribes	AZ
Salt River Project	State Agencies	AZ
San Carlo Apache Tribe	Native American Tribes	AZ
San Carlos Irrigation Project-BIA	Native American Tribes	AZ
San Felipe Pueblo	Native American Tribes	NM
San Ildefonso Pueblo	Native American Tribes	NM
San Juan Pueblo	Native American Tribes	NM
San Tan Irrigation District	Irrigation Districts	AZ
Sandia Pueblo	Native American Tribes	NM
Santa Ana Pueblo	Native American Tribes	NM
Santa Clara Pueblo	Native American Tribes	NM
Santo Domingo Pueblo	Native American Tribes	NM
Silver State Energy Association	Power Marketers	NV
South Texas Electric Cooperative	Cooperatives	TX
Southern Ute Indian Tribe	Native American Tribes	CO
St. George, City of	Municipalities	UT
Sulphur Springs Valley Electric Cooperative	Cooperatives	AZ
Taos Pueblo	Native American Tribes	NM
Tesuque Pueblo	Native American Tribes	NM
Thatcher, Town of	Municipalities	AZ
Tohono O'odham Utility Authority	Native American Tribes	AZ
Tonto Apache Tribe	Native American Tribes	AZ
Tooele Army Depot	Federal Agencies	UT
Torrington, City of	Municipalities	WY
TransAlta Energy Marketing (US)	Power Marketers	CAN
Tri-State Generation and Transmission Assoc.	Cooperatives	CO

Customer	Customer Type	State
Truth or Consequences, City of	Municipalities	NM
Tucson Electric Power Company	Investor-owned Utilities	AZ
University of Utah	State Agencies	UT
Utah Associated Municipal Power Systems	Municipalities	UT
Utah Municipal Power Agency	Municipalities	UT
Utah State University	State Agencies	UT
Ute Indian Tribe	Native American Tribes	UT
Ute Mountain Ute Tribe	Native American Tribes	CO
Wellton-Mohawk Irrigation District	Irrigation Districts	AZ
Willwood Light and Power Company	Cooperatives	WY
Wind River Reservation	Native American Tribes	WY
Wray, City of	Municipalities	CO
Wyoming Municipal Power Agency	Municipalities	WY
Yampa Valley Electric Association	Cooperatives	CO
Yavapai Apache Nation	Native American Tribes	AZ
Yavapai Prescott Indian Tribe	Native American Tribes	AZ
Yomba Shoshone Tribe	Native American Tribes	NV
Yuma Proving Grounds	Federal Agencies	AZ
Yuma, City of	Municipalities	CO
Zia Pueblo	Native American Tribes	NM
Zuni Pueblo	Native American Tribes	NM