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

Ning Jiang | Season Martin | Julia Morton | Skyler Murphy

May 18th, 2015

Master's Group Project
Bren School of Environmental Science and Management
University of California, Santa Barbara

Faculty Advisor
Naomi Tague, PhD

External Advisors
Ken Nowak, PhD | Bob Wilkinson, PhD

Client
Douglas Kenney, PhD | Western Water Policy Project

Bren School of Environmental Science & Management
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

Western Water Policy Program
WWW.WATERPOLICY.INFO

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

As authors of this Group Project report, we are proud to archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

Ning Jiang

Season Martin

Julia Morton

Skyler Murphy

The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

ADVISOR: Naomi Tague

DATE

Disclaimer

This document was prepared as an account of work sponsored by the Bren School of Environmental Science and Management. All research, views, opinions and recommendations are those solely of the authors and do not necessarily state or reflect those of any of the entities interviewed including:

Arizona Department of Water Resources
Bureau of Reclamation
Central Arizona Project
Colorado River Board of California
Metropolitan Water District of Southern California
Southern Nevada Water Authority
Western Area Power Administration

All photos, illustrations, figures and tables are those of the authors or in the public domain unless otherwise cited.

Acknowledgements:

This project would not have been possible without the generous support of many individuals. We'd first like to thank our client Doug Kenny for agreement to work with us, his knowledge of the Colorado River Basin and guidance on this project. Additionally, our faculty advisor Naomi Tague provided essential visioning and technical support. Ken Nowak was crucial especially for our water supply and hydropower analysis. Bob Wilkinson provided decisive guidance on the energy-water nexus. In addition to our official advisors, we had significant assistance from many professionals across the Colorado River Basin. We'd like to thank the following individuals for providing indispensible responses to our questions and feedback on our analysis:

Arizona Department of Water Resources	Thomas Buschatzke Evelyn Erlandton Don Gross
Bureau of Reclamation	Dan Bunk Keith Cooper Terrance Fulp Kib Jacobson Carly Jerla Jonathan Sanchez
Environmental Defense Fund	Jennifer Pitt
Metropolitan Water District of Southern California	William Hassencamp
Pacific Institute	Micheal Cohen
Southern Nevada Water Authority	Colby Pellegrino
Stanford University	Frank Wolak
The Nature Conservancy	Robert Wigington
UCSB - Bren School of Environmental Science and Management	Andrew Ayres Brian Castle Eric Fournier Allison Horst Brandon Kuczenski Gary Libecap Leslie Sanchez
University of Arizona	Karl Flessa
University of Montana	Chris Neher
Utah State University	Jack Schmidt
Western Area Power Administration	Jeff Ackerman Rodney Bailey
Western Area Power Administration - Desert Southwest Region	Gloria Jordan Michael Simonton
Western Resource Advocates	David Berry

Table of Contents

List of Figures

List of Tables

Executive Summary

Much of the western United States depends on the Colorado River for municipal water supply and agricultural irrigation, making it one of the most important and over-allocated natural resources in the nation. In addition to water resources, the Colorado River is an important source of hydroelectricity, water recreation, tourism and ecological habitat (Senate Energy and Natural Resources Committee, 2013). Supporting approximately 40 million people and irrigating over 5.5 million acres of land across seven states and two countries, virtually every drop of the Colorado River is allocated to a consumptive use (Bureau of Reclamation, 2012a). With some of the nation's fastest growing urban populations dependent on the river for their water supply, demand is steadily growing. With the addition of climatic variability and prolonged drought, water levels in Lake Mead, a key storage reservoir in the Lower Basin, have dropped to precipitously low levels recently, further stressing current water availability in the Basin.

To begin addressing potential water shortages, the Department of Interior issued the *Colorado River Interim Guidelines* in 2007. Predominantly focused on water allocations to the Lower Basin states (California, Arizona and Nevada), the guidelines specify water levels in Lake Mead that trigger water delivery curtailments to the Lower Basin. The Environmental Impact Statement generated during this process provides a broad overview of shortage call impacts on various stakeholders. Additionally the *Colorado River Basin Water Supply and Demand Study* in 2012 outlined the probability of shortage situations in the Basin, and evaluated potential mitigation strategies. However, neither study quantifies specific impacts on individual stakeholder groups at specific water levels in Lake Mead as it continues to shrink. Furthermore, though media attention has focused water supply impacts, water released from Lake Mead also supports hydropower generation, a recreation industry, and environmental needs. The continued decline of Lake Mead's water level will have far reaching impacts on all four user groups, which has yet to be adequately addressed in a rigorous analysis.

A comprehensive analysis was needed to address those implications, which is becoming increasingly timely, given that there is a 54% probability Lake Mead will drop below 1,075' by 2017, triggering the first set of mandated curtailments set forth in the agreement (Central Arizona Project, 2014b).

Utilizing designated elevations specified in the *Interim Guidelines* (1,075', 1,050', 1,025', and 1,000') this project evaluated the impacts of a declining reservoir level on key users in the Lower Colorado River Basin. Specifically:

1. The vulnerability of different Lower Basin States and sectors to curtailments in water deliveries.
2. Operational and financial implications of reduced reservoir levels on hydropower generation at Hoover Dam.
3. Recreational use changes on Lake Mead, and associated changes in revenue for key stakeholders.
4. Ecological and water quality impacts to the Lower Colorado River Basin.

A multi-faceted approach was necessary to adequately achieve the project objectives. Focused literature reviews and interviews with key river and sector experts developed a thorough understanding of the processes and policies behind targeted impacts. A vulnerability index was developed to determine the potential impact of curtailments on the agricultural, municipal and industrial, and tribal water users in the Lower Basin states. Utilizing existing models of hydropower generation from Hoover Dam, the financial impact of power generation reduction to Hoover contractors was quantified at each key elevation. An existing model of recreation use on Lake Mead was updated with the most recent elevation data to illuminate the financial impact of the decreased water levels in question. To understand ecological and water quality impacts, current literature was synthesized, and changes in hydropower revenue available to key environmental programs in the basin was quantified.

Our analysis found that declining Lake Mead level leads to substantial and quantifiable impacts to all four user groups:

- **The first to be curtailed is not always the most vulnerable**: It is generally assumed that the priority of water rights determines vulnerability and consequently, Nevada water users should be the most vulnerable to water supply curtailments, and California users the least vulnerable. Our analysis concludes that the opposite is true. Impacts to Central Arizona Project users, as expected, will be significant, but will be confined to agricultural users, not municipal or tribal water users.

- **The cost of hydropower could roughly quintuple**: Hydropower generation will decline as Lake Mead shrinks, increasing energy costs. Costs paid by contractors for hydropower and spot market power will roughly double at 1075', triple at 1050', quadruple at 1025' and quintuple at 1000'. Though hydropower rates will surpass spot market rates at lower elevations, Hoover customers are contractually bound to purchase Hoover power until 2067.

- **Reductions in visitation could be reduced by half**: Recreation at Lake Mead National Recreation Area will decline potentially low enough to render the National Park Service economically unviable due to increased infrastructure maintenance cost to keep up with low reservoir levels.

- **The greatest environmental impacts are indirect**: Reduced agricultural runoff could threaten the Colorado River Delta since it is the main water source for the Delta's ecosystems. Additionally, funding for the Salinity Control Program will be reduced due to declines in hydropower revenue.

This analysis does not project when Lake Mead will reach the curtailment elevations, but instead provides both quantitative and qualitative frameworks to support decision making as shortages occur.

Project Significance

The Colorado River is arguably one of the single most important natural resources in the western United States. It is an important source of drinking water, electricity generation, agricultural irrigation, recreation, tourism, and supports one of the largest riparian corridors in the West (Senate Energy and Natural Resources Committee 2013). Spanning seven states and two countries, it supports approximately 40 million people (*Colorado River Basin Water Supply and Demand Study: Executive Summary* 2012). Some of the country's fastest growing urban populations depend on the river for water supply, rapidly increasing demand. Furthermore, significant natural stream variability has decreased annual flows since the river was first apportioned in 1922. Increasing demand and decreasing flows are already creating allocation problems within the Colorado River Basin. Numerous studies have quantified decreases in the Basin's future flow. Despite projection differences, it is widely accepted that temperature increases from climatic variability will further diminish streamflow making the supply-demand imbalance a permanent reality for the Colorado River (Vano et al. 2014).

Lake Mead, a key reservoir created to reduce flood risk and mitigate supply variability, has reached record low levels in the past several years due to prolonged drought and high water demand. In addition to the obvious supply issues this presents, low water levels carry additional implications for the diverse user groups relying on the Colorado River. The Department of Interior started to address potential shortage issues through the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead* in 2007. Predominantly focused on Lower Basin state allocations, the *Interim Guidelines* specify surface elevations in Lake Mead that will trigger delivery curtailments to the Lower Basin (1,075', 1,050' and 1,025' feet above average sea level).

Bureau of Reclamation currently projects there is a 54% probability that Lake Mead's surface elevation will reach the first curtailment level, 1075', in 2017 (Central Arizona Project 2014b). It is not a question of if, but when, these key reservoir levels are reached as persistent drought conditions and climatic variability pose significant impacts on runoff and river flows. Additionally, as the surface elevation of Lake Mead decreases, its capacity decreases as well. However, due to its irregular shape, the relationship between capacity and elevation is not linear. Reservoir capacity decreases more rapidly at low reservoir levels (Figure 1). Furthermore, sedimentation that has been occurring since 1935 has raised the surface bed of the reservoir (though compaction over time has reduced the sediment volume slightly), furthering the decrease in total capacity (1.5 MAF in total since 1935). Since the construction of Glen Canyon Dam in 1963, sediment inflow has been reduced by a tenth (National Park Service 2015).

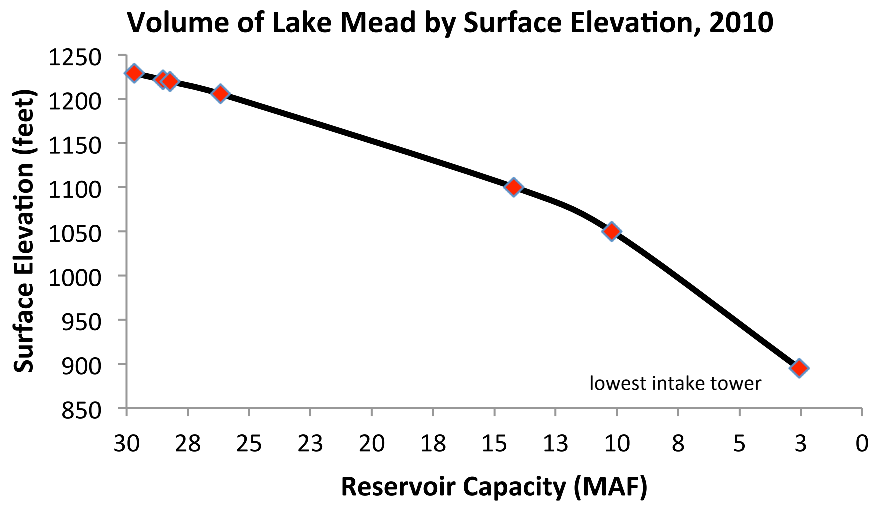

Figure 1: Comparison of Lake Mead volume capacity to surface elevation.

Over-allocation of water is one main reason for the decline of reservoir levels in Lake Mead. Full apportionment of water to the Upper and Lower Basin, as well as Mexico, totals 16.5 MAF (Bureau of Reclamation 2011). Allocations were made in accordance with Law of the River, based on the ten wettest years in a past 100-year record (National Research Council 2007). However, the hydrology of the river is highly variable, and has averaged 15 MAF over the past 100 years (Bureau of Reclamation 2011). The basin used 15.3 MAF per year on average from 1998 to 2007 (Bureau of Reclamation 2011), mostly by Lower Basin States with more urban centers, agricultural production, and drier climates. The Upper Basin has chronically under-used its annual allocation of 7.5 MAF due to inadequate storage capacity and smaller dependent populations centers, which the Lower Basin gladly siphoned to satisfy its large demand (Hecox, Boepple, and Gottfried 2012). Rapid population growth in cities dependent on the Colorado River's water such as Denver, Albuquerque, Las Vegas, Tucson, Los Angeles, and San Diego, in the 1990's and 2000's initiated prolonged stress on the Basin's allocations (National Research Council 2007). The Upper Basin's unused portion is increasingly insufficient in supporting existing Lower Basin needs. Finally, the Colorado River no longer annually meets the Sea of Cortez, physical proof of its over-allocation. As Upper Basin States grow and demand more water, less unused water will be available to Lower Basin States, furthering the supply and demand imbalance (*Colorado River Basin Water Supply and Demand Study: Executive Summary* 2012).

Drought is another cause of the river's declining flows and decreasing reservoir levels. The current drought the Basin is experiencing started in 2000. Lake Mead's surface elevation has gradually declined and is currently hovering around 1,080' as of December 2014, not far above its first curtailment level of 1,075', designated by the *Interim Guidelines*. Climate change is likely to compound the climatic and hydrologic challenges to the Colorado River Basin in the future. Across the basin temperatures are expected to increase between 2-2.5°C ± 1°C and projected precipitation changes range from −4 ± 12% to −2.5 ± 6%. The projected decrease in streamflow at Lee's Ferry is likely due to the increased temperature range from 5% to 35%. Additionally, changes in precipitation will also impact streamflow. A projected 5% decline in precipitation will yield a 10-15% decline in streamflow at Lee's Ferry. Finally, natural variability in the Colorado River Basin indicates records of prolonged dry periods. These mega-droughts combined with the reductions in streamflow due to climate change could result in long periods of streamflow much lower than has been documented in the historic record (Vano et al. 2014).

The dialogue started by the *Interim Guidelines* is essential for effective future planning in the Basin. However, noteworthy gaps persist. The Guidelines stop short of specifying allocations in the event that Lake Mead drops below 1,000’, not a far-fetched scenario. The Environmental Impact Statement completed during the Interim Guideline process outlined the impacts to water rights holders over a 50-year time period, but did not address specific vulnerability of each state and sector to water delivery curtailments.

Academics, BOR, and Basin States have conducted several studies in recent decades to discuss the challenges of sustainably managing the Colorado River to balance the dwindling supply and growing demand. The most recent, comprehensive study was done by BOR in 2012. The *Colorado River Basin Water Supply and Demand Study* (Basin Study) defined the current imbalance in water supply and demand and projected a range of possible imbalance scenarios that the Basin might face by 2060, primarily due to uncertainty in future water supply (*Colorado River Basin Water Supply and Demand Study: Executive Summary* 2012). The Basin Study also explored a range of adaptation or mitigation solutions, to supplement the current programs aimed at reducing water consumption or increasing water supply.

However, gaps still remain. Although the basic state level water allocations are well documented, how water is further distributed within each state is less clear. This project, will clearly illustrate how water is distributed within each Lower Basin state. Based on different vulnerability factors, the project will identify which water users are most vulnerable to curtailments during shortage conditions. The project will provide valuable information that may be utilized in future analysis of the social and economic implications of water allocations and cuts among Lower Basin users as reservoir levels continue to drop.

Several studies have quantified the economic costs of Colorado River water’s ancillary services, such as electricity production, in the event of decreased flows in the Basin. Those that have looked at Hoover’s hydropower production have analyzed the impacts on a broader scope. Hoover Dam hydropower brings important economic benefit to the Lower Basin states because it is made available to contractors at extremely low rates. As reservoir levels drop, hydropower generation will decrease and contractors will be forced to purchase more expensive power in the open market. Both the Interim Guideline’s EIS and the Basin Study have considered the general economic impact of lost hydropower if flows into Lake Mead continue to decline. However, neither of these studies extensively quantifies the lost hydropower nor the financial impact to hydropower customers at each shortage elevation delineated in the Interim Guidelines This project will provide a baseline analysis of how entities with contracts for Hoover hydropower will be financially impacted by lost hydropower at lower reservoir levels, with implications for their retail customers.

Recreation in Lake Mead is also an important economic factor in the Basin States. Visitation rates and access points to recreational activities depend on reservoir levels. Although one study has correlated reservoir volume with visitation rates, the study did not project impacts to visitation at extremely low water levels. Additionally, reductions in visitation have not been linked to changes in access points.

The ecosystem of the Colorado River is linked with hydrology of the river. Although anthropogenic development in the river has drastically changed the natural environment, work is still being done to preserve the remaining pieces of ecosystem. While the impact of low reservoir levels in Lake Mead on both reservoir and downstream ecosystems has be been studied, this information has not been gathered in a comprehensive report, nor has the impact on environmental program funding structures in the Lower Basin been addressed.

This analysis attempts to synthesize existing information on the impacts of declining reservoir levels in Lake Mead on four key sectors:

1. **Water supply** deliveries to key sectors in the Lower Basin states
2. **Hydropower** generation and the overall cost of power bought by Hoover Dam power contractors
3. **Recreational** use and reservoir access points
4. **Ecosystems** and funding for key environmental programs

This study builds on existing work and provides a comprehensive analysis that synthesizes information from a variety of Colorado River stakeholders. Looming water insecurity and competing needs, combined with the complexity of western water law and delicate political relationships hinder information sharing between stakeholders. This project proposes to fill the gap by developing a complete picture of potential future economic implications for four key Colorado River stakeholder areas—hydropower consumers, the recreation industry, water supply and delivery systems, and Lower Basin ecosystems and funding structures—as Lake Mead levels decline. An integrated comprehensive analysis of potential future scenarios is critical to managing this complex situation as equitably as possible.

Project Objectives

As the Colorado River Basin moves into the future, hydrologic conditions are likely to worsen with increasing climatic variability and demand for the river's resources. Within the next two years, Lake Mead will likely drop below 1075', triggering the first curtailment from the *Interim Guidelines* (*24-Month Study* 2014; Pitt 2014). The project focuses on the implications of extreme low reservoir storage conditions, which are expected to occur within the next decade, rather than assessing the probability of these conditions occurring in the future.

The project will utilize the key elevations outlined in the *Interim Guidelines* for evaluating the impacts of declining reservoir levels. Specified reservoir elevations for Lake Mead include 1,075', 1,050', 1,025' and 1,000'. This project will assess the implications at the key elevations by answering the following research questions:

Water Supply	**Overall Question: What are the distributional effects to each state and sector of water delivery curtailments at each key elevation?**
	Q1) How will changes in allocation at 1,025', 1,050', and 1,075' be distributed amongst different sectors in each state[1]? **Q2)** How vulnerable are different states and sectors to changes in Colorado River was supply.
Hydropowe	**Overall Question: What are the operational and financial implications of reduced reservoir levels on hydropower generation at Hoover Dam?**
	Q3) How will hydropower generation change at each designated elevation? **Q4)** How will be the financial impact of lost generation on entities with contracts for Hoover hydropower[2]?
Recreation	**Overall Question: What are the changes in recreational use at Lake Mead National Recreation Area?**
	Q5) How will recreational visitation change? **Q6)** What are the impacts of low reservoir elevations on access points?
Environment	**Overall Question: Are there other environmental impacts associated with declining reservoir levels?**
	Q7) How will water delivery curtailments impact ecosystem in the Lower Colorado River below Hoover Dam and the Colorado River Delta? **Q8)** What are the impacts to water quality, specifically salinity? **Q8)** How is funding to key environmental programs impacted by reduction in hydropower revenues[3]?

[1] State curtailments are known for 1,075'-1,025', but unknown for 1000'. Sectors include: municipal/industrial, agriculture, and tribal. Sector allocations within each state will analyze priority rights assuming no changes in existing arrangements

[2] Contractors such as Metropolitan Water District, Southern Nevada Water Authority, and smaller utilities sell hydropower to retail customers.

[3] If hydropower generation at Hoover Dam decreases, profits will decrease and therefore funding for ecosystem restoration/mitigation programs will be affected.

General Background

The Colorado River Basin is situated in the southwestern portion of the US. From the headwaters the river flows through high semi-arid alpine environments of Wyoming and Colorado. It gradually descends into warmer, drier, and lower elevations as it flows through Utah, New Mexico, Arizona, Nevada, and California, before entering northern Mexico. It splits naturally into two basins—Wyoming, Colorado, Utah, and New Mexico forming the Upper Basin, while the Lower Basin consists of Arizona, Nevada, and California (Figure 2).

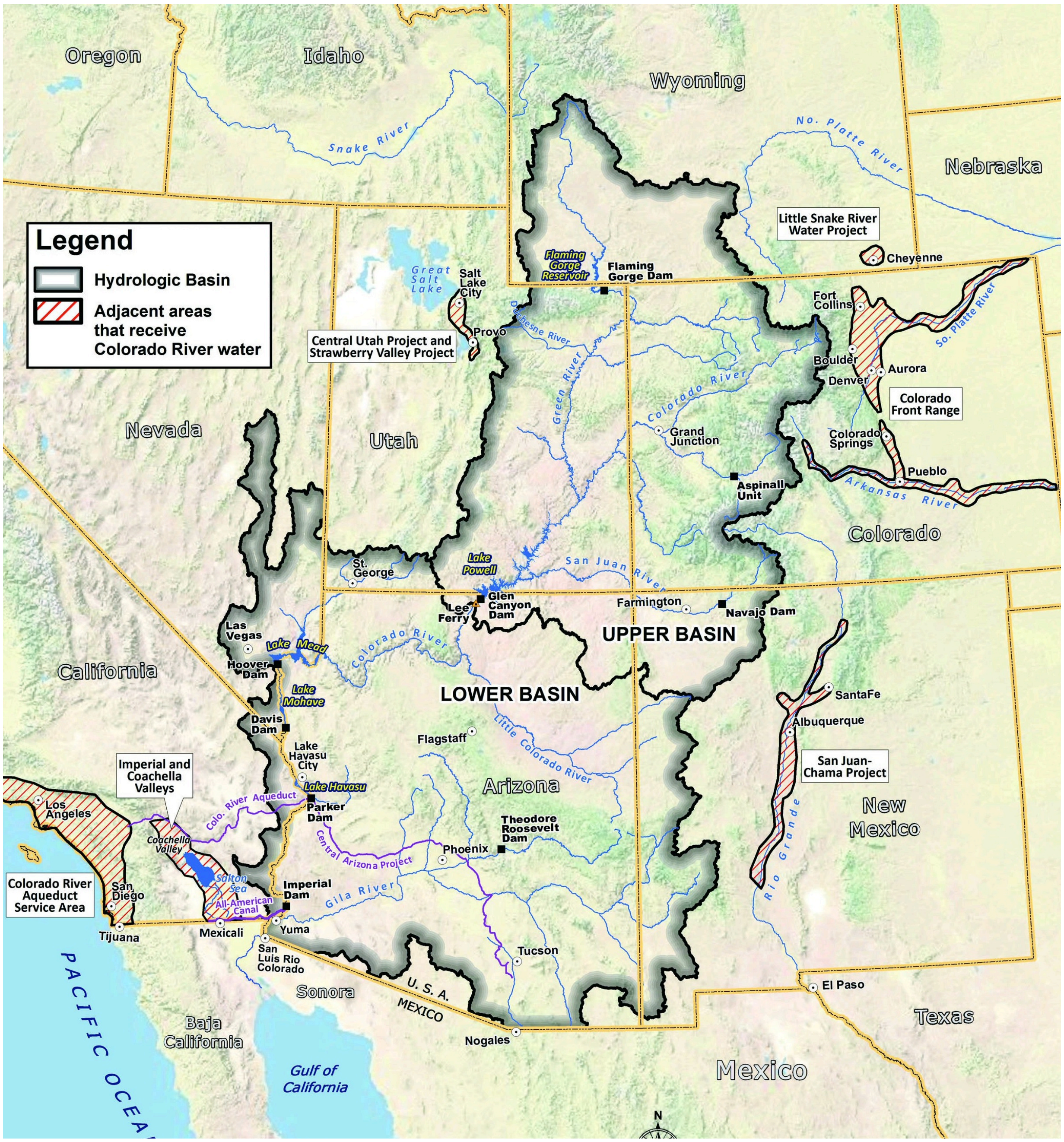

Figure 2: Map of Colorado River Basin (*Colorado River Basin Water Supply and Demand Study: Executive Summary* 2012).

Snowmelt in the Rocky Mountains mainly drives the river's hydrologic cycle. The 100-year flow record demonstrates large inter-annual variability; however, past climate reconstructions show prolonged wet and dry periods (Figure 3). Below average annual flows since the early 2000's are rapidly decreasing supply and the Colorado River is accumulating a large water debt (National Research Council 2007).

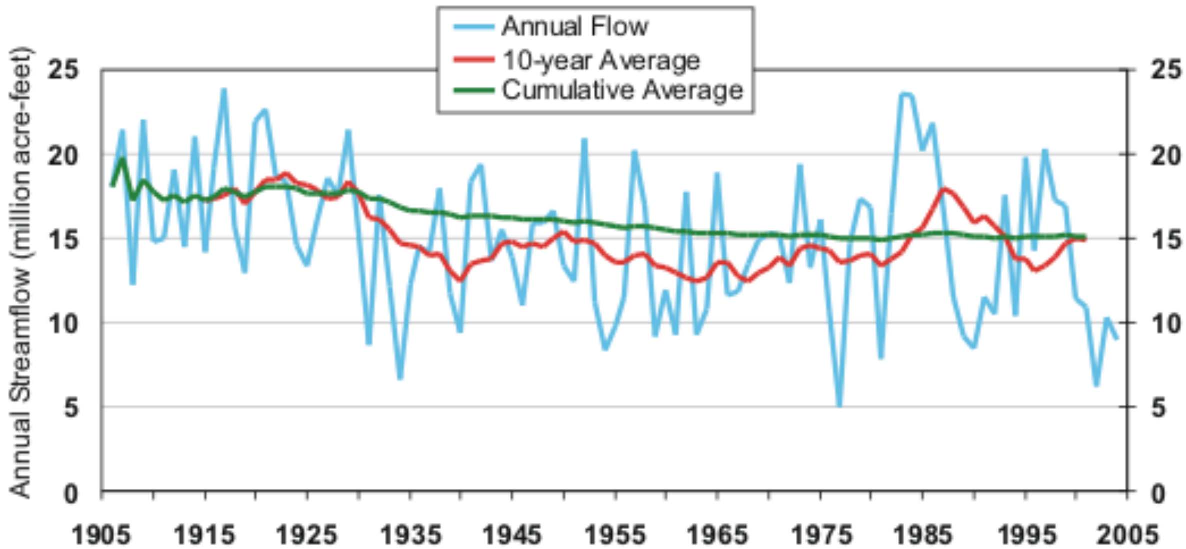

Figure 3: Natural streamflow of the Colorado River at Lees Ferry, Arizona, 1906-2004 ("Colorado River Streamflow: The Lees Ferry Gaged Flow Record," n.d.).

A series of dams and diversion projects control the wild and variable nature of the Colorado River for better utilization by southwestern communities. Glen Canyon and Hoover are the two largest dams on the Colorado River system. The reservoirs created behind the dams—Lake Powell and Lake Mead—provide storage for the seven basin states and Mexico to reliably obtain water deliveries.

As such, Lake Mead is a central component of the water supply system in the southwest. When Hoover Dam was authorized, its functions, in order of importance, were and still are, flood control, water delivery, and power generation. Lake Mead's elevation depends on Colorado River runoff and releases from Lake Powell upstream. At full capacity, 1,221.4' above sea level, the reservoir holds 28,945,000 acre-feet (AF), approximately the river's entire flow for two years (Bureau of Reclamation 2012b). The stored water serves a multitude of uses including: running a hydropower plant; providing municipal, industrial, and agricultural water to Arizona, California, Nevada, and Mexico; providing recreational opportunities; and maintaining downstream flows for ecosystems.

Colorado River Basin Stakeholders

More than 70% of the water delivered from the Colorado River to Lower Basin states is used for agriculture (*Colorado River Basin Water Supply and Demand Study: Executive Summary* 2012). The four largest water users in the state of California are the Imperial Irrigation District, Coachella Valley Water District, Palo Verde Irrigation District and Metropolitan Water District of Southern California (MWD) ("Colorado River Water Users Association" 2014). While agriculture may be the largest consumptive use of water in the Lower Basin, urban and industrial uses are increasing the pressure on water managers in the West. With populations in California, Arizona and Nevada projected to double between 1995 and 2025, urban and industrial water demand will grow (Campbell 1997). Population growth will cause water demand to consistently exceed supply in the Basin, illustrated in the *Colorado River Basin Water Supply and Demand Study* (Figure 4). The continuously growing demand for water from the Colorado emphasizes the importance of a strong understanding of where the water is going and how it is being used.

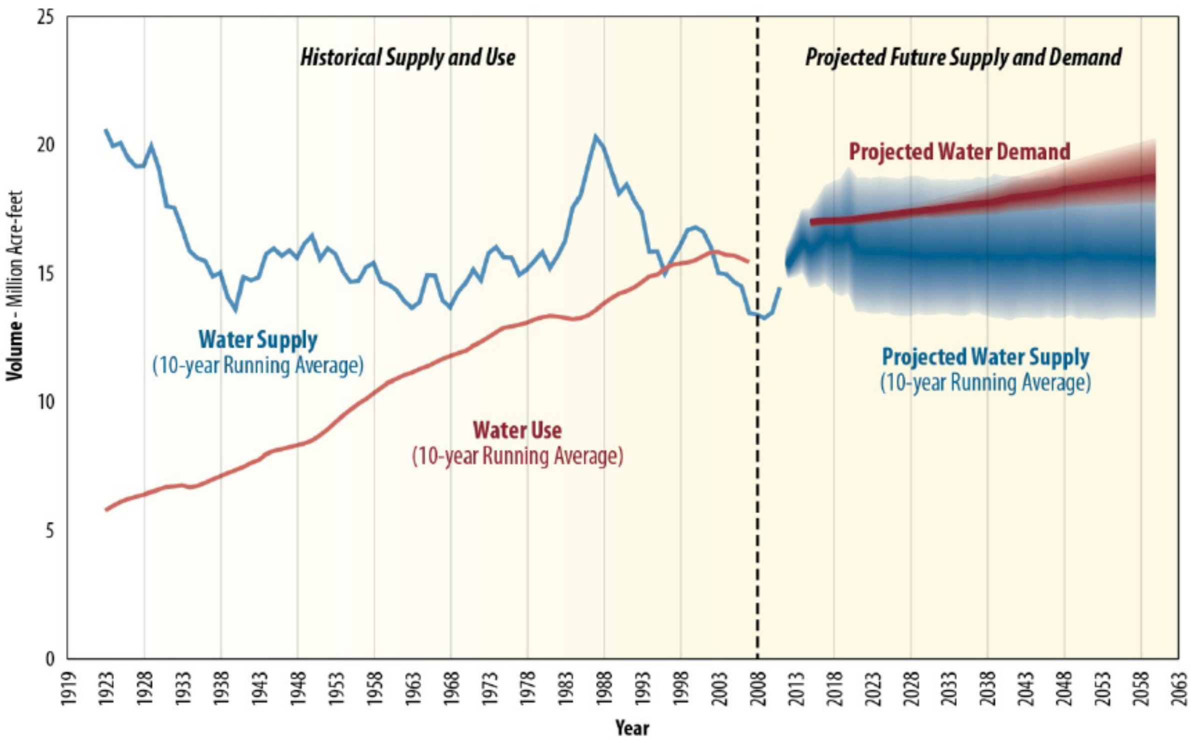

Figure 4: Historical and projected supply and demand in the Colorado River Basin (*Colorado River Basin Water Supply and Demand Study: Executive Summary* 2012).

Hoover Dam is the sixth largest hydroelectric power facility in the US. Each year, the powerplant generates 4.5 million megawatt-hours (MWh) of hydroelectricity, provides power to 1.3 million people, and covers peak demand for numerous cities in Nevada, Arizona, and California (Bureau of Reclamation 2012b; Zimmerman 2010). Hydropower from Hoover Dam is the Southwest's cheapest power source. WAPA is legally mandated to only cover basic operational costs, not profit, by selling power, resulting in extremely low rates available to energy contractors. (U.S. Energy Information Administration (EIA) 2014; Zimmerman 2010).

Lake Mead National Recreation Area provides recreational opportunities to over seven million visitors each year. Visitation supports the National Park Service and more than 125 small businesses that support the recreation industry. Additionally, the Lower Colorado River supports a variety of habitats and species.

Water from the Colorado River fulfills a wide variety of needs. Today, a diverse set of users with conflicting needs has evolved, each with a stake in the future of the basin. As the operator of Hoover Dam, the Bureau of Recreation is a major player in virtually all facets of river management. Major cities such as Las Vegas, Los Angeles and Phoenix, as well as major water districts in Nevada – SNWA, Arizona – Central Arizona Project, and California – MWD are concentrated on fulfilling municipal water needs. Farmers and major irrigation districts such Imperial Valley Irrigation District and Palo Verde Irrigation District are concerned about the future viability of their livelihood. Members of approximately twentytwo Native American tribes depend on the Colorado River for food, cultural practices, and/or water supplies. Finally, non-consumptive uses such as recreation and ecological needs depend on a healthy functioning river and reservoir system.

Colorado River Basin Governance

Governance of the Colorado River Basin is complex and politicized. A majority of western water law in the Basin states is governed by prior appropriation, which grants the first users first rights to water. Water rights holders are required to use their amount allocated for beneficial use or they lose the right for future use. Beneficial use has traditionally only applied to human uses such as agricultural, municipal, or industrial. Non-consumptive uses such as in-stream flows and recreational uses were not historically considered beneficial (Hecox, Boepple, and Gottfried 2012), however some states have recently revised the definition to include such purposes. Prior appropriation is also not typically applied across state lines; instead, arrangements are sought to reflect the different rates of development in sub-regions.

A complex and voluminous set of interstate compacts, Congressional Acts, bi-national treaties, and Supreme Court decisions, collectively known as the Law of the River, lay out the allocation and management guidelines on the Colorado River. Largely designed to accommodate natural hydrologic anomalies of the river's flow exacerbated by climatic variations, the Law of the River includes over ten major legal agreements (National Research Council 2007).

In 1922, the Colorado River Compact became the first major agreement of the Law, partitioning the river's total annual flow between the Upper and Lower Basins. The Compact allocated 7.5 million acre-feet (MAF) annually to both the Upper and Lower Basins, as well as providing an additional 1 MAF to the Lower Basin as available. The agreement also provided for a later allocation of 1.5 MAF to Mexico, as a modification to the Treaty in 1944. The Compact was flawed from the start—initial total annual flow designation was based on hydrologic measurements made during the ten wettest years of the past 100 years, making the full allocation of 16.5 MAF a significantly higher value than the average flow of 15 MAF (National Research Council 2007).

Key agreements and decisions in Lower Basin management include the Boulder Canyon Act of 1928 and *Arizona vs. California* (1963). In addition to ratifying the Compact, the Boulder Canyon Project Act was mainly a response to homesteaders' inability to control the river's variable flow to serve growing population and irrigational needs in California. Annual water allocations to California, Arizona, and Nevada were specified along with authorization of the Hoover Dam's construction in order to moderate the river's flows (Hecox, Boepple, and Gottfried 2012). With the addition of authorizing the Secretary of Interior as the final decision-maker in all Lower Basin issues, the Boulder Canyon Act essentially delineated the river's management in the Lower Basin (National Research Council 2007).

In 1963 *Arizona vs. California* became a landmark Supreme Court decision regarding the role of tributary flows in annual allocations. California was protesting a major diversion project planned by Arizona on the basis that they were already using their annual allocations by appropriating water in the Gila River, a tributary to the Colorado River, before it reached the mainstem Colorado. Siding with Arizona, the Court upheld the right to appropriate and use tributary flows without impacting annual mainstem allocations put forth in previous agreements. In the future, this decision would allow Arizona to construct the Central Arizona Project (CAP), a major water supply line for the state today (Kuhn 2007).

Congressional Acts in 1956 and 1968 authorized additional storage and reclamation projects. Specifically, the Colorado River Storage Project Act of 1956 outlined the development plan for the Upper Basin including the construction of Glen Canyon Dam. The 1968 Colorado River Basin Project authorized the Central Arizona Project. To pacify California's concerns, CAP's rights were designated junior to California's, and would be curtailed first during a shortage, a provision that has become salient as reservoir levels recently declined. Finally, in 2007 the Lower Basin states negotiated the *Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operation of Lake Powell and Lake Mead* to specify allocation administration during potential shortages.

Colorado River Interim Guidelines

The *Interim Guidelines* establish elevations in Lake Mead that trigger coordinated management of Lake Mead and Lake Powell in surplus and drought conditions. The operations and protocols outlined in the *Interim Guidelines* are effective through December of 2025, at which point they will be reviewed. Lower Basin states will have a chance to make revisions and adopt a new annual operating plan effective January 2026 (Department of Interior, Bureau of Reclamation 2007).

As storage in Lake Mead storage declines, the importance of these shortage protocols is amplified. The *Interim Guidelines* specify three key elevations in Lake Mead that trigger water delivery curtailments to Lower Basin states in order to prolong the useful life of the reservoir. As the elevation of Lake Mead drops from 1,075', to 1,050' and 1,025', water allocations to Arizona, Nevada, and California decrease accordingly (Table 1). Additionally, at 1000' a consultation is triggered between the Lower Basin states and the Bureau of Reclamation.

In addition to reservoir elevations for low storage conditions, normal (1,075' - 1,145') and surplus (above 1,145') conditions were also specified. The Intentionally Created Surplus (ICS) process, available in surplus conditions, allows water users in the Lower Basin to gain water credits by decreasing mainstem water use. The decreased mainstem uses can be achieved through efficiency upgrades in either water transportation, extraordinary conservation such as fallowing cropland, use of desalinization in place of Colorado River water, the purchase of tributary water rights, or the importation of non-Colorado River water to the system. Users are incentivized to create surplus in exchange for eligibility to receive additional deliveries equal to the quantity of surplus they created. It is important to note that the Secretary of the Interior can cancel the delivery of ICS water in shortage years.

Table 1**:** Designated elevations in Lake Mead and water allocations for California, Arizona, and Nevada established in the *Interim Guidelines*.

Lake Mead Drought Thresholds		
Lake Mead Elevation	**Water allocations**	**Reductions in Deliveries**
Above 1,075 feet "Normal Condition" or "Surplus Condition"	full 7.5 maf plus available surplus deliveries	4.4 maf to California, 2.8 maf to Arizona, 300,000 af to Nevada (No Reductions)
Below 1,075 feet and above 1,050 feet	7.167 maf	4.4 maf to California, 2.48 maf to Arizona (12% reduction), 287,000 af to Nevada (5% reduction)
Below 1,050 feet and above 1,025 feet	7.083 maf	4.4 maf to California, 2.4 maf to Arizona (17% reduction), 283,000 af to Nevada (6% reduction)
Below 1,025 feet and above 1,000 feet	7 maf	4.4 maf to California, 2.32 maf to Arizona (20% reduction), 280,000 af to Nevada (7% reduction)

General Methods

This project explores the effects of declining Lake Mead water levels on water supply and delivery, hydropower, recreation users, and the ecosystem. The impacts to each area of interest were evaluated at the four elevations – 1,075', 1,050', 1,025', and 1'000 – at which curtailments or consultation will be triggered in accordance with the *Interim Guidelines* (Figure 5). Curtailments (i.e. reductions in water delivery to each Lower Basin state) at the first three key elevations were outlined and agreed to by the Lower Basin states and Bureau of Reclamation. If Lake Mead reaches 1,000', a consultation between the Lower Basin states and the Bureau of Reclamation would be triggered.

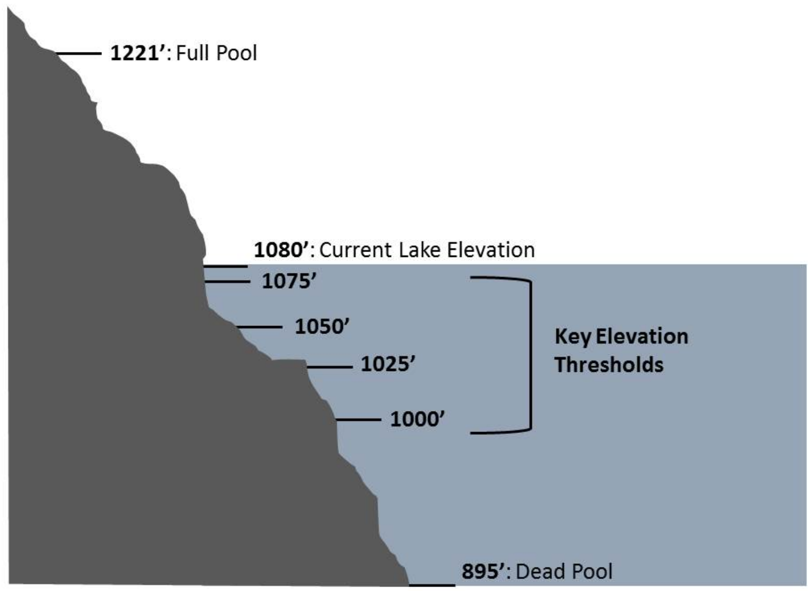

Figure 5**:** Key elevations in Lake Mead with full pool, current reservoir elevation, and dead pool.

Water Supply

Water deliveries in the Lower Basin are divided between California, Nevada and Arizona. Within each state, water is used by agricultural users, municipal and industrial users and tribal users. To determine the impact to water supply delivered to each sector within each state, a vulnerability index was developed. Information was gained from a focused review of state priority water rights and water use by sector, and from sector expert interviews.

The indexes are divided into two categories, fixed and dynamic. Fixed indexes stay constant at various reservoir levels and include: percent of apportionment each sector is using, priority of water right within the state and in the basin, additional water supply and storage, and projected water use growth by 2060. The dynamic index is access to water right, which changes at different key elevations. Based on the "law of the river" Arizona is further divided into the Central Arizona Project (CAP) and the State of Arizona, while the other states are evaluated overall.

Hydropower

To illustrate the financial implications for hydropower contractors a model was developed to calculate total cost of acquiring the amount of energy equal to a contractors full hydropower allocation for all fifteen contractors at each key elevation. As reservoir levels decline, hydropower generation decreases and contractors have to buy supplemental power in the spot market. Costs are a function of hydropower rates, spot market energy rates, and the amount of energy purchased on the spot market due to reductions in Hoover hydropower generation. Model inputs include hydropower generation, hydropower allocation, proportion of hydropower received, the price of hydropower and the price of spot market energy. The model outputs costs to each contractor. The total cost at each reservoir level is the sum of individual contractor's cost.

Hydropower generation at each key elevation was simulated using the Bureau of Reclamation's Colorado River Simulation System model. Two scenarios (wet or dry) were developed for each key elevation to accommodate for uncertainty in hydrologic conditions within the Basin for any given year.

Hydropower allocations for each contractor were calculated according to the Hoover Power Allocation Act. Each contractor is entitled to a fixed proportion of hydropower generated by Hoover Dam. As hydropower generation is reduced at lower reservoir levels, each contractor receives proportionally lower hydropower. The difference is to be made up by power purchased on the spot market.

Hydropower price is represented by a composite power rate set by WAPA for the year of 2013 as a baseline. Spot market prices are based on the 2013 rates from the energy-trading hub in the each contractors regional energy market. Each contractor is assumed to purchase the power deficit caused by loss of hydropower with the region of its geographic location.

Recreation

The impact of declining reservoir levels on recreational uses was evaluated with a model developed by Neher et al (2013). The model correlated reservoir storage volume with recreational visitation based on data from 1996 and 2011. Storage volume at each reservoir level was calculated, and was used to estimate recreational visitation rates at each key elevation. In addition, the impacts on key access points to recreational activities were determined based on data from the National Park Service.

Environment

The effects of lower Lake Mead reservoir levels on the lower Colorado River ecosystem were divided into three major areas: the river corridor ecosystem and the Colorado River Delta, water quality, and impacts on funding to key environmental programs. Literature review and expert interviews were used to answer our research questions. Water security for Lower Colorado River Multi-Species Conservation Program (LCR MSCP) restoration projects was determined based on results from Water Supply section. Quantitative analysis of funding impacts was done based on results from Hydropower section.

Water Supply

Introduction

Lake Mead's secondary function, behind flood control, is storing water for delivery to the downstream farmers, tribes and urban centers of the Lower Colorado River Basin states – California, Arizona and Nevada (Figure 6). The Boulder Canyon Project Act of 1928 allocated 7.5 MAF to share amongst the Lower Basin states, 4.4 MAF to California, 2.8 MAF to Arizona and 300,000 AF to Nevada. All three states depend heavily on the Colorado River water stored in Lake Mead to support thriving agriculture industries, large metropolitan areas, Native American Tribes and wildlife conservation areas. To preserve the availability of this water supply as levels in Lake Mead decline, the Bureau of Reclamation has established curtailments in water deliveries to the Lower Basin states correlated to critical water elevations. The reduction of available Colorado River water will have a direct effect on water users across the Lower Basin.

Figure 6: Water diversion infrastructure in the Lower Colorado River Basin. In California, the Colorado River Aqueduct diverts water for MWD, Palo Verde Irrigation District diverts water from Palo Verde Diversion Dam, the Coachella Canal delivers water to the Coachella Valley and the All American Canal delivers water to Imperial Irrigation District. In Arizona, the Central Arizona project diverts water from Lake Havasu, behind Parker Dam, to deliver water to the urban centers of Central Arizona. Finally, Nevada diverts water for the as Vegas area directly from Lake Mead, behind Hoover Dam.

To understand the magnitude of the effect that reductions in Colorado River water could have on Lower Basin water users, several studies have been published. The Bureau of Reclamation has produced the two most prominent studies, the Interim Guideline Environmental Impact Statement (EIS) and the Colorado River Basin Supply and Demand Study (Basin Study). The EIS produced the Shortage Allocation Model (Bureau of Reclamation 2007b) that modeled the distribution of water shortages amongst Lower

Basin water users based on their consumption and priority water use. The Basin Study defined current and future imbalances in water supply and demand in the Colorado River Basin overall and the individual Basin States that receive Colorado River water over the next 50 years (through 2060). Additionally, the Basin Study sought to develop and analyze adaptation and mitigation strategies to resolve those imbalances (*Colorado River Basin Water Supply and Demand Study: Executive Summary* 2012). In addition to the studies published by Bureau of Reclamation, Arizona State University recently conducted a study of the economic importance of the Colorado River in the Upper and Lower Basin states (James et al. 2014). This study assessed the economic vulnerability of the Colorado River Basin states to reductions in water supply under the extreme circumstances of complete loss of the resource and no replacement supply.

By building off previously conducted research, our study ties together multiple characteristics of each Lower Basin state and water use sector influencing how vulnerable their water resources are to declining reservoir levels. Our analysis accounts for variables influencing the magnitude of impact felt by each state and sector are each key reservoir elevation in Lake Mead. This approach allows us to present a more complete analysis of how vulnerable Arizona, California and Nevada are to potential shortages in Colorado River water as well as how agriculture, municipal/industrial and tribal water uses will be effected within each state. To do this, our analysis seeks to answer the following research questions:

1. How will changes in allocation at 1,025', 1,050', and 1,075' be distributed amongst different sectors in each state?
2. How vulnerable are different states and sectors to changes in available Colorado River water?

Specific Background

Colorado River water is distributed within the Lower Basin states through prioritized contracts with the Bureau of Reclamation. In accordance with the prior appropriation system, contracts are prioritized through seniority with the oldest rights holding the highest priority. In the Lower Colorado River Basin there two categories of water rights: rights established under the Boulder Canyon Project Act of 1928 and water rights that were in existence prior to the act. Rights established prior to 1928 are referred to as Present Perfected Rights (PPRs) and have seniority based solely on the date they were established. Water rights established after Boulder Canyon Project Act are divided into priority users starting at 1st and working down. The number of priority classes varies between states depending on how the rights are organized. When a shortage is called in a basin, it is the lowest priority water users that have their use cut first. A lower priority water user must have their use completely eliminated before a higher priority water user will have their use cut. For this reason, senior rights holders have a much stronger and more reliable claim to water.

California

The 4.4 MAF of Colorado River water allocated to California is primarily used for agriculture in the Imperial Valley, Coachella Valley and Palo Verde. The agricultural water use in these districts is the highest priority right in the state. Together, these three regions irrigate over 1 million acres of crops and generate over $1 billion in annual revenue ("Agriculture" 2015).

The metropolitan area of Southern California, including greater Los Angeles area and San Diego County, supports a population of roughly 20.4 million people who rely on the Colorado River as a significant portion of their municipal and industrial water (*Colorado River Basin Water Supply and Demand Study: Executive Summary* 2012). The Metropolitan Water District of Southern California (MWD) serves as the right holder and distributor of Colorado River water to Southern California and is the lowest priority right holder in the state. While MWD has other sources of water, imported water supplies such as the Colorado River and the State Water Project are an essential part of their water portfolio (Metropolitan Water District of Southern California 2014), making up approximately 36% of the total water supply. In addition to the water contracts held for diversion of Colorado River water, MWD has contracted water transfers with the higher priority right holders of Palo Verde Irrigation District and Imperial Irrigation District in which water is purchased and transferred to MWD annually through the fallowing of crops. These transfers supplement the water demand in MWD service area and lessen the stress on local water resources. The quantity of water transferred is agreed upon each year and can be adjusted based on the availability of alternative water supplies and costumer demand.

Finally, there are the federal rights allocated to the state of California. This includes Native American tribal lands for the Colorado River Indian Tribes, the Fort Mohave Indian Tribe, the Quechan Tribe and the Chemehuevi Tribe. These tribal rights are relatively small in comparison to other uses in the state but are of the highest priority and are essential to the tribes' livelihoods.

Arizona

Arizona's use of their Colorado River water apportionment of 2.8 MAF can be divided into two geographic areas: water used by Mainstem water users and water delivered by the Central Arizona Project (CAP). Colorado River water use along the river corridor is most concentrated in the Yuma area of southwestern Arizona. CAP carries water from the Colorado River to Central Arizona where it is used to alleviate pressure placed on groundwater resources in the region (Figure 7).

Figure 7: Map of the Central Arizona Project used to deliver Colorado River water to the urban, agricultural and tribal centers of Central Arizona (Arizona Department of Water Resources 2014b).

Colorado River water in the Mainstem region is predominantly used for agricultural. In Arizona, roughly 25 percent of the state's water is provided by the Colorado River. Of that 25 percent, about 80 percent is used for agriculture ("Agriculture" 2015). After agriculture, tribal water use in Arizona accounts for a large portion of Colorado River water use with over seven tribes holding Colorado River water rights. Finally, along the Mainstem, municipal and industrial water use accounts for the lowest portion of water use with the main municipal/industrial water use being the city of Yuma.

The Colorado River Basin Project Act authorized the construction of the CAP in 1968. The premise of CAP was to allow Arizona to fully utilize their 2.8 MAF of Colorado River water and to help to alleviate the pressure being placed on the over drafted groundwater basins of Central Arizona (Arizona Department of Water Resources 2014c). CAP holds a 4th priority water right in Arizona to divert the balance of the 2.8 MAF apportionment not utilized by other water users along the river corridor (Bureau of Reclamation 2014g). This has historically added up to a sum of approximately 1.5 MAF each year. Within CAP, water is distributed between agricultural, municipal/industrial and tribal users. In addition to these three sectors, CAP also delivers water for groundwater replenishment and recharge. The water used for agriculture as well as replenishment and recharge is considered excess water and is distributed through annual contracts rather than long-term contracts. Agricultural water users in CAP have first priority to excess water through the Agricultural Settlement Pool, which was established as part of the Water Settlements Act of 2004. Once the Agricultural Settlement Pool obligation is fulfilled, water is then distributed to the Central Arizona Groundwater Replenishment District to help meet replenishment obligations and then to the Arizona Water Banking Authority, the Central Arizona Groundwater Replenishment District and the Federal Government for statutory firming of tribal water rights (Central Arizona Project 2014a). Unlike the Colorado River corridor water use in Arizona, the largest portion of water distributed by CAP is put to municipal and industrial uses in the large urban areas of Phoenix and Tucson. Along with municipal and industrial water users in the CAP, tribal water use accounts for a large portion of water consumption of water diverted by the CAP.

In order for California to agree with the rest of the Lower Basin to authorize the construction of CAP, Arizona had to concede that CAP and all 4th priority water rights in Arizona would be junior to California (*Colorado River Basin Project Act* 1968). The main reason for this concession was California's historic dependence on Arizona's unused apportionment of Colorado River water. This seniority of California's water right is the reason that California does not share in the shortages established in the Interim Guidelines.

Management of surface water in Arizona is intricately connected to groundwater conditions therefore, it is critical to understand the Groundwater Management Code established in the Groundwater Management Act of 1980. Prior to the Groundwater Management Code (Code), groundwater water was in severe overdraft in Central Arizona. With an average annual rainfall of less than 10 inches, Arizona depends on groundwater to supply 40% of their water use (Arizona Department of Water Resources 2014c) A primary goal of the Code was to eliminate severe overdraft of groundwater and achieve a safe-yield of groundwater. Safe-yield is defined as a long-term balance between the annual amount of groundwater withdrawn in the AMA and the annual amount of natural and artificial recharge (Arizona Department of Water Resources 2014a). To achieve this goal, Active Management Areas (AMAs) were established in areas with sever groundwater over draft. Under the Code four AMAs were established for Phoenix, Pinal, Prescott and Tucson. Each AMA is allocated a quota of groundwater that is allowed to be withdrawn for the year. If the water withdrawn within an AMA exceeds the quota, the Central Arizona Groundwater Replenishment District has an obligation to replenish the overdrafted groundwater reservoir in that AMA with surface water.

The amount of groundwater extracted within the AMAs is limited through strict permitting and monitoring of groundwater wells as well as a provision to not allow any new land to be irrigated. This provision limits agriculture within AMAs to land that was in production between 1975 and 1980 (Arizona Department of Water Resources 2014a). As a final provision to provide secure water resources to Arizona municipal and industrial water users, the Groundwater Management Code established groundwater recharge programs through the Arizona Water Banking Authority to store unused surface water in groundwater basins. This water is additional to natural groundwater reservoirs and is not drawn upon unless natural water resources are unable to meet demand. If a situation arises in which this resources is drawn upon, guidelines for accessing this water are established by a joint recovery plan developed by the Arizona Water Banking Authority, the Arizona Department of Water Resources and the CAP.

Nevada

Nevada holds the smallest apportionment of Colorado River water in the Lower Basin with only 300,000 AF of the 7.5 MAF (*Boulder Canyon Project Act* 1928). Use of Colorado River water in Nevada is centralized in the Las Vegas urban area of Southern Nevada where the Colorado River provides 85% of the total water resources and the other 15% is provided by groundwater ("Agriculture" 2015). Because the Colorado River water right holders are all within close proximity the Southern Nevada Water Authority (SNWA) was created to act as the managing body of water resources for the region. Within SNWA there are seven member agencies including Big Bend Water District, Boulder City, Clark County Water Reclamation, Henderson, Las Vegas, Las Vegas Valley Water District and North Las Vegas.

Nevada is different from the other Lower Basin states because no main stem Colorado River water is used for agriculture. In other parts of the state, agriculture accounts for nearly 90% of the water use, including water from Colorado River tributaries the Muddy River and the Virgin River ("Agriculture" 2015). In southern Nevada where water is pulled from the main stem of the Colorado River at Lake Mead, all water is put to domestic use (Bureau of Reclamation 2015). In addition to the municipal and industrial water users in the Las Vegas area the Fort Mojave Indian Tribe has land within southern Nevada and utilizes a small quantity of Nevada's Colorado River apportionment.

Interim Guidelines Curtailments

The Colorado River Interim Guidelines for Lower Basin Shortages published by the Bureau of Reclamation in 2007 established guidelines for how Lower Basin water supply would be managed at low reservoir levels in Lake Mead. When the reservoir levels in Lake Mead reach specific elevations, curtailment of water deliveries to Lower Basin states are triggered (Table 2). Because of the Lower Basin states' dependence on Colorado River water, reductions in water deliveries linked to declining reservoir levels will increase the vulnerability of the water resources within each state.

Table 2: Water delivery curtailments to Lower Basin states tied to Lake Mead surface elevation

Lake Mead Elevation	California	Arizona	Nevada
1,075' to 1,050'	4.4 MAF	2.48 MAF (12% reduction)	287,000 AF (5% reduction)
1,0505' to 1,025'	4.4 MAF	2.4 MAF (17% reduction)	283,000 AF (6% reduction)
1,025' to 1,000'	4.4 MAF	2.32 MAF (20% reduction)	280,000 AF (7% reduction)

Because each state's Colorado River water is cut by different amounts, the vulnerability of their water resources will be different as reservoir levels decline in Lake Mead. The Interim Guidelines establish that California will not receive any curtailment to their water delivery from the Colorado River at any reservoir level. As previously mentioned, to ensure California's agreement to the authorization of CAP, Arizona conceded that California's Colorado River water rights would be senior Arizona's 4th priority Colorado River water rights holders, including all water diverted by the CAP. This seniority prevents California's Colorado River water diversions from being curtailed below their 4.4 MAF entitlement unless all 4th priority water rights holders in Arizona are curtailed. In addition to California's lack of curtailment, Nevada receives significantly lower reductions in comparison to Arizona. This is a result of the Arizona – Nevada Shortage Sharing Agreement established in 2007 (Arizona Department of Water Resources et al. 2007, -). In this agreement, the distributions of curtailments of the first 500,000 AF of water cuts in the Lower Basin were agreed upon between the two states. Arizona agreed to take the larger burden of the shortage and in exchange Nevada paid a sum of $8 million to Arizona to assist in offsetting the impacts of the increased shortage.

Methods

Past studies regarding water supply within the Lower Colorado River Basin have focused on specific areas of a complex problem to illustrate the impact of reduced water deliveries from throughout the Lower Basin. The Bureau of Reclamation's Shortage Allocation model uses modeling to quantifying specific distributions of shortages to water users across the Lower Basin water users. Shortages are allocated through two scenarios strictly on the basis of water rights priorities and are not directly linked to shortage elevations in Lake Mead. The study of economic importance conducted by Arizona State (James et al. 2014) analyzes the significance of Colorado River water to individual states' economies through the extreme assumption of complete loss of access and no replacement to Colorado River water. The gap left by these analyses that our study fills is to take a more holistic view of the Lower Colorado River Basin water users by incorporating multiple variables that influence their use of, and dependence on, Colorado River water. These variables then allow us to assess the vulnerability of Lower Basin states and water use sectors to shortages, all within the framework of the Interim Guidelines.

Vulnerability Index

An index of potential vulnerabilities was created to qualitatively determine the magnitude of the impact to Lower Basin states – California, Arizona and Nevada – from curtailments at the key Lake Mead elevations outlined in the Interim Guidelines. In the vulnerability index, five variables were used to determine the potential impacts to the Lower Basin states overall, as well as, the impacts to key sectors within each state. Consistent with the division of water use within the Colorado River Basin, the sectors included in the analysis were Agriculture, Municipal/Industrial and Tribal. The vulnerability variables were divided into two categories, fixed and dynamic variables. The fixed variables, are not affected by lowering levels in Lake Mead while, the dynamic variable is directly correlated with lowering reservoir levels. The fixed variables considered in our analysis were:

- The total percent of apportionment of Colorado River water currently in use within each sector.
- The overall priority of water rights within each sector.
- The amount of developed additional water storage or supply available to each state and sector.
- The projected growth of water demand within each sector.

Each of these variable influences how dependent each state and sector is on Colorado River water and therefore how vulnerable they would be to any curtailment in water deliveries. The dynamic variable considered in our analysis is:

- The amount of the water right available to each sector at the different shortage elevations in Lake Mead.

The combination of the five vulnerability variables will illustrate how shortages will be distributed across the Lower Colorado River Basin as well as highlight which states and sectors are most threatened by potential shortage calls. The analysis of multiple water use variables in each state and sector will highlight the overall vulnerabilities as well as identify which characteristics in each state and sector are the greatest contributors to water supply vulnerability.

Fixed Variables

Percent Apportionment Consumptively Using

Colorado River water is allocated to each Lower Basin state by the apportionments laid out in the Boulder Canyon Project Act of 1928. Therefore, the water right held by each state is referred to as the state's apportionment. Within each state, the apportioned water is then distributed to the different sectors through water contracts.

Each Lower Basin state strives to fully utilize their full apportionment of water each year to get the full benefit out of the Colorado River resource. However, if a state is utilizing their full apportionment, any curtailment will directly affect water consumption within the state. On the other hand, if current use is less than the full apportionment, a curtailment may not have an immediate impact depending on the size of the reduction relative to the current portion of contract being used.

The variables describing current water use are measured in percent where a higher percent indicates greater vulnerability. The percentages were calculated using the Colorado River water contracts per state as provided by the Bureau of Reclamation (Bureau of Reclamation 2014e; Bureau of Reclamation 2014b; Bureau of Reclamation 2014c; Bureau of Reclamation 2014d; Bureau of Reclamation 2014f) and the actual water diversions as accounted for in the Bureau of Reclamation's 2013 Colorado River Accounting and Water Use Report for the Lower Basin (Bureau of Reclamation 2014g). The percentage represents the division of the sum of 2013 diversions by the sum of internal state contracts.

Priority of Right

The priority of the water rights that each water contractor in each state holds influences whether they will be impacted by a curtailment call across the Lower Basin. Lower priority right holders will be the first to bear any shortages and must be completely eliminated before a higher priority right holder will have to curtail water use. Within the framework of the Law of the River, lower priority water right holders are significantly more vulnerable than higher priority right holders.

This variable was measured by a HIGH, MEDUIM or LOW value to indicate the overall priority of the sector within the water rights priority structure. This study indicates the different priority for sector within each state and for state within the Lower Basin.

Developed Additional Water Storage and Supplies

Each state and sector has different supplemental water storage or supply sources, each with varying degrees of reliability. If a sector has a reliable alternate source of water to utilize at the time of a curtailment, it reduces their vulnerability to reductions in delivery of Colorado River water.

This variable is measured by YES (reliable), YES (unreliable) and NO. The distinction between reliable and unreliable indicates whether the alternate water source can dependably sustain the water demand of the sector in any circumstance. A source would be unreliable if it is either insufficient to make up for the lost Colorado River water or if it's reliability is highly variable from year to year.

Percent change in projected overall water demand

Water demand within each sector may change in the future and this variable attempts to articulate the differences in future projected water use between sectors. Appendix C from the Bureau of Reclamation's "Colorado River Supply and Demand Study" (Bureau of Reclamation 2012d) was used to determine future water use. This appendix projects the water demand per sector in each state in the 2060. This study used Scenario A from the Basin Study, which follows current growth trends. It is important to note that this study does not take into consideration the limitation of water available from the Colorado River. Because of this, the projected demand for Colorado River water in each state exceeds the individual apportionments. The water demand that exceeds the states' apportionment will need to be satisfied with supplemental sources outside of the Colorado River Basin.

The variable is measured as a percent to indicate the change as given in the Basin Study between 2015 water demand and 2060 water demand. A projected increase in water demand would serve to increase the vulnerability of the sector by eliminating any buffer of unused apportionment and increasing dependence on Colorado River water.

Dynamic Variables

Percent Water Right Available

The only variable that changes as reservoir levels in Lake Mead decline is the availability of the individual water rights. This variable indicates how the curtailments spelled out in the Interim Guidelines are distributed to different sectors within the Lower Basin states. This illustrates what sectors are impacted by a curtailment calls at each key elevation and what sectors are not.

By looking at the shortages at each elevation in the context of the fixed variables established in this study, the overall vulnerability of the state and the individual sectors can be determined.

Separation of Arizona into Mainstem the Central Arizona Project

Since Arizona water users are separated into two distinct groups, Mainstem and CAP users, the vulnerability index divided Arizona vulnerability into these two user groups. The vulnerability of Arizona's Mainstem users and CAP users were analyzed separately. Since current water use in Arizona leads CAP to receive all state shortages, it is necessary to understand how the water curtailments would be distributed amongst the users within CAP.

CAP user group were divided into the same sectors, agriculture, municipal/industrial and tribal with the addition of an "Excess" sector. CAP's internal water allocation consists of long-term contracts to municipal/industrial and tribal water users and yearly contracts with agricultural users. The balance of water remaining after all contracts are fulfilled is then distributed to the Central Arizona Groundwater Replenishment District to help meet replenishment obligations and then to the Arizona Water Banking Authority, the Central Arizona Groundwater Replenishment District. The "Excess" sector refers to this left over water used for groundwater recharge and replenishment.

Data Sources

The sources of data utilized to create the vulnerability index include industry publications from municipalities, state water management entities, Bureau of Reclamation and industry expert interviews.

Municipalities and state agencies responsible for distribution Colorado River water in the Lower Basin all publish articles, reports and data relevant to water management and water shortage response. As the direct link between the federally managed Lower Basin and the different sectors within each state, these entities provide key data for evaluating the vulnerability of different sectors. Key water management entities used in this study include

- Metropolitan Water District of Southern California
- Imperial Irrigation District

- Palo Verde Irrigation District
- The Southern Nevada Water Authority
- The Central Arizona Project
- Arizona Department of Water Resources

As the managing body of the Lower Colorado River Basin, the Bureau of Reclamation (BOR) is the key source of information regarding the "Law of the River", which is the apportionments of Colorado River water to each Lower Basin state and the contracts to that water held within each state. Additionally, BOR provided details on the actual water diversions across the entire Lower Basin. The "Law of the River" consists of the bills, acts and court settlements that make up the legal structure for how the Colorado River water is managed across the Lower Basin. Particularly relevant to the water supply vulnerability analysis are the Boulder Canyon Project Act of 1928, the California Seven Party Agreement of 1931, Arizona vs. California US Supreme Court Decision of 1964 and the Colorado River Basin Project act of 1968. These documents provide the background legal framework for how and why Colorado River water is allocated across the Lower Basin. BOR also provided the source of Colorado River water diversion contracts held within each state as well as the actual diversions by those contract holders. The documents used to determine the contracts were pulled from the BOR records for the Lower Colorado River Water Delivery Contracts Entitlement Listing that was last updated in 2014. To determine the actual diversions to these contract holders, this study used the BOR's Colorado River Accounting and Water Use Report for California, Arizona and Nevada for 2013. By using these two documents together, this study was able to determine how water in the Lower Basin is being distributed between the different sectors and what proportion of the allocated water rights are being utilized.

The final source of data used in this analysis is data collected from interviews with industry professionals across the Lower Basin. By speaking with the professionals who are responsible for the water management across the Lower Basin, this study was able to identify areas of vulnerability as well as gain valuable insight into how potential shortages may be managed that may not be apparent in published literature. Key professionals that were interviewed for this analysis include:

- Colby Pellegrino – Southern Nevada Water Authority
- Thomas Buschatzke – Arizona Department of Water Resources
- William Hassencamp – Metropolitan Water District of Southern California
- Terrance Fulp – Bureau of Reclamation
- Ken Nowak – Bureau of Reclamation
- Jennifer Pitt – Environmental Defense Fund

As a final step in the analysis, the preliminary results from the vulnerability index were vetted with these industry professionals across the Lower Basin. Professionals within each Lower Basin state were asked to provide direct feedback on the structure and preliminary findings of the vulnerability index to ensure the accuracy of the methods used in this study and soundness of the results.

Results

The following water supply vulnerability index results are presented for each vulnerability index variable by state. The full vulnerability index table is included in Appendix A1. The heat map indicated high (red) and low (green) vulnerability.

Percent Apportionment Used in 2013

	California	Arizona: Mainstem	Arizona: Central Arizona Project	Southern Nevada
	100%	56%	100%	77%
Justification	California is consumptively using their full apportionment of Colorado River water. The majority of the water is utilized by the large irrigation districts to satisfy agricultural and a small portion of municipal use. The remaining water is utilized by MWD for municipal and industrial water use. MWD often relies on water transferred by Palo Verde Irrigation District and Imperial Irrigation District transfer through crop fallowing and MWD as well as on additional Intentionally Created Surplus supplies to satisfy their full demand.	Arizona's users along the main stem of the Colorado River currently consumptively use 56% of their Colorado River entitlements. This use is divided amongst agriculture, municipal/industrial and tribal water users with the largest portion of use in the Yuma-Mesa area. The portion of Arizona's Colorado River water apportionment that is not used along the main stem is diverted to the CAP bring the state wide consumption to the full 2.8 MAF.	The Central Arizona Project has a water right to the balance of Arizona's Colorado River water apportionment not used by higher priority main stem users. For this reason, the amount of water available to CAP is dependent on the demand of the main stem users and that CAP diversions always brings Arizona's state wide water consumption to the full 2.8 MAF apportionment. Water within the CAP is distributed between municipal/industrial, tribal and agricultural use. In addition to these sectors, the CAP also uses excess water for groundwater recharge and replenishment as well as federal firming.	Because of Southern Nevada's proximity to Lake Mead, it is possible for them to return water to the reservoir and reduce their consumptive use. Through the "return flow credit program", Southern Nevada is able to treat their wastewater and then return that water to Lake Mead. This allows Southern Nevada to divert more than their 300,000 AF apportionment while keeping their consumptive use below their 300,000 AF. The current consumptive use is approximately 77% of their total apportionment.

Priority Water Right

<table>
<tr><th></th><th colspan="3">California</th><th colspan="3">Arizona: Mainstem</th><th colspan="4">Arizona: Central Arizona Project</th><th colspan="3">Southern Nevada</th></tr>
<tr><th></th><th>Ag</th><th>M&I</th><th>Tribal</th><th>Ag</th><th>M&I</th><th>Tribal</th><th>Excess</th><th>Ag</th><th>M&I</th><th>Tribal</th><th>Ag</th><th>M&I</th><th>T</th></tr>
<tr><td>State</td><td>High</td><td>Low</td><td>High</td><td>High</td><td>High</td><td>High</td><td>Low</td><td>Low</td><td>Med</td><td>Med</td><td>NA</td><td>High</td><td>High</td></tr>
<tr><td>Basin</td><td>High</td><td>High</td><td>High</td><td>Med</td><td>Med</td><td>Med</td><td>Low</td><td>Low</td><td>Low</td><td>Low</td><td>NA</td><td>M/H</td><td>M/H</td></tr>
<tr><td>Justification</td><td colspan="3">The Seven Party Agreement (SPA) clearly establishes how California's Colorado River water apportionment is distributed within the state. The agricultural irrigation districts of Imperial Valley, Palo Verde and Coachella are given first priority to Colorado River water over the municipal and industrial water use of MWD. Because of this structure, municipal and industrial water use has the lowest priority in California.

Outside the distribution set in the SPA, there are numerous Present Perfected Rights (PPRs) that make up agricultural, municipal and industrial and tribal water rights. These rights hold priority based on the date of their enactment. All tribal water rights in California are high priority PPRs. Agriculture also holds numerous PPRs, including the large irrigation districts of Imperial Valley and Palo Verde. The combination of these PPRs and the high priority set in the SPA makes agriculture a high priority user in the California. There is only one significant PPR held for municipal and industrial water use by the City of Needles. Outside the PPRs the low priority of MWD and San Diego County Water Authority makes municipal and industrial water use a low priority.

Within the Basin, all water rights in California are high priority, due to the agreement made to authorize the construction of the CAP. To get California to agree to the authorization of the CAP, all water rights in Arizona established after 1968, including rights within the CAP were all made junior to California rights.</td><td colspan="3">The priorities of water rights within Arizona are well distributed amongst the different sectors. The majority of water rights in Arizona outside the CAP are first, second or third priority rights. Because this study separates the CAP from the other Colorado River water uses in Arizona, the sectors within the state are considered to have an overall high</td><td colspan="4">Because the CAP is a 4th priority user within Arizona, all sectors within CAP are considered to hold equally low priority across the basin. Within the CAP however, there is a clear priority structure. In CAP municipal and industrial and tribal rights hold high priority with long-term contracts as well as NIA contracts. Despite their high priority within CAP, these sectors are still 4th priority rights within Arizona. For this reason they are given a medium priority in the vulnerability index in relation to other Colorado River water rights within Arizona.

Agriculture holds a low priority within the CAP and within the state because agriculture in the CAP does not hold long-term contracts. Instead it depends on annual contracts to excess water allocated to the Agricultural Settlement Pool (Ag Pool). Similarly, there are contracts to excess water beyond the Ag Pool that are renewed anally. These contracts are held for groundwater recharge and replenishment as well as federal firming of tribal water rights. Because the Ag Pool has first priority to excess water, the various annual contracts held for additional excess hold the lowest priority within the CAP and the state. In the vulnerability index, both of these sectors are considered to hold equally low priority as they are currently both impacted at the first level of curtailments.</td><td colspan="3">Since Nevada uses no mainstem Colorado River water for agriculture, only municipal and industrial and tribal water rights are considered to have priority water rights. Tribal and municipal/ industrial water rights are considered to have the same priority right. Because Nevada shares in the Lower Basin shortages along with Arizona it is considered to have a medium/high priority within the basin. This is lower than California, which does not share in the shortages.</td></tr>
</table>

Developed Additional Water Storage and Supply

<table>
<tr><td rowspan="3"></td><td colspan="3">California</td><td colspan="3">Arizona: Mainstem</td><td colspan="4">Arizona: Central Arizona Project</td><td colspan="3">Southern Nevada</td></tr>
<tr><td>Ag</td><td>M&I</td><td>Tribal</td><td>Ag</td><td>M&I</td><td>T</td><td>Excess</td><td>Ag</td><td>M&I</td><td>Tribal</td><td>Ag</td><td>MI</td><td>T</td></tr>
<tr><td>No</td><td>Yes (UR)</td><td>No</td><td>Yes (UR)</td><td>Yes(R)</td><td>No</td><td>No</td><td>Yes (UR)</td><td>Yes (R)</td><td>YES(R)</td><td>NA</td><td>Yes (R)</td><td>No</td></tr>
<tr><td>Justification</td>
<td colspan="3">The agriculture and tribal lands that are utilizing Colorado River water have little access to additional water supplies. The arid desert environment of these lands coupled with the quantity of water required for irrigation of crops and other uses makes the Colorado River the only viable source of water to support the industries and way of life for these two sectors. The other water source available to these sectors is deep groundwater that cannot serve as a replacement to Colorado River water. The Coachella Valley Water District additionally uses California State Water Project water to replenish their groundwater resources.

Municipal and industrial water users on the other hand have access to a more diverse water portfolio through various additional groundwater, surface water and other water sources. The vulnerability index qualifies the supplemental water resources as unreliable however, because of the large water demand and the frequency of droughts in California. The California State Water Project serves as the other critical sources of imported water and is very susceptible to drought conditions in the northern portion of the state. Because of this, MWD often relies on Intentionally Created Surplus to satisfy its full demand.</td>
<td colspan="3">Rules and regulations drafted in the Arizona Groundwater Management Act of 1980 only apply to the Active Management Areas (AMAs) of Central Arizona. Therefore there are not the restrictions on groundwater pumping present for the Mainstem water users. However, because of the proximity to the Colorado River corridor, groundwater pumping by Mainstem users is typically considered to be diversions from the Colorado River because of the connectivity of the groundwater to the river.

While there is some groundwater that is not within the Colorado River basin in the boundaries of the Yuma Mesa area, our analysis considers there to be no supplemental water resources for mainstem water users.
Throughout the state of Arizona a growing area of supplemental water supply is reclaimed water from treatment plants. This is a promising water supply but is not considered a reliable water source in this analysis.</td>
<td colspan="4">As part of Arizona's Ground Water Management Act of 1980, agricultural users have the ability to pump groundwater. However, barriers such as high cost to drill new wells or repair existing unmaintained wells due to dependence on river water and dropping groundwater levels make accessing this water difficult. For this reason the agricultural users in the state of Arizona are considered to have access to additional yet unreliable groundwater resources.

Municipal and industrial water users in Arizona are considered to have access to reliable alternative groundwater resources. The Groundwater Management Act of 1980 prevented the mining of groundwater to save it for municipal and industrial use in instances of extreme drought. As part of this process, the Joint Recovery Plan was created to govern how groundwater would be extracted in such cases. There is not enough groundwater to provide a permanent sustainable substitute to Colorado River water, only enough to serve as a buffer to get through drought years until there is enough Colorado River water to meet demand again.

Tribal lands have the expressed right to extract groundwater under the Winters doctrine. Additionally the Federal Government uses excess CAP water to firm tribal water rights, providing a reliable resource for tribes to fall back on in a time of shortage.

Excess water in the CAP is considered to have no alternative water resources to Colorado River water. This is because the majority of the excess water used is for groundwater recharge and water banking. If the Colorado River cannot provide water for these excess uses, there are no other surface water sources to replace it. Groundwater replenishment through the Central Arizona Groundwater Replenishment District, however, has developed an expanded water portfolio to help them meet their replenishment obligations.</td>
<td colspan="3">SNWA has been recharging a groundwater basin in Las Vegas with excess Colorado River water. This groundwater basin can serve as a buffer to get through drought years but cannot replace the Colorado River water. Therefore, SNWA has a variety of Intentionally Created Surplus water credits built up as well as agreements with both California and Arizona to store water on their behalf. Additionally, SNWA is also pursuing groundwater resources in other less inhabited regions of Nevada. The combination of these resources can serve as a reliable supplemental water resource to Colorado River water for municipal and industrial water uses in Nevada.

Tribal water use in Nevada however, is considered to have no access to these alternative water resources. The very limited groundwater resources available to the tribal land in Nevada cannot serve as a reliable alternative to Colorado River water.</td></tr>
</table>

Percent Change in Projected Use Growth Within Sector

<table>
<tr><th rowspan="3"></th><th colspan="3">California</th><th colspan="3">Arizona: Mainstem</th><th colspan="4">Arizona: Central Arizona Project</th><th colspan="3">Southern Nevada</th></tr>
<tr><th>Ag</th><th>M&I</th><th>Tribal</th><th>Ag</th><th>M&I</th><th>Tribal</th><th>Excess</th><th>Ag</th><th>M&I</th><th>Tribal</th><th>Ag</th><th>MI</th><th>T</th></tr>
<tr><td>-2%</td><td>18%</td><td>0%</td><td>0%</td><td>86%</td><td>1%</td><td>NA</td><td>-100%</td><td>92%</td><td>48%</td><td>NA</td><td>75%</td><td>0%</td></tr>
<tr><td>Justification</td>
<td colspan="3">California agriculture is projected to decrease from 710,000 acres to 690,000 acres by 2060 (Bureau of Reclamation 2012d). The water delivered per acre is also projected to decrease by 1%. These changes result in a reduction of Agricultural water demand from 3,230,000 AF in 2015 to 3,159,000 AF in 2060, an overall 2% reduction in Colorado River water demand.

There are currently 20.4 million people in California who use Colorado River water. The Basin Study projects that by 2060 this population will increase to 27.6 million. While the per capita water use is projected to decrease by 12%, the overall municipal and industrial demand for Colorado River water is projected to increase 18% by 2060. It is important to note that this growth is projected to occur in the Coachella Valley, Imperial Valley and along the main stem river corridor with no net growth coming from MWD.

There is no projected change in tribal water demand in the state of California.</td>
<td colspan="3">The there is no projected net change in agricultural water demand for the Mainstem Colorado River water users due to the high priority rights of agricultural users in the Mainstem region.

The per capita water use across Arizona Colorado River water users is predicted to decrease by 4% while the population is projected to increase by approximately 50%. In the Mainstem region, this translates to a predicted growth of 86% in the municipal/industrial water demand.

Tribal water demand in the Mainstem region is projected to grow by 1% between 2015 and 2060.</td>
<td colspan="4">Agricultural water use demand for Colorado River water in Central Arizona is projected to reduce to 0 by 2060. This is due to decline of the Agricultural Settlement Pool and its eventual elimination in 2030. This will force farmers to rely solely on groundwater for irrigation and could potentially lead to agricultural land conversion to urban land.

Municipal and industrial use in Central Arizona represents the largest area of growth in Colorado River water demand. Projected population growth in the urban areas of Phoenix, Tuscon, Scottsdale, etc. as well as potential conversion of agricultural land to urban land lead to a predicted growth in Colorado River water demand by 92% in 2060.

Tribal water demand in Central Arizona is predicted to increase by 48% in 2060. This is largely due to the Arizona Water Settlement Act allowing tribes to realize their water rights and increase their Colorado River water use.</td>
<td colspan="3">There is no current agricultural water use or predicted development of agricultural use of mainstem Colorado River water in Nevada.
The Bureau or Reclamation's Colorado River Basin Supply and Demand Study projects a growth of the Nevada population using Colorado River water from the current 2.6 million to 4.4 million in 2060. However, the per capita water use is predicted to decline by 20%. This leads to a net increase in municipal and industrial water demand from 289,000 AF in 2015 to 506,000 AF in 2060, a 75% increase.
There is no predicted change in tribal demand of Colorado River water in the state if Nevada.</td></tr>
</table>

Percent of Water Right Available

	California			Arizona: Mainstem			Arizona: Central Arizona Project				Nevada		
	The distribution of shortages across the Lower Colorado River Basin clearly spell out that California never receives a curtailment of Colorado River water below their 4.4 MAF apportionment. However, in the Colorado River Basin Project Act of 1968 that authorized the construction of the CAP, it was established that in a case of a shortage in the Lower Basin, California could not divert any more than their 4.4 MAF. This cuts off California's ability to draw any Intentionally Created Surplus water stored in Lake Mead at the first curtailment elevation of 1,075'.			Per the Arizona Shortage Sharing Workgroup Recommendations, the 4th priority water users in the Mainstem region will share in the Lower Basin curtailments applied to Arizona. However, in order for these users to be included in the shortages they must be utilizing close to their full entitlement of 164,652 AF. At current water use (roughly 50,000 AF), they are not sharing in any shortages and all shortages will be applied to CAP.			Since CAP is a 4th priority water right holder in the Arizona they share in the curtailments applied to Arizona in the case of a shortage call. All 4th priority water users in Arizona share the curtailments during Lower Basin shortage. However, at current water use CAP will take the full amount of shortages applied to Arizona (Arizona Department of Water Resources 2006). Per the Director's Shortage Sharing Recommendations, 4th priority water right holders outside of the CAP will share in shortages when they reach their full entitlement. Within the CAP, curtailments are distributed first to the excess water annual contractors, then to the Agricultural Settlement Pool and finally to the NIA water pool and municipal/industrial and tribal long-term contract holders.				Nevada receives a small portion of the curtailments to the Lower Basin in the case of a shortage call. The curtailments received by Nevada at each key elevation are as follows: • 1,075 feet = 13,000 AF • 1,050 feet = 17,000 AF • 1,025 feet = 20,000 AF As the lowest priority water right holders, Municipal and industrial water users will take all of the curtailments placed on Nevada. The tribal water user will never receive curtailments under the Interim Guidelines.		
	Ag	M&I	Tribal	Ag	M&I	Tribal	Excess	Ag	M&I	Tribal	Ag	MI	T
1075	100%	100%	100%	100%	100%	100%	0%	53%	100%	100%	NA	96%	100%
1050	100%	100%	100%	100%	100%	100%	0%	33%	100%	100%	NA	94%	100%
1025	100%	100%	100%	100%	100%	100%	0%	13%	100%	100%	NA	93%	100%

Discussion

By combining the different variables within the vulnerability index, this study is able to identify what states and sectors are most vulnerable to potential shortage calls in the Lower Colorado River Basin (Table 3). Vulnerabilities within each state depend on water use characteristics of each state and sector and how water is managed. For this reason, vulnerability is not a direct function how much water is being curtailed in each state.

Table 3 A summary table from the Vulnerability Index using a heat map to illustrate the areas of greatest vulnerability within each state and water use sector. Red means high vulnerability and green means low vulnerability.

State	**California**			**Arizona Mainstem**			**Arizona Central Arizona Project**				**Nevada**		
Sector	**Ag**	**M/I**	**Tribal**	**Ag**	**M/I**	**Tribal**	**Excess**	**Ag**	**M/I**	**Tribal**	**Ag**	**M/I**	**Tribal**
% Apportionment Used	100%			56%			100%				77%		
State Priority	HIGH	LOW	HIGH	HIGH	HIGH	HIGH	LOW	LOW	MED	MED	NA	HIGH	HIGH
Basin Priority	HIGH	HIGH	HIGH	MED	MED	MED	LOW	LOW	LOW	LOW	NA	MED/ HIGH	MED/ HIGH
Additional Water Storage and Supplies	NO	YES (UR)	NO	YES (UR)	YES (R)	NO	NO	YES (UR)	YES (R)	YES (R)	NA	YES (R)	NO
Future overall water demand	-2%	18%	0%	0%	86%	1%	NA	-100%	92%	48%	NA	75%	0%
1075: Percent of Water Right Available	100%	100%	100%	100%	100%	100%	0%	53%	100%	100%	NA	96%	100%
1050: Percent of Water Right Available	100%	100%	100%	100%	100%	100%	0%	33%	100%	100%	NA	94%	100%
1025: Percent of Water Right Available	100%	100%	100%	100%	100%	100%	0%	13%	100%	100%	NA	93%	100%

California

At first glance, California appears not to be impacted by shortage calls in the Lower Basin because their 4.4 MAF apportionment does not decrease at any curtailment elevation in Lake Mead. However, after reviewing the water contracts and percent of California's apportionment currently being utilized coupled with the availability of supplemental water resources, we find that California is vulnerable to a shortage call despite not having their actual apportionment cut.

California currently consumes their full apportionment annually and often relies on the ability to call on excess water. Dependence on excess water is built into the legislation that establishes the Colorado River water apportionments. The Seven Party Agreement of 1931, which allocated California's apportionment from the Boulder Canyon Project Act itself allocated 5,362,000 AF of water when the Boulder Canyon Project Act only apportioned 4.4 MAF to California. Of the 4.4 MAF apportionment, MWD is entitled to 550,000 AF. However, they have priority to the first 662,000 AF of excess water. As the lowest priority water user in California, Metropolitan Water District (MWD) is the most dependent on excess water. In 2013 MWD consumed a total of 1,012,715 MAF of water, demonstrating their dependence on surplus water. This surplus water can be composed of ICS water, unused apportionment from other Lower Basin States or unused entitlement from higher priority California water users.

California's vulnerability lies in the loss of ability to access excess water when curtailments occur. It is clearly stated in the Colorado River Basin Project Act of 1968 that in the case of a shortage, California is unable to divert any more than 4.4 MAF from the Colorado River. This means that California will not be able to draw on any excess water upon which it often relies, including any previously created ICS water. The inability to draw on the excess Colorado River water supply that has been created through ICS can significantly impact both MWD and the San Diego County Water Authority. The impact of this loss of access to excess water is brought about by the unreliability of the California State Water Project and local water supplies as alternative sources of water. In 2014, a statewide drought reduced the California State Water Project's deliveries to 5% capacity. Often, in times of drought in California, MWD has been able to rely on water stored in Lake Mead to supplement its Colorado River water to make up for the supply gap. If a drought year in California, such as 2014, were to coincide with a shortage call in the Lower Basin, water supplies available to MWD could be limited, potentially causing shortages to municipal and industrial water users across southern California (Hassencamp 2014). The effects of the loss of excess water and the unreliable nature of supplemental water resources coupled with MWD's high demand makes municipal and industrial water users the most vulnerable in California.

The agricultural irrigation districts with senior rights such as Imperial Irrigation District and Palo Verde are less vulnerable due to the seniority of their water rights. Imperial Irrigation District, Palo Verde Irrigation District and the Yuma Project Reservation District all appear to be currently utilizing more than their contracted amounts as shown on the Bureau of Reclamations "Colorado River Accounting and Water Use Report Arizona, California and Nevada: Calendar Year 2013" and "Listings of Individual Water Entitlements in the State of California" (Bureau of Reclamation 2014e; Bureau of Reclamation 2014g). However, the Seven Party Agreement clearly states that the combined water use of those three entities is to not exceed 3,850,000 AF per year. Currently the combined consumption is 3,441,992 AF, giving these irrigation districts a significant buffer to increase their use within the 4.4 MAF allocations. These agricultural users do have a low priority water right to a combined 300,000 AF that would be eliminated completely when they loose access to drawing excess water from the Colorado River. This should have no direct impact on their water consumption.

Arizona

At each curtailment elevation in Lake Mead, Arizona takes the largest portion of the shortage. At 1,075 feet in Lake Mead, Arizona takes 83% of the shortage called. This decreases to 82% at 1,050 feet and 77% at 1,025 feet (Arizona Department of Water Resources et al. 2007). All shortages will be applied to the most junior water users in the state, which, in Arizona's case are the 4th priority water right holders. The Director's Shortage Sharing Workgroup Recommendations of 2006 details how any shortage will be distributed across 4th priority Colorado River water users (Arizona Department of Water Resources 2006). In these recommendations, the 4th priority water users not within CAP would share in all shortages depending on their water use and the total consumptive use of higher priority water users. In order for these users to take a shortage, they must first be utilizing the full non-CAP 4th priority entitlement of 164,652 AF. If, as a whole, 4th priority users outside CAP are utilizing less than 164,652 AF, then CAP will take the full Arizona shortage. If the full 164,652 entitlement is being utilized, then the 4th priority users are curtailed proportionally to how much water is available for their use after higher priority water users have claimed their water. The percent of curtailment applied outside CAP is calculated by dividing the 4th priority entitlement of 164,652 AF by the water available after 1st, 2nd and 3rd priority users consumptive use. At current high priority water use this equates to 10% curtailment to all 4th priority users outside CAP and the remaining shortage applied to CAP. It is important to note that the Bureau of Reclamation has not approved the Director's Shortage Sharing Workshop Recommendations because not all 4th priority users participated in the workshop. The state of Arizona, however, is confident that in the time of a shortage all parties will agree to the recommendations made (Buschatzke 2015).

Currently, the 4th priority water users outside CAP are only using 50,111 AF of their entitlement. This means that CAP will bear the full burden of any shortage that is called in the near future and that 4th priority river corridor water users have low risk of curtailment. However, because of projected population growth in Arizona, it is likely that 4th priority water users will eventually reach their full entitlement, though it is hard to determine when this will happen. At this point they will share in the shortage with the percentage cut being applied equally.

Central Arizona Project

As the largest 4th priority Colorado River water user in Arizona, CAP will carry the majority of the curtailments resulting from a shortage call. Because non-CAP 4th priority water users are not utilizing their full entitlement, CAP will take the full Arizona curtailment in the near future (Arizona Department of Water Resources 2006). Within CAP, shortages will be distributed to water users based on the CAP's internal priority structure.

There are three categories in CAP: long-term contracts, NIA water contracts and short-term excess water contracts. Municipal, industrial and tribal water users hold long-term contracts and are the high priority water users within CAP. NIA water contracts are additionally made up of municipal/industrial and tribal water users. Water that is not used by long-term contractors or NIA contracts goes into the excess water. Excess water is distributed between agricultural water users, groundwater banking and replenishment agencies, and the Bureau of Reclamation (Central Arizona Project 2014a). Agricultural water users have first priority to excess water through the Agricultural Settlement Pool. The Agricultural Settlement Pool currently consists of 400,000 AF. The pool declines to 300,000 AF in 2017, 225,000 AF in 2024 and then to 0 AF in 2030 and beyond (Central Arizona Project 2013). After the Agricultural Settlement Pool has been distributed the remaining water is made available to the Arizona Water Banking Authority (AWBA), the Central Arizona Groundwater Replenishment District (CAGRD) and the Bureau of Reclamation. All excess water is distributed through short-term contracts that must be renegotiated on an annual basis.

The amount of excess water available each year is dependent on the use of the higher priority water users. As higher priority municipal, industrial and tribal water users increase use of contracted water, less water is available for excess water users. However, as the Agricultural Settlement Pool diminishes over time, there will be stepped increases in excess water made available in 2017, 2024 and 2030. After satisfying the long-term municipal/industrial and tribal contracts and the Agricultural Settlement Pool, CAP has estimated the amount of water that will be available to other excess use as follows (Central Arizona Project 2014a):

- 2015 – 93,000 AF
- 2016 – 75,000 AF
- 2017 – 157,000 AF
- 2018 – 139,000 AF
- 2019 – 121,000 AF

As the lowest priority water use, the water available to the AWBA, CAGRD and the Bureau of Reclamation will be the first to have their use curtailed if a shortage is called in the Lower Basin. The first curtailment made to Arizona at 1,075 feet in Lake Mead is 320,000 AF. This effectively eliminates the water available to the AWBA, CAGRD and Bureau of Reclamation and takes away portion of the

Agricultural Settlement Pool. At current water use the water curtailments made to Arizona never make it through all of the excess water to effect long-term municipal, industrial or tribal contract holders in CAP (Figure 8). At 2013 water use, the Agricultural Settlement Pool is reduced to as low as 13% of its 400,000 AF allotment at an elevation of 1,025 feet in Lake Mead. If future water consumption brings long-term contractor water use to level where they are effected by water curtailments, the means of distributing shortages amongst these users is spelled out in the Arizona Water Settlements Act of 2004.

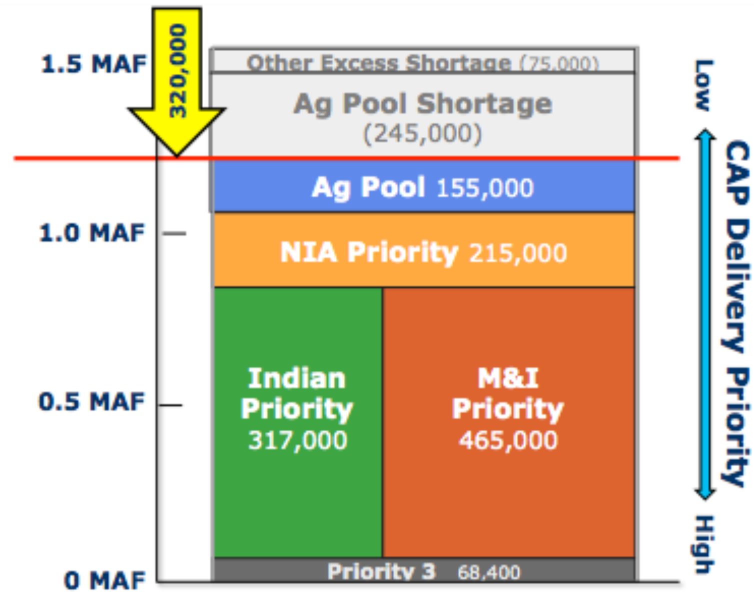

Figure 8: At current water use in Arizona, CAP will take all curtailments. As the lowest priority water users, excess water and Agricultural Settlement Pool water are the first to be cut (Arizona Water Banking Authority, Arizona Department of Water Resources, and Central Arizona Project 2014)

Groundwater Banking, Recharge and Replenishment

A major and immediate implication of water shortages applied to Arizona and the CAP is the loss of water available for groundwater banking/recharge and replenishment. The Arizona definitions of banking and recharge and replenishment are outlined below:

- *Banking and Recharge*: Surface water that is stored in groundwater aquifers to provide future water supply.
- *Replenishment*: Surface water pumped into a groundwater aquifer to directly replace groundwater that was pumped out of that aquifer.

The loss of water banking and recharge prevents the AWBA from placing more water into storage to serve as supplemental water supply for municipal and industrial water users in central and southern Arizona. The AWBA was created largely to store unused Colorado River water in groundwater aquifers that could then be drawn on in times of drought when municipal and industrial, as well as tribal, water demand cannot be met by surface water supply. Currently, AWBA has over three million AF of water stored in groundwater aquifers for this purpose with additional individual entities storing another 6 million AF (Buschatzke 2015). While this is sufficient water to support municipal and industrial and tribal use for some time, without recharge from excess Colorado River water, this resource becomes finite and not a sustainable water supply.

The CAGRD has an obligation to replenish water in each Active Management Area (AMA) established under the Groundwater Management Act. An AMA is an area defined as having heavy dependence on mined groundwater. There are currently five AMAs designated in central and southern Arizona: Prescott, Phoenix, Pinal, Tucson, and Santa Cruz (Arizona Department of Water Resources 2014a). A common goal of the AMAs is to obtain a sustainable yield of groundwater in which the annual amount of groundwater withdrawn is no greater than the amount of water being annually replaced. The amount of water that the CAGRD is obligated to replenish is the amount of groundwater pumped by or delivered to its members that exceeds the pumping limitations imposed on each AMA. Historically, the CAGRD has depended heavily on utilizing excess CAP water to meet the replenishment obligations. However, combined impact of the prospect of a shortage call eliminating the access to any excess water and the overall declining availability of excess water due to increased long-term contractor consumption has made it necessary to develop a portfolio of alternate water supplies. These supplies include (Central Arizona Groundwater Replenishment District 2014):

- A CAP M&I priority subcontract for 7,996 acre-feet per year
- A 100-year lease of 2,500 acre-feet per year of Non-Indian Agricultural (NIA) priority CAP water from the White Mountain Apache Tribe.
- Long-term storage credits assumes 302,000 AF over 30 years = 10,067 acre-feet per year.
- CAP NIA priority subcontract for 18,185 acre-feet per year.
- Effluent lease of 2,400 acre-feet per year.
- Effluent credit purchase assumes 242,000 acre-feet over 100 years = 2,420 acre-feet per year.

The revised distribution of access to excess water in CAP for 2015 through 2019 established a 35,000 AF cap on excess water that the CAGRD can use to meet its replenishment obligations. The revised plan requires the CAGRD to utilize these additional resources first, with the exception of the long-term storage credits before they can access the 35,000 AF of excess CAP water. Only if the additional supplies prove to be insufficient, will the excess CAP water can be utilized. However, if a shortage is called in the Lower Basin, the 35,000 AF of water will not be available. This will place more stress on making the other sources of water produce the water needed to meet the annual obligated replenishment and may require the CAGRD to begin accessing their long-term storage credits.

The loss of CAP water available for groundwater recharge and replenishment may not have immediate implications on water use in Arizona, however, the long-term implications are potentially significant. The loss of recharge capabilities will place increased stress on finite groundwater stored for municipal and industrial use in the case of extreme droughts or prolonged shortages. Decreased water available for replenishment will place increase reliance on alternative water sources to meet CAGRD replenishment obligations.

Agricultural Settlement Pool

At each curtailment level the Agricultural Settlement Pool receives curtailments to their supply. Under 2013 water use, the Agricultural Settlement Pool gets as low as 13% of its full entitlement at an elevation of 1,025 feet in Lake Mead. Agricultural water users receiving this water will have to turn more to pumping groundwater to meet their irrigation demands. The potential implications of this include farmers facing cost barriers of digging new wells to access groundwater and an increased burden on groundwater supplies. Furthermore, if the agricultural water user is within an AMA, then they must have grandfathered irrigation rights to extract groundwater at all. If they had become dependent on water available through CAP that is in excess to their grandfathered irrigation right, then they would only be able to extract groundwater in accordance with their grandfathered irrigation right. In addition to these barriers faced by farmers, there will be an overall increased burden placed on groundwater due to the increased dependence of irrigation. The consequences of this can be magnified when considered along with the decreased water available for the CAGRD to meet its replenishment obligations.

Nevada

Despite receiving portions of Lower Basin curtailments, the combined effects of SNWA's return flow program and their diverse water supply portfolio makes Nevada the state with the lowest overall vulnerability. In past years, the elevation of SNWA's water intakes in Lake Mead has caused significant concern for Nevada's ability to access water at lower reservoir levels. Recent development of an additional 3rd water intake in Lake Mead will allow SNWA to withdrawal water as far down as 1,000' in Lake Mead (Southern Nevada Water Authority 2015b). Water managers in the Lower Basin are working collaboratively to ensure that Lake Mead water levels will not reach 1,000' making Nevada's vulnerability to not being capable of accessing their water null.

Under the Boulder Canyon Project Act, Nevada has an apportionment of 300,000 AF of Colorado River water from the Boulder Canyon Project Act. However, because of a return flow program they are able to divert a greater amount of water from Lake Mead and keep their actual consumptive use below 300,000 AF. The return flow credit program allows the SNWA to return all municipal and industrial wastewater treated at wastewater treatment plants into Lake Mead for 1:1 credit (Southern Nevada Water Authority 2015a). This accounts for a large portion of SNWA water use and significantly reduces Nevada's consumptive use of Colorado River water. In 2013, the total amount of water diverted by SNWA was 433,559 AF and they were able to keep their total consumptive use at 223,563 AF, only 75% of their 300,000 AF (Bureau of Reclamation 2014g).

At the lowest curtailment elevation of 1,025 feet in Lake Mead, Nevada has their water allocation cut by 20,000 AF. This brings their total allocation to 280,000 AF, which is still above their current consumptive use. The buffer provided by the return flow program keeps Nevada's vulnerability to a shortage call in the Lower Basin relatively low in comparison to both Arizona and California. The return flow program effectively negates interior municipal and industrial water use from consumptive use. This includes water used for toilets, sinks, showers and any water that enters the sewer system to be delivered to a wastewater treatment plant. While there are system losses of interior water use, the largest area of consumptive use for Nevada is exterior irrigation of lawns and golf courses where water used cannot be captured back into the return flow program. The consumptive nature of exterior irrigation makes the suburban development of Las Vegas the area of greatest water consumption as apposed to the large casinos the city is known for.

The return flow program gives Nevada the capacity to absorb some additional urban growth projected by the Colorado River Basin Supply and Demand Study. However, additional water supplies are necessary to sustainably accommodate projected growth and the corresponding increased water demand. In response to this, SNWA has established strong supplemental water supplies to offset their Colorado River water demand. SNWA has a developed several interim and permanent water supplies, including water banked in Arizona, California and Nevada, as well as ICS credits. In the case of a shortage in the Lower Basin, Arizona has agreed to allow SNWA to draw on its Intentionally Created Surplus water as long as it does not cause the total amount of water diverted in the Lower Basin to exceed 7.5 MAF (Arizona Department of Water Resources et al. 2007). SNWA also has also obtained groundwater permits and a right-of-way for the development of a pipeline system to convey this permitted groundwater in central and eastern Nevada for SNWA use (Southern Nevada Water Authority 2009).

Across the Basin

While the effects of water shortages on groundwater recharge and replenishment in CAP are not immediately consequential, they pose a serious long-term threat to the state's water resources making Arizona highly vulnerable to a shortage call in the Lower Basin. Without water available for groundwater recharge, the dependability of the finite water stored for municipal and industrial use is weakened due to the lack of natural recharge. This increases the long-term vulnerability of municipal and industrial water users of CAP. Decreased water available for groundwater replenishment increases the vulnerability of water users in CAP by increasing the stress on alternative water resources available to CAGRD to meet their replenishment obligations. The ability of the CAGRD to meet their replenishment obligation is an essential function of the Groundwater Management Code in helping to achieve sustainable yields of groundwater in AMAs. Agricultural water users in Central Arizona stand to be immediately impacted by a Lower Basin shortage. While their full entitlement through the Agricultural Settlement Pool is not completely eliminated, the must make up for any lost CAP surface water by increasing the pumping of groundwater for irrigation. Because of cost barriers and groundwater pumping restrictions, CAP agriculture is highly vulnerable to reduced delivery of Colorado River water through CAP.

The combination of California's maximized use of Colorado River entitlements and the unreliability of supplemental water supplies makes the municipal and industrial water users of MWD vulnerable to declining reservoir levels in Lake Mead. At the key surface elevation of 1,075' California looses access to withdrawing water in excess to their 4.4 MAF entitlement including any ICS credits that have been created. This loss of available excess water is of concern in California largely due to the frequency of drought affecting the amount of water available to MWD through the State Water Project. In years that the State Water Project is unable to meet its deliveries, MWD often relies on drawing excess Colorado River water to make up the supply. If a Lower Basin shortage was to correspond with a drought event in California then MWD would have significantly diminished water supplies to rely on to meet their customer demand.

Despite receiving curtailments to Colorado River water deliveries under the Interim Guidelines, Nevada remains the least vulnerable state to a shortage call in the Lower Basin. SNWA's return flow credit program provides sufficient buffer to allow Nevada to keep its consumptive water use below their entitlement, even through the lowest level curtailments brought about by shortage calls in the Lower Basin. Additionally, SNWA has a developed several interim and permanent water supplies, including water banked in Arizona, California and Nevada, as well as ICS. Unlike California, Nevada is able to utilize their ICS water in the event of a shortage call under the provision that it does not cause the total Lower Basin diversions to exceed 7.5 MAF. The SNWA also has obtained groundwater permits and a right-of-way for the development of a pipeline system to convey this permitted groundwater in central and eastern Nevada for SNWA use. Finally, the upcoming completion of the 3rd water intake in Lake Mead will allow SNWA to withdrawal water from as low as 1,000' elevation in Lake Mead. This eliminates the concern of Nevada's ability to access their water supply as reservoir level decline in Lake Mead.

Hydropower

Introduction

While Hoover Dam was primarily built to regulate the Colorado's flows, control floods, and store water for delivery to downstream users, the Hoover Powerplant, completed in 1936, harnesses the river's power for electricity generation. Hoover Powerplant is owned and operated by the Bureau of Reclamation. By generating hydropower while simultaneously delivering water to Lower Basin users, the Hoover Powerplant makes the Hoover Dam financially solvent by providing funding for operations through electricity sales.

While there have been many studies about the economic value of Colorado River water, few of these analyses specifically covered the value of Colorado River water used in hydroelectric generation. The most comprehensive study addressing hydropower impacts is found in the Final Environmental Impact Statement (EIS) completed as part of the *Interim Guidelines*. The *EIS* quantifies the change in hydropower generation and the associated economic value for each basin management alternative proposed. The economic value is quantified on a regional scale, but does not include finer scale impacts to individual contractors (ie. entities contracted for Hoover hydropower). Furthermore, the impact to ancillary services such as reserves, ramping, and dynamic regulation are discussed, but not quantified. Finally, these economic impacts are considered for the entire time period of each proposed scenario, rather than at discreet elevations as the surface elevation of Lake Mead drops (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007).

Additionally, a recent federal report discusses the impact of climate change on federal hydropower production. While the report mentions the Colorado River Basin, a majority of its focus on the Western Area Power Administration's (WAPA) service area is in the Missouri River Basin. The study projects that federal hydropower generation will increase in the near and long-term future mostly due to projected runoff increases and reservoir storage capabilities in the Missouri River (US Department of Energy 2013). However, Hoover Powerplant has already seen a decrease in generation capacity with decreased flows from drought and over-allocation.

This project aims to understand the operational and financial implications of reduced reservoir levels in Lake Mead on hydropower generation at Hoover Powerplant at each key elevation 1,075', 1,050', 1,025', and 1,000'). These implications will be determined by answering two questions:

1) How hydropower generation changes at each key elevation?
2) What will be the financial impact of lost generation on entities with contracts for Hoover hydropower?

Specific Background

Hoover Powerplant Mechanics

Located downstream of the dam itself, the Hoover Powerplant has a generation capacity of 2,079 MW. The plant is separated into two wings, one on the Arizona side and one on the Nevada side. Each wing is approximately 650 ft. long and eight stories tall. The Arizona wing has nine commercial Francis turbine generators (A1-9) and one in-house generator (A-0) driven by a Pelton Waterwheel unit. The Nevada side has the same set-up, less one generator (N0-8) (Bureau of Reclamation 2012b).

Hydropower generation occurs when the kinetic energy in falling water is converted into mechanical energy to power a generator. At Hoover Powerplant, the four intake structures in Lake Mead adjacent to the dam are opened up, spilling water through the attached penstocks into the powerhouse (Bureau of Reclamation 2007a). As gravity pulls water through the narrowing penstocks, pressure in the water column builds up. When the water reaches the waterwheel units, the force of the pressure turns the turbine's blades. The turbines are attached to generator units, which rotate giant magnets past copper coils inside, generating electricity in the process. Water used in the hydropower generation process is then discharged downstream of the powerplant in the Colorado River (Bonsor, n.d.) .

Operating head refers to water pressure in the penstocks, and determines the capacity for hydropower generation in a plant at any given time. Operating head is measured by the distance between the surface of the reservoir and the turbines (Bonsor, n.d.). The turbines at Hoover are designed to operate effectively between 590' and 420' head. Average operation occurs within the 510'-530' range (Bureau of Reclamation 2009). As reservoir levels decline, operating head also decreases, diminishing available generation capacity.

As water in Lake Mead is released downstream through Hoover Dam, the Hoover Powerplant generates hydropower. The water orders of Lower Basin users determines the amount of water available for release, which in turn determines the generation the generation capacity at specific time steps. As a result, Hoover hydropower generation follows water use's seasonal pattern. Generation decreases during winter months, and increases during summer months (Bureau of Reclamation 2007a).

Efficiency Upgrades

Even though the Hoover Powerplant has a generation capacity of over 2,000 MW, decreasing water levels in Lake Mead has diminished that capacity over time. For every 1 foot drop in the surface elevation of Lake Mead, 5.7 MW of generating capacity is lost (Illia 2010). In June 2014, the powerplant's capacity had been reduced by 94 MW, with the downward trend expected to continue (*Hoover Coordinating Committee Meeting* 2014).

To combat the declining generation capacity, the Bureau of Reclamation (BOR) has been slowly updating the plant to increase efficiency at low reservoir levels, which are becoming increasingly more common in the Colorado's new climate regime. The capacity of most generators has increased since original installation through efficiency upgrades and replacements (Table 4).

Table 4: Original and present generating capacity of individual turbine units at Hoover Powerplant. (Bureau of Reclamation, n.d.)

Hoover Powerplant Generators			
Unit #	**Original Capacity (kW)**	**Increased Capacity (kW)**	**Present Capacity (kW)**
A0	2,400		2,400
A1	82,500	47,500	130,000
A2	82,500	47,500	130,000
A3	82,500	47,500	130,000
A4	82,500	47,500	130,000
A5	82,500	47,500	130,000
A6	82,500	47,500	130,000
A7	82,500	47,500	130,000
A8	40,000	21,500	61,500
A9	50,000	18,500	68,500
N10	2,400		2,400
N11	82,500	47,500	130,000
N12	82,500	47,500	130,000
N13	82,500	47,500	130,000
N14	82,500	47,500	130,000
N15	82,500	47,500	130,000
N16	82,500	47,500	130,000
N17	82,500	44,500	127,000
N18	95,000	36,000	131,000

In 2010, BOR started the process of replacing four of the original Francis turbines with new wide-head turbine runners. The original turbines are designed to operate at reservoir levels above 1,050', however, at lower operating heads cavitation causes pitting in the turbines' metallic parts, increasing wear and tear on the units as well as reducing power generation efficiency. The new turbines are designed to be more efficient across a wider range reservoir levels with lower operating head. The new, wide-head turbines have a wider surface, which is necessary because lower reservoir levels decrease operating, which decreases the pressure to move the turbines (Cooper and Sanchez 2014). The first new wide-head turbine, on N-8, was installed in 2012. The new N-1 turbine was installed in 2014, with N-5 and A-1 replacements expected in 2015 and 2016, respectively. There are not currently any plans to replace another other turbines other than the ones listed above. The exact improvement in performance is unknown since the efficiencies of the new turbines cannot be tested until the reservoir actually drops to sub-1,050' elevations. However, one year after N-8's runner replacement, initial efficiency improvement estimates are around 2%, which could translate into approximately $200-300 million in economic benefit (Nowak 2014).

Electricity in the Southwest

Wholesale Open Electricity Markets

The wholesale open electricity market (referred to as the spot market in this analysis) is a trading platform where excess generated energy is bought and sold before being re-sold to end-use consumers. Energy transactions in the spot market occur daily or in the form of short-term trades. These markets are open to anyone who can connect to the grid (Electric Power Supply Association 2015). Sellers include utilities with excess power and independent power producers. Buyers include utilities and electricity traders. Energy sales are regulated by the Federal Energy Regulatory Commission (FERC) because they transmitted on multi-state transmission lines and, therefore, considered interstate sales (The Division of Energy Market Oversight 2012).

The United States is divided into energy regions for the purpose of balancing energy supply and demand, managing transmission needs, and regulating sales and trades. Depending on which energy region its located in spot electricity markets can have one of two different regulatory structures—traditional or Independent System Operator (ISO).

In traditional markets, utilities decide when and how generating units are dispatched to meet demand, and control the transmission lines. Rates in traditional markets are characterized as cost-based, meaning they are based on the cost of using each energy generation option available within the regional market. Cost-based rates consider the expenses of all energy production, transmission, and distribution in the region, and ensure that sellers receive a fair return on capital. Utilities in traditional markets are usually vertically integrated. They own/operate their own generating units and transmission lines, and tend to preferentially use their own generating units over other competitively available market supplies. Traditional markets also include all federal power marketing systems such as Western Area Power Administration (The Division of Energy Market Oversight 2012).

In contrast to traditional markets, a competitive market determines operational decision in Independent System Operator (ISO) markets. ISO electricity rates are characterized as market-based, and are primarily determined by competitive market forces. ISO operators do not own generation or transmission infrastructure in the region, but instead use the competitive market to determine the providers and pricing of generated energy and the necessary ancillary services. Buyers and sellers negotiate rates according to strict rules set by the market operator (The Division of Energy Market Oversight 2012).

The Northwest and Southwest regions are regulated as traditional markets. The Northwest region includes Washington, Oregon, Idaho, Utah, and Nevada, while the Southwest region includes Arizona (Figure 9) (Federal Energy Regulatory Commission 2007). Hydroelectric dams along the Columbia River provide approximately two-thirds of the electricity needs in the Northwest region. During peak spring/summer runoff, surplus hydropower is often sold to the California and the Southwest markets (Federal Energy Regulatory Commission 2010). The Southwest region relies on nuclear and coal powerplants, mostly in Arizona and the Four Corners area (The Division of Energy Market Oversight 2012).

California's market is organized as an ISO called CAISO (California Independent System Operator). CAISO started operations in 1988 after California restructured its electric industry and its coverage area includes the whole state. CAISO is predominantly supplied by natural gas, but also imports a fourth of its supplies from the Northwest and Southwest regions.

Energy is priced and traded through hubs within each region. Trading hubs are found at the nexus of major transmission lines. The major hubs in the Northwest are Mid-Columbia (MID-C), California-Oregon Border (COB), and Nevada-Oregon Border (NOB). The major hubs in the Southwest are Palo Verde, Lake Mead, and Four Corners. Trades in CAISO occur across 300 smaller trading nodes, but are aggregated at SP15 and NP15 for the purpose of simplified price reporting (Figure 9).

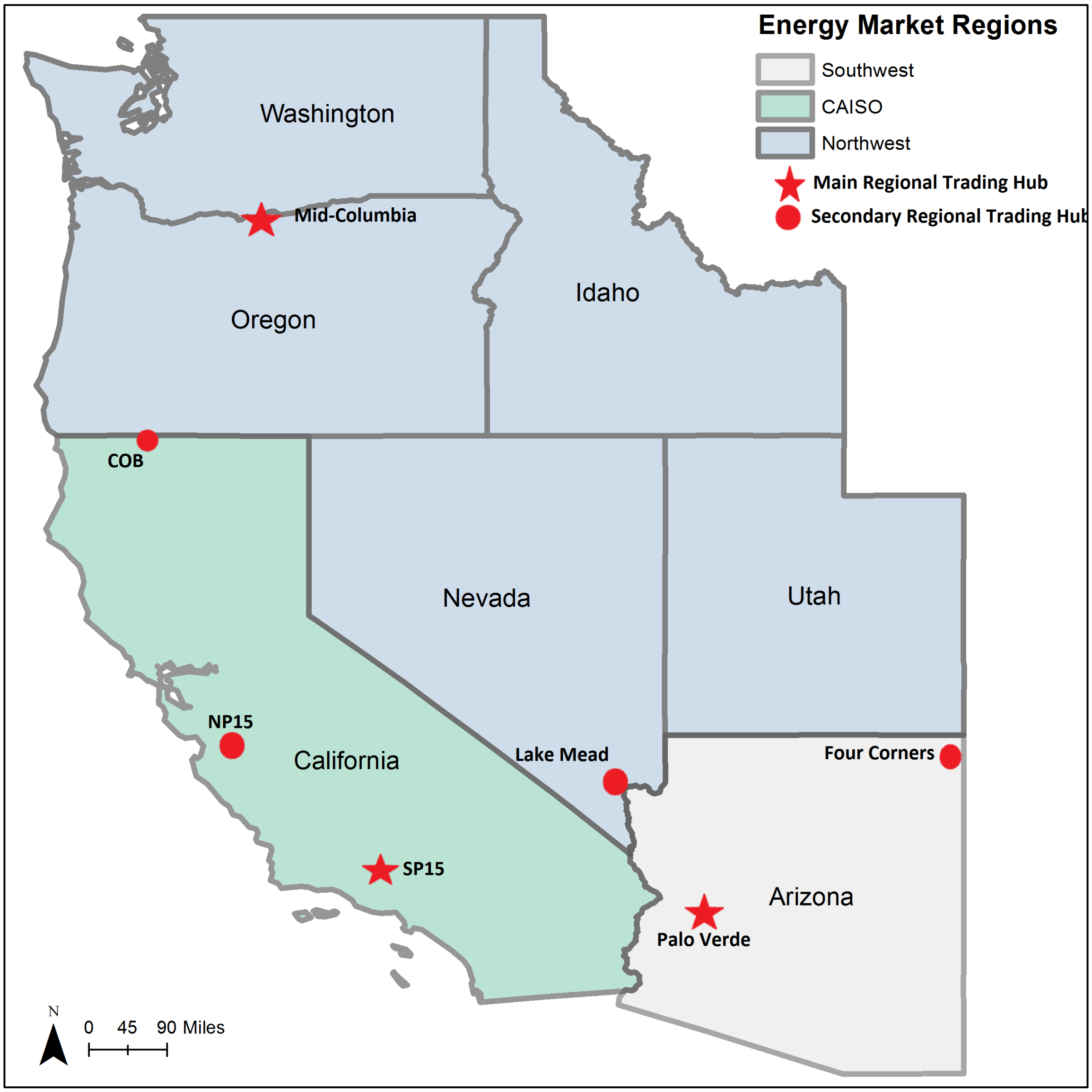

Figure 9: Regional Energy Markets in the Western US. Southwest (gray) and Northwest (blue) are traditional markets. CAISO (green) is an ISO. Main trading hubs (stars) and secondary trading hubs (circles) in each region are indicated in red.

Spot market pries are influenced by a variety of factors, including the market's regulatory structure, the cost of available energy sources, the supply-demand balance, and timing. ISO's tend to have higher energy rates than traditional markets because rates are derived from competitive market mechanisms. Prices increase when supply or demand shifts create an imbalance, forcing markets to employ less efficient, more expensive generating units to meet demand (The Division of Energy Market Oversight 2012). Additionally, rates are elevated in the summer as demand for cooling increases. Likewise, rates during peak load times in the morning and at night are higher than off-peak rates during the day (Figure 10).

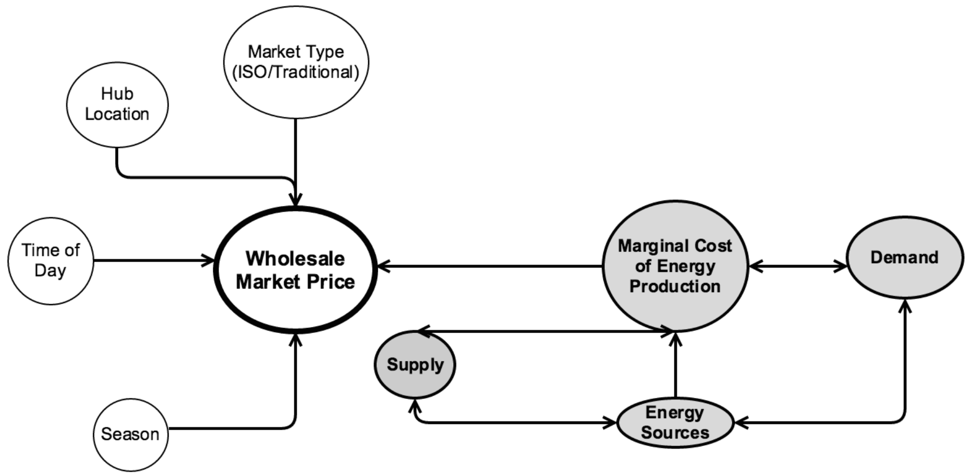

Figure 10: Conceptual model of factors influential in determining spot market energy prices. Factors in gray boxes were unable to be included spot market price estimation within the analysis.

Significance of Hoover Hydropower

Hydropower from the Hoover PowerPlant is extremely valuable because its low cost, operational flexibility in ramping and regulation, and reserve capacity.

Hoover hydropower is marketed under the Boulder Canyon Project through the Desert Southwest Region of the Western Area Power Administration (WAPA). WAPA is a federal power marketing administration that also owns and operates the transmission lines associated with hydropower distribution. As stated in the Flood Control Act of 1944, WAPA's mandate to sell energy generated at federal facilities to "preference customers" at the lowest possible rate. (Western Area Power Administration 2014).

WAPA's hydropower rate is extremely low, because the revenues only have to cover the operating costs of Hoover Dam and Powerplant. Since 1996, each entity with a contract for Hoover hydropower (referred to as contractor) has been responsible for covering the percentage of operating costs proportionate to their contract. Unlike the spot market, where rates change seasonally and with the time of day, WAPA's rate is constant over a 24-hour period and throughout the year. Most Hoover hydropower is delivered during core peak hours, which is the 4-5 hours during peak load time when the most electricity is demanded. Peak spot market rates are an average of prices over the 16-hour peak load time. However, if spot market prices were isolated over just the core peak hours, rates could increase by up to 20% to reflect peak demand (Simonton 2015). WAPA's Hoover contracts are valuable because while their rates change as the amount of hydropower generation and operational costs change, they historically been several times smaller than rates secured on the spot market or through long-term power purchase.

The operational flexibility of hydro energy sources makes Hoover hydropower even more valuable in terms of customer ramping and regulation needs. WAPA can provide large amounts of electricity on-demand because initiating hydropower generation from the potential energy of stored reservoir water is much faster and more efficient than other traditional fuel plants. Generating sources that require outside energy sources to jump-start operations must constantly maintain a low level of production to maintain inertia, even when no electricity is needed. In contrast, as soon as water flows through the penstocks, the Hoover's turbines start generating electricity. The Hoover Powerplant can ramp up 1 MW/min or to full capacity of a 130 MW unit in five minutes (Cooper and Sanchez 2014).

The electricity market is unique in that supply must meet a constantly fluctuating demand in a dynamic fashion. Hoover has the ability to regulate demand needs on a second time step. Every 4 seconds send WAPA a signal with their energy needs, which WAPA aggregates to send to Hoover. Ramping limitations limit most other generation facilities from regulating on a second-by-second basis, because they must constantly transmit the loads they generate.

Finally, Hoover's massive structure builds stability into the system even during severe system disturbances. Contractors use Hoover for power demand and reserve power. All utilities must maintain reserve power equal to the amount of load being utilized. Reserves must be able to deployed quickly, and spot market energy purchases do not include reserve power. Therefore, most utilities either build their own reserve generation or have additional long-term power purchase agreements to fulfill the need.

Hoover was never meant to be the sole power supplier for any utility, but rather to serve as a cheap peak load supply, reserve power, and to regulate the Southwest's electrical grid (Bureau of Reclamation 2007a). The Hoover Powerplant is a significant contributor to the stability and reliability of the Southwest's electrical grid because of its' stability, capacity, and operational flexibility.

Hoover Power Allocations

Hydropower from the Hoover Powerplant is allocated to contractors by congressional acts. Each congressional act states the Secretary of Energy's obligation to delivery energy to different entities. Allocations for Hoover's hydropower were originally delineated in the Boulder Canyon Project Act in 1928. The Boulder Canyon Project Act authorized preferred entities to enter into 50-year contracts from 1937 to 1987. In 1984, the Hoover Power Plant Act was passed, securing contracted allocations from 1987 until September 31, 2017. Most recently, the Hoover Power Allocation Act of 2011 outlined renewed contract allocations starting October 1, 2017 through 2067 (

Table 5). Approximately 19% of hydropower is allocated to entities in Arizona, 54% to entities in California, and 25% to entities in Nevada.

In the Hoover Power Allocation Act, contracted entities are allocated firm and contingent capacity on a seasonal basis. Firm and contingent capacity correspond to energy and power, respectively. Power, measured in kW's, is the rate at which work is done (i.e. energy transmitted). Energy is the capacity to do work, or power integrated over time, measured in kWh's. Therefore, firm capacity is energy actually delivered to the contractor, and contingent capacity is a customer's reserve power. Contingent capacity can also be thought of as the actual amount of capacity power available, based upon reservoir levels, unit outages, and power plant improvements.

The seasonality of allocations is based on historic water releases in the Lower Basin. Approximately 70% of water released from Lake Mead occurs during the summer season (March-September), and 30% during the winter (October-February) (Western Area Power Administration 1984). Accordingly, summer allocations are much larger than winter allocations.

Hoover hydropower is distributed to different contractors via four different schedules—A, B, C, and D—in the Hoover Power Allocation Act.

Schedule A includes entities leased power in the original 1928 Boulder Canyon Project Act. Schedule B contractors received allocations in 2011 in exchange advance funding for efficiency upgrades of the powerplant's generating units. The Southern California cities are part of the Southern California Public Power Authority (SPCCA), which contributed $27 million (Southern California Public Power Authority 2008). Arizona's Schedule B allocations are distributed by the Arizona Power Authority (APA), and Nevada's are distributed by the Colorado River Commission of Nevada (CRC) (Western Area Power Administration 2012).

Schedule C allots any energy generated in excess of 4.5 million MWh on a priority basis. (*Hoover Power Allocation Act* 2011). Schedule D power, also first allocated in the 2011 Act, will be marketed to entities without pre-existing contracts for Hoover hydropower. Schedule D's resource pool was created by siphoning off 5% of Schedule A and B's allocations. Native American tribes have first priority for consideration, and their energy needs will be fulfilled by WAPA (Western Area Power Administration 2012). Proposed Schedule D allocations were released in August 2014. Final allocations are expected at some point in 2015.

Table 5: Hoover Power Allocation Act of 2011 - Entity allocations.

Schedule A	**Contingent**	**Firm Capacity (MWh)**		
Contractor	**Capacity (MW)**	**Summer**	**Winter**	**Total**
Metropolitan Water District of Southern Californa	249.95	859.16	368.21	1227.38
City of Los Angeles	495.73	464.11	199.18	663.28
Southern California Edison Company	280.25	166.71	71.45	238.16
City of Glendale	18.18	45.03	19.30	64.33
City of Pasadena	11.11	36.62	16.55	53.18
City of Burbank	5.18	14.07	6.03	20.10
Arizona Power Authority	190.87	429.58	184.11	613.69
Colorado River Comission of Nevada	190.87	429.58	184.11	613.69
United States, for Boulder City	20.20	53.20	22.80	76.00
Totals	*1462.32*	*2498.07*	*1071.73*	*3569.80*

Schedule B	**Contingent**	**Firm Capacity (MWh)**		
Contractor	**Capacity (MW)**	**Summer**	**Winter**	**Total**
City of Glendale	2.02	2.75	1.19	3.94
City of Pasadena	9.09	2.40	1.04	3.44
City of Burbank	15.15	3.60	1.57	5.17
City of Anaheim	40.40	34.44	14.96	49.40
Ciy of Azusa	4.04	3.31	1.44	4.75
City of Banning	2.02	1.32	0.58	1.90
City of Colton	3.03	2.65	1.15	3.80
City of Riverside	30.30	25.83	11.22	37.05
City of Vernon	22.22	18.55	8.05	26.60
Arizona	189.86	140.60	60.80	201.40
Nevada	189.86	273.60	117.80	391.40
Totals	*507.98*	*509.06*	*219.80*	*728.85*

Schedule C- Priority	
1st-Arizona: first 200,000 MWh of excess energy generated during any year of operation.	
2nd-AZ, CA, NV: to meet Schedule A, B, D obligations up to 26,000 MWh.	
3rd-AZ, CA, NV: divided equally between states.	

Schedule D	**Contingent**	**Firm Capacity (MWh)**		
Contractor	**Capacity (MW)**	**Summer**	**Winter**	**Total**
New entities allocated by Secretary of Energy	69.17	195.64	45.38	241.01
New Entities Allocated by State				
Arizona	11.51	17.58	7.53	25.11
California	11.51	17.58	7.53	25.11
Nevada	11.51	17.58	7.53	25.11
Totals	*103.70*	*248.38*	*67.98*	*316.35*

Contract Provisions

Entities allocated Hoover hydropower must enter into a contract with WAPA in order to receive their allocation. Contracts do not require a specific percentage of peak-off peak load delivery. Therefore, a majority of Hoover power is delivered during core peak hours (Simonton 2015).

If water availability within the Colorado River Basin decreases generation capacity at Hoover Powerplant, the Secretary of Energy has the authority to adjust the amount of energy offered in proportion to the allocations outlined in the Hoover Power plant Act of 2011. Contractors may request WAPA to procure them supplemental energy from the spot market. However, WAPA is not financially responsible for the added energy costs if supplemental energy at the contracted rate cannot be found (Western Area Power Administration 2014). Furthermore, when Hoover's generation capacity decreases, contractors are contractually bound to purchase the hydropower generated and to pay their full portion of the Hoover's operating costs.

Contracted Entities Background

Fifteen entities have contracts with WAPA for hydropower generated at the Hoover PowerPlant. Contractors include public utility companies, municipal utilities, and entities in Arizona and Nevada created for the purpose of distributing hydropower and water from the Colorado River Basin. Descriptions of each contractor can be found in Appendix B.

Methods

The declining surface elevation of Lake Mead results in changes in hydropower generation, which in turn has consequences for Hoover Powerplant contractors (Figure 11). Hydropower generated by the Hoover Powerplant is fully allocated to fifteen contracted entities via the Hoover Power Allocation Act of 2011. Each contracted entity has a contract with Western Area Power Authority (WAPA) for the amount of energy allocated to them in the Act. However, if streamflow in the Colorado River Basin is reduced by any natural/unnatural mechanism, including drought or a shortage call in the Lower Basin, causing the powerplant to generate less energy, WAPA markets proportionally less power to each contractor. WAPA's rates are expected to increase during shortage periods to allow WAPA to cover Hoover's operational costs. Furthermore, contractors are obligated to purchase the amount of power marketed to them by WAPA during these periods When the hydropower generation shortfall occurs, it is anticipated that contractors will purchase supplemental energy from the spot market to fulfill their original contract. Spot market rates are historically higher than WAPA rates, which will change a contractor's total cost of energy acquisition. The change in total cost of acquiring energy represents the financial impact to contractors at each key elevation in Lake Mead.

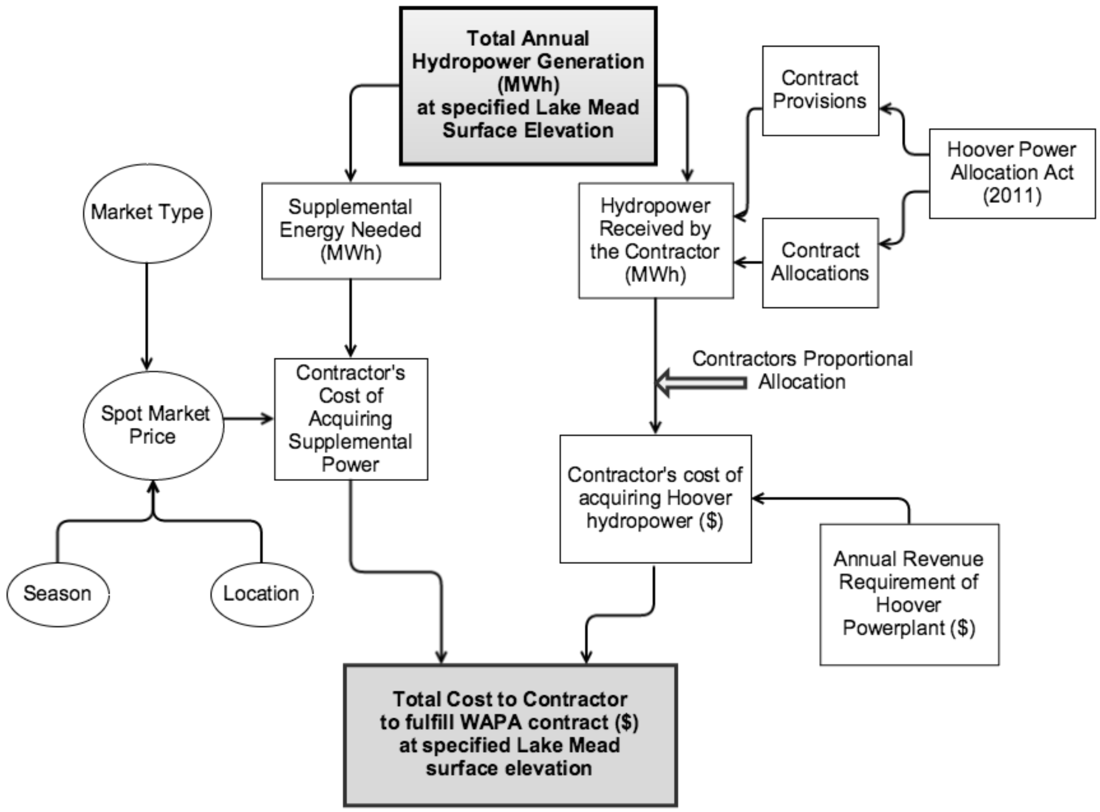

Figure 11: Conceptual Model of financial impact to contractors from change in hydropower generation as reservoir levels in Lake Mead decrease.

Existing Approaches

The most similar study done on hydropower generation is the power system analysis of the Flaming Gorge Dam for the purpose of understanding endangered species impacts on the Green River in Utah. A model simulating the Green River's hydrology and the dam's operation rules were integrated with an energy pricing model in order to optimize electricity generation at the Flaming Gorge powerplant. The Streamflow Synthesis and Reservoir Regulation (SSARR) model, used to simulate hydrology and dam operations was developed by the US Army Corp of Engineers and is similar to RiverWare's Colorado River Simulation System software. SSARR replicates rainfall/snowmelt-runoff patterns and snow accumulation, and routes streamflow downstream under free and controlled flow operations. The AURORA model quantifies the economic value of generated hydropower by normalizing it to future projected spot market prices in the area. AURORA model satisfies both supply and demand needs by using dynamically changing competitive market fundamentals to inform energy rates. AURORA was also used by the Bonneville Power Association, another federal power marketing association, to simulate pricing in the Northwest Energy region (*Operation of Flaming Gorge Dam Final Environmental Impact Statement: Power System Analysis Technical Appendix* 2002). While the AURORA model would have been an excellent choice to incorporate dynamic energy market pricing structures into this analysis, obtaining a license for this proprietary software was cost prohibitive.

Hydropower Cost Model Execution

The developed conceptual model illustrating the relationship between reservoir levels in Lake Mead and the financial impact on entities with contracts for Hoover hydropower was implemented using R

Statistical Software. Sensitivity analyses were applied to the spot market and Hoover hydropower rates. For the Hoover hydropower rates, a +-20% range was chosen, based on historic variability in WAPA's annual revenue requirement between 1998-2013. The same range was chosen for spot market rates. The +-20% range was discretized into +-10% increments for both variables.

Hydropower Cost Model Limitations

The goal of the implemented Hydropower Cost Model is to compute the costs of fulfilling hydropower contracts if the surface elevation of Lake Mead falls below a series of key elevations as defined by the Interim Guidelines. The model does not attempt to predict *when* reservoir levels will reach each key elevation, but instead computes the additional energy costs likely to occur in years when key elevations in Lake Mead occur.

Hydropower generation is influenced by management decisions in river operations. Operational priorities, stated in the Boulder Canyon Act, partially influence management decisions. Current operations optimize flood control and water supply needs, since hydropower is a secondary priority. Given the difficulty of how priorities will change in the future, the hydropower generation model assumes a continuation of current operating rules, which could be limiting in the event of future changes in preference.

Energy prices are influenced by many factors, most of which change over time and require complex modeling to adequately address. Changing fuel sources, consumer demand, and energy generation supply, as well as additional social and political factors, exert a significant amount of control on spot market prices, but could not be accounted for within the scope of this model. For example, there may be a relationship between the amount of power generated by Hoover Powerplant and spot market prices in the region. Decreased Hoover generation will decrease the overall energy supply, which may, in turn, increase the value of remaining supply unless other generation plants come on board. However, that feedback relationship is not represented given its complexity. Instead a sensitivity analysis is provided to compare model estimates across a range of spot market prices.

Given the simplification of these inputs in the model design, it is not intended for the results to be interpreted as definitive cost predictions at lower reservoir levels. Instead, the goal of the model and the analysis is to highlight the energy cost change in relative terms in order shed light on the magnitude of, and/or pattern in, change to be expected. However, it is vital to consider how the complexities of hydropower generation and spot market rates might generally impact the results were they to be included.

Hydropower Cost Model Structure

A deterministic economic model was designed in order to quantify the relative financial impacts of declining reservoir levels on Hoover's hydropower contractors.

The financial impacts are expressed as the change in total cost of fulfilling energy needs designated in the original WAPA contracts. The change in cost to a contractor is a function of the change in WAPA and spot market energy rates and the amount of energy the contractor has to purchase on the spot market due to reductions in Hoover Powerplant generation. The relationship and parameters of the cost to an individual contractor is outlined below:

$$C_C = R_{WC}\,(GT_e \times P_C) + [R_{SC}][A_C - (GT_e \times P_C)]$$

C_c = Total cost to individual contractor ($)
R_{SC} = Cost of electricity ($/MWh) on the open market
R_{WC} = Cost of electricity ($/MWh) bought from WAPA (Hoover Powerplant)
A_C = Power allocated to each contractor (MWh)
GT_e = Total hydropower generation at reservoir elevation e (MWh)
P_C = Contractor proportion of sum of all contractors power allocation

The model outputs the cost to the individual contractor (C_C), and the total cost at each reservoir level is the sum of each individual contractor's cost. Based on contract conditions, it is assumed that contractors will purchase spot market power to supplement hydropower when their full allocation is not available from the Hoover Powerplant (Western Area Power Administration 2014), and that contractors will continue to pay for Hoover hydropower for the duration of their WAPA contracts regardless of the amount of hydropower received[4] (Simonton 2015). See Appendix B for data used in the analysis.

Model Components

Hydropower Generation (GT_e)

GT_e, measured in MWh's, is the total amount of hydropower generated annually at each key elevation in Lake Mead (1,075', 1,050', 1,025', and 1,000') and assuming reservoir levels are high enough to make the full allocation available. GT_e is calculated using year-long scenarios for each shortage elevation developed from Colorado River Simulation System (CRSS) model data. In order to implement the Hydropower Cost Model, a separate model depicting hydropower generation at Hoover Powerplant as a function of reservoir levels had to be developed.

Water release schedules from Hoover Dam and the turbine's operating head are the main drivers of hydropower generation at Hoover Powerplant (Figure 12). Water release schedules are influenced by river management decisions and water levels in Lake Mead, and operating head is a function of the reservoir levels.

[4] WAPA contracts bind contractors to Hoover hydropower purchases through 2067, despite the amount of hydropower produced and relative hydropower rate. Theoretically, contractors are still financially responsible for their portion of Hoover Powerplant operating costs even if is no long physically possible to produce hydropower. CRSS data shows this point when Lake Mead is approximately at an elevation of 1,015' (Bureau of Reclamation 2014i).

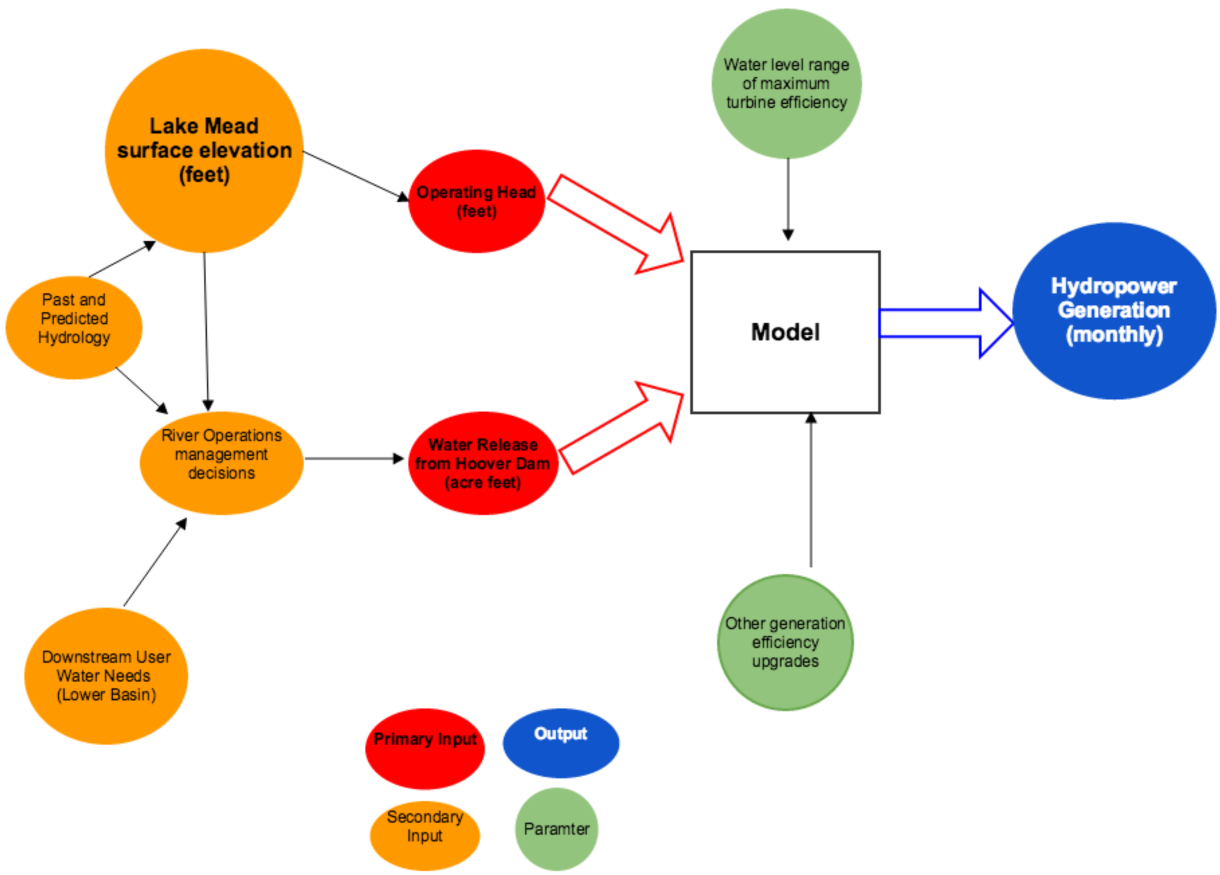

Figure 12. Conceptual Model of Hydropower Generation at Hoover Dam.

Two data sets were utilized to develop the hydropower generation model—the historic record of Lake Mead operations and data from the Colorado River Simulation System (CRSS) model. Historic data obtained from the Bureau of Reclamation (BOR) included actual generation, Lake Mead's surface elevation, and water releases from Hoover Dam. All parameters were in a monthly time-step, with records from January 1967 through July 2014 (Bureau of Reclamation 2014h). The CRSS dataset had 112 runs covering 46 years each, and included Lake Mead's surface elevation, generation, operating head, and tailwater elevation (Bureau of Reclamation 2014i). Of note, the historic data only reflects conditions as low as the lowest observed elevation to date (approximately 1,080'), while the CRSS data reflects conditions as low as 1000'.

The Colorado River Simulation System (CRSS) simulates basin-wide hydrology and river operations for use in deciding day-to-day operations and long-term policy and planning. It was developed by BOR in the 1970's, implemented in RiverWare software in 1996, and is now maintained by BOR's Colorado River Modeling Work Group. It has been used in numerous planning and environmental compliance studies within the Basin such as the *Colorado River Basin Supply and Demand Study*, developing the Interim Guidelines, and the Lower Colorado River Multi-Species Conservation Program. Additionally, every year at least two official simulations are run in January and August.

The CRSS model simulates major reservoir operations on a monthly time-step using a water budget to account for water entering (i.e. precipitation), leaving (i.e. consumptive use, out-of basin diversions, and evaporation), and moving through the system (i.e. storage in reservoirs and instream flow). Input data include: natural flows, physical process parameters (i.e. evaporation rates), initial reservoir conditions, future diversion and depletion schedules for the Basin States and Mexico, and operational rules for Lake Mead and Lake Powell (Bureau of Reclamation 2012c).

Using CRSS model data, two scenarios were developed with the help of BOR staff for each key elevation in order to account for the importance of climatic conditions and management decisions on water release schedules. The two scenarios provide bounds for the extremes in climatic conditions within the Basin.

The scenario approach mimics the projection process already employed by Bureau of Reclamation (BOR) for managing water in the Colorado River Basin. BOR determines river operations for the upcoming calendar year based on Lake Mead's January 1st surface elevation and the Basin's predicted climatic conditions during the year. The developed scenarios span a one-year time period, starting with a key surface elevation of Lake Mead on January 1st. The January 1st reservoir level in Lake Mead is reflects the cumulative impacts of climatic conditions and management decision of multiple prior years. The two scenarios account for uncertainty in hydrologic conditions and management decisions within the Basin for any given year. While management operations are based on the starting reservoir level and the predicted climatic conditions for that year (after January 1st), actual hydropower generation is a direct result of the climatic conditions that actually occur, which determine subsequent water inputs to the reservoir for the remainder of the year. The "wet" scenarios start at the specified elevation, and end with similar or higher reservoir level in Lake Mead. The "dry" scenarios decline drastically throughout the year, ending near or under the next shortage level.

The scenarios model cumulative monthly generation, in MWh, over the year. The reservoir level was assumed to remain relatively constant throughout the month. The scenarios do not include efficiency gains from recent wide-head turbine upgrades because of limitations in BOR's understanding of precisely how they will behave at lower reservoir levels and delayed updates to CRSS. Therefore, the generation output at lower reservoir levels should be viewed as a lower bound. The yearly scenarios drawn from CRSS model runs were chosen within a two to four year period in order to minimize impacts of potential variation in reservoir operations with respect to time during the course of the CRSS simulation.

Power Allocations

Allocated (A_c)

$A_{C,}$ is the full (or original) amount of hydropower, measured in MWh, allocated to contractors. Each contractor's A_C term is based on the allocation amounts stated in the Hoover Power Allocation Act of 2011 (Table 5), which take effect on October 1, 2017. The 2011 Act's allocations were chosen because the project analyzes costs of potential scenarios that might happen in the future. Furthermore, it is unlikely that the Lake Mead will enter shortage conditions before 2017 when allocation amounts in the 2011 Act take effect.

Several entities are allocated energy in both Schedule A and Schedule B. Those contractors' total allocation reflects the sum of both schedule allotments. Given that Schedule D allotments still have not been finalized, they were treated as a single entity. Schedule C allotments were not considered in the analysis since no Schedule C energy was delivered in 2013 (*Hoover Coordinating Committee Meeting* 2014). If reservoir levels continue to decrease, it is expected that there will continue to be no Schedule C energy to deliver.

In order to address the seasonality of hydropower allocations, it was assumed that contractors were delivered an equal amount of hydropower in each month of the marketing season. The winter allocation amount was divided evenly between every month between October and February. The summer allocation amount was divided evenly between every month between March and September.

Proportion (P_c)

P_C is the contractor's proportion of the total amount of allocated hydropower to all contractors in the Hoover Power Allocation Act (i.e. the sum of all contractor allocations). P_C*GT_e, is the proportionate amount of power each contractor receives of their original allocation. If low flows or reservoir levels prevent Hoover Powerplant from generating the full 4.5 million MWh, WAPA will adjust the amount of energy such that contractors receive the proportionate (P_C) amount to total generation. The amount of power received each month was reduced by equal proportion.

Energy Costs

Hoover Hydropower (R_{WC})

R_{WC} is the rate a contractor pays for hydropower from Hoover Powerplant. Western Area Power Association (WAPA), the entity in charge of marketing Hoover hydropower, determines the price of Hoover's hydropower through a specific rate-setting methodology.
WAPA's rates are function of the amount of generated hydropower sold and operational costs on an annual basis. At the beginning of WAPA's Fiscal Year, WAPA determines the amount of revenue required to fulfill all fiscal expenses for the year related to hydropower production from Hoover Dam. The annual revenue requirement (also known as a base charge) is total operational and maintenance expenses for the year less water sales, previous year revenue carry-over, and additional miscellaneous revenues anticipated for the year ("Boulder Canyon Project Power Repayment Study Executive Summary," n.d.).

For rate setting purposes, WAPA splits the annual revenue requirement evenly between charges for capacity and energy sales. Capacity and energy sales are WAPA's equivalent of contingent and firm capacity terms used in the Hoover Power Allocation Act (i.e. power and energy). Capacity sales are measured in kW's (sometimes kW/month) and is the instantaneous amount of power available needed to meet customer demand. Energy sales are measured in kWh's and is the amount of power (i.e. electricity) delivered over time[5] (United States Department of Energy and Western Area Power Administration 2009). Essentially, contractors' pay for the actual electricity received as well as the potential to receive electricity on demand. WAPA determines a separate rate for capacity and energy sales.

The composite rate combines capacity and energy rates to represent an average rate for Hoover hydropower (similar to spot market rates). R_{WC} assumes that the composite rate is constant throughout the year. WAPA calculates composite rates by dividing the total annual capacity and energy sales charges (i.e. the base charge) by total annual energy sales. Total generation (GT_e) is equivalent to total annual energy sales. Capacity sales are not accounted for in this analysis because they are the static equivalent of energy sales.

In the analysis, the price of Hoover hydropower is represented by a composite rate. The composite rate formula, measured in dollars per MWh, is based on WAPA's current rate setting methodology.

[5] 1 kWh delivered requires 1 kW of capacity. Or 1kW delivered over 1 hour equals 1 kWh.

$$Composite\ Rate\ (R_{WC})\ = \frac{AR_{2013}}{GT_e}$$

AR_{2013} = WAPA's Annual Revenue Requirement in 2013
GT_e = Total annual hydropower generation at reservoir level e

WAPA's actual 2013 base charge was used for the Annual Revenue Requirement (AR_{2013}) because 2013 is baseline year for the analysis. 2013 was chosen because it is the last full year of data available for hydropower generation, energy rates, and reservoir levels, and had observed reservoir levels closest to actual shortage conditions. To ensure that WAPA's actual 2013 base charge was not an operational or maintenance cost anomaly, all base charges for 1996-2013 were converted to 2013 dollars and compared to the 2013 base charge. 2013 base charge data was within one standard deviation of the average of all 1996-2013 base charges ("Boulder Canyon Project Power Repayment Study Executive Summary," n.d.).[6]

WAPA's Fiscal Year aligns with a Water Year, October 1-September 31. This conflicts with BOR's Fiscal Year, January 1-December 31, which determines the timeframe of the generation scenarios. This timeframe of this analysis follows BOR's Fiscal Year. Since WAPA's rate is constant throughout the year, the results are not impacted if the WAPA rate is assumed for a Calendar Year instead.

Spot Market Rates (R_{SC})

Contractors will replace hydropower shortfalls from their WAPA contracts will energy from the spot market. R_{SC} is the rate a contractor would pay, measured in dollars per MWh, for supplemental energy from the spot market. The hydropower cost model assumes that contractors will buy supplemental energy from the spot market because supplemental power needs will vary enough inter-annually to prohibit contractors from entering into long-term power purchase agreements as a cheaper alternative.

In the United States, energy markets are regionally delineated. The analysis in this project is concerned with the Northwest, Southwest, and California regions (Figure 9). International Exchange (ICE) records energy trades through a few central hubs in each region. R_{SC} assumes that contractors will obtain supplemental energy via the closest proximal trading hub in their energy region unless otherwise indicated. Since spot market rate data is often utilized in futures energy trading, the rate data needed for the analysis was considered sensitive proprietary information. Data available for the analysis was limited to one energy-trading hub per region (Northwest-Mid Columbia, Southwest-Palo Verde, and California-SP15). Therefore, the pertinent regional hub with available data determined each contractor's spot market rate in the analysis. Schedule D was assigned to the Palo Verde hub because tribal energy needs are prioritized in the Schedule D allocations, and the tribal buyers are most concentrated near the Palo Verde hub.

Spot market rates were obtained from the U.S. Energy Information Administration (EIA). EIA obtains its data through a special agreement with ICE, a brokerage platform for over-the-counter and futures energy trades (Intercontinental Exchange 2014). EIA's spot market rate data is composed of weighted

---

[6] 1996-2012 base charge values were inflated to 2013-dollar values using the standard inflation formula and the compound annual growth rate.
\$2013 Value Annual Revenue Requirement$_t$ = Annual Revenue Requirement$_t$ * (1+ GDP growth rate)$^{(2013-t)}$
Compound Annual GDP growth rate = $[(\frac{GDP_{2013}}{GDP_t}\ \hat{}\ (1/_{2013-t})-1)*100]$
The U.S. Nominal GDP for each year was obtained from the Bureau of Economic Analysis (Johnston and Williamson 2015).

daily averages[7] of traded electricity prices at the specified trading hub. Monthly averages of the available daily averages were calculated for 2013, the baseline year of the analysis. All hubs reflect Day-Ahead, Peak Load pricing. SP-15 prices reflect quasi swaps, meaning prices from 3000+ energy-trading nodes are aggregated to calculate SP15's rate due to its location in an ISO market. Off-peak load rates were not utilized because a majority of Hoover hydropower is delivered during peak hours.

The spot market rates obtained from EIA were further adjusted in order to reflect the added value of Hoover hydropower being delivered during core peak hours. Electricity rates change on an hourly basis. Core peak load occurs from 4-11 PM when the most electricity is demanded, and electricity prices are the highest. However, peak rates are the average of hourly rates over the 16-hour peak load time period (8 AM-11 PM). Accordingly, spot market rates were increased by 13.5% to reflect core peak load prices[8] (Simonton 2015). This rate increased should be viewed as a lower bound since it does not reflect the value added by flexibility and ramping, regulation, and reserve power unique to hydropower produced at Hoover Powerplant.

Results

Overall, a contractor's cost of acquiring the total amount of energy allocated to them in the Hoover Power Plant Act increases at lower reservoir levels in Lake Mead. To understand the financial impact of lower reservoir levels on Hoover hydropower contractors, the model's output at each elevation was represented in three different ways:

1) *Cost to Individual Contractors:* dollars paid by each contractor for combined hydropower (WAPA) and spot market energy in order to acquire the total amount of energy specified in original WAPA contracts. The *costs* of WAPA and spot market energy, individually, are also discussed;
2) *Total Cost to all contractors:* sum of individual contractors' *costs* (dollars)—includes WAPA and spot market costs;
3) *Combined unit price*: per unit cost of combined WAPA and spot market energy bought by an **individual** contractor (dollars/MWh). *WAPA unit price* refers to the unit cost of hydropower and *spot market unit price* refers to the unit cost of spot market energy for each contractor.

The analysis' results focus on the change in output representations between each key elevation in both generation scenarios. In the "wet" scenarios, the reservoir level stays relatively stable throughout the year, while in the "dry" scenarios the reservoir level decreases to the next key shortage elevation by the end of the year. Key findings are as follows (Table 6):

1) The change in a contractor's costs increases with the amount of hydropower originally allocated. Contractors purchasing from the same spot market hub experience the same percent change in costs;
2) Unit price behavior at each key elevation
    a. The combined unit price increases at lower key elevations;

---

[7] Daily weighted average price is calculated with the following formula: I = ∑ (P*V)/T
Where P = Price of individual transaction; V = Volume of individual transaction; and
T = Total Volume of all qualifying transactions

[8] Based on calculations by a WAPA Power Marketing manager, spot market rates were increased by 13.5% to reflect core peak load pricing. Using hourly rate for the Lake Mead trading hub, the average percent difference between core peak and peak prices was found for the time period, October 1, 2013 to September 30, 2014. Core Peak hours are considered 4-11 PM, Peak Hours are considered 8 AM-11 PM.

    b. Contractors purchasing from the same spot market hub will pay the same combined unit price;
    c. WAPA unit price increases as reservoir levels decline, but is the same for all contractors;
    d. Spot market unit price stays constant at all elevations, but differ for each contractor based on the spot market hub used to purchase supplemental energy.
3) The costs (total and individual) and the combined unit price both peak at 1,000', but the shape of the relationship with value changes between key elevations is different in "wet" and "dry" scenarios:
    a. In "wet" conditions the change in unit price/costs between elevations is higher as reservoir levels decline;
    b. In "dry" conditions the change in unit price/costs between elevations more closely resembles a linear relationship.

Table 6: General trend in cost changes as reservoir levels decrease. Includes: total power purchased, unit price, costs to individual contractors, and total cost across all contractors.

	WAPA	**Spot market**	**Combined**
Amount of Power Purchased	Decrease	Increase	Constant
Unit price	Increase	Constant	Increase
Costs to individual contractors	Constant	Increase	Increase
Total Cost across all contractors	Constant	Increase	Increase

For individual contractors, the relative magnitude of change in costs between key elevations is influenced by two factors: the amount of hydropower originally allocated and the spot market hub used to purchase supplemental energy. Contractors with the largest allocations have the highest expenditure for both the portion of hydropower received and the supplemental energy bought to replace lost hydropower (Figure 13). At each elevation a contractor's costs ranges from several thousand to several million dollars (Table 7) depending on their original allocation. Contractors purchasing energy from the same spot market hub experience an equal percent change in cost between each key elevation. Contractors using SP15, have the highest percent change, while Mid-Columbia users have the lowest.

Table 7: Combined costs for an individual contractor at each elevation.

Cost for Individual Contractor ($)		
Elevation	**Max**	**Min**
Full Allocation	23,500,058	24,263
1075'	46,184,291	47,615
1050'	68,806,822	49,814
1025'	88,030,277	59,075
1000'	106,327,605	109,632

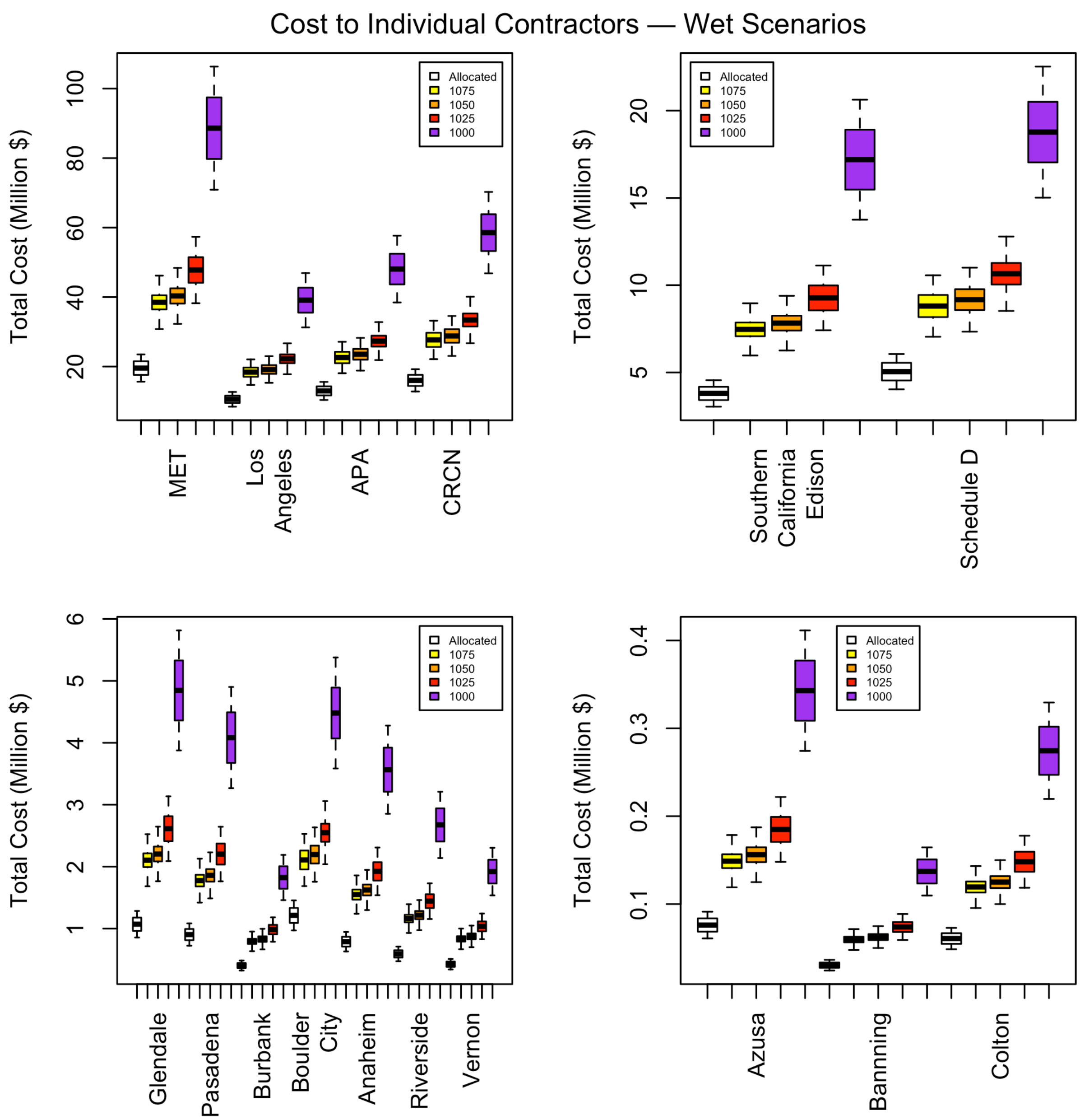

Figure 13: Individual contractor costs (combined WAPA and spot market) at each key elevation for the wet scenario.

Similarly, contractors purchasing supplemental power from the same spot market hub will pay the same combined unit price (Figure 14). This will be discussed further in the Discussion section, and is caused by the behavior of the WAPA and spot market unit prices at each key elevation. WAPA unit price of energy increases as reservoir levels decrease, but the spot market unit price is constant at all key elevations (Figure 15). Though both wet and dry scenarios have increasing WAPA unit price through key elevations, they have a different unit price at each elevation because different amounts of total hydropower are generated. The dry scenario WAPA unit price increases much more substantially between key elevations than the wet scenario unit prices. On the other hand, spot market prices at each trading hub stay constant through each key elevation because they are a function of outside market forces, not reservoir levels, in the hydropower cost model. Again, as with the percent change in costs, contractors' purchasing energy from SP15 will experience the highest combined unit cost because the SP15 unit cost is the highest of all trading hubs.

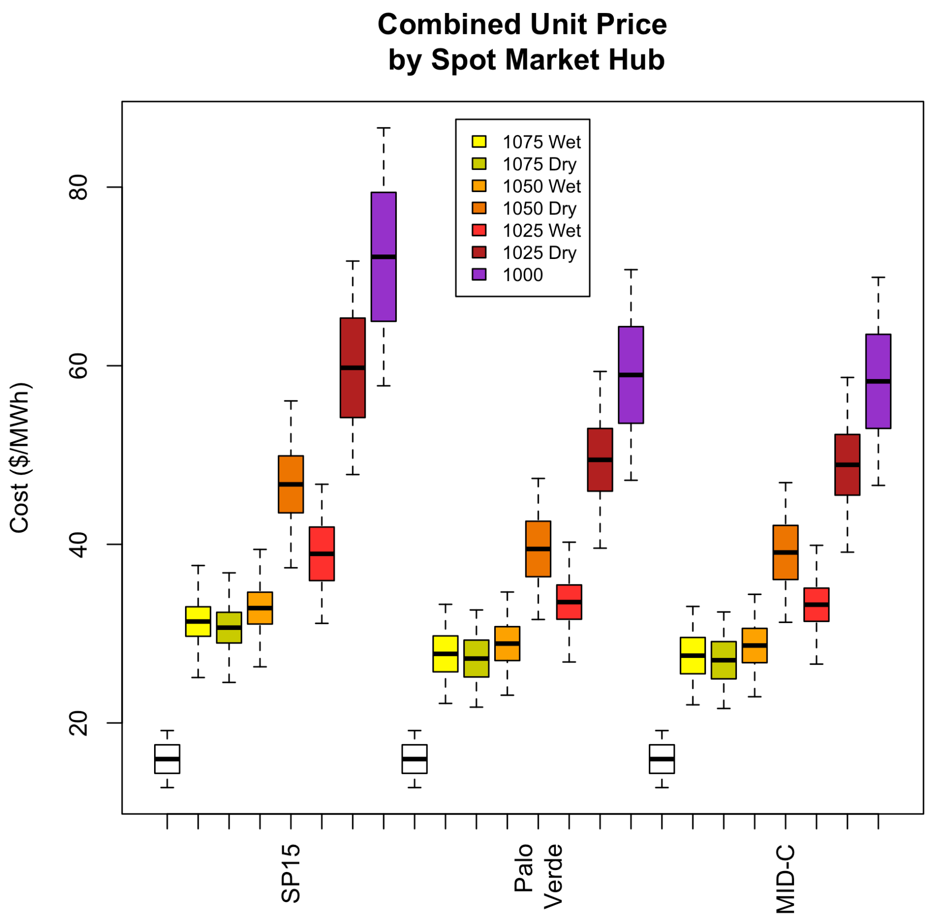

Figure 14: Combined Unit Price of energy by spot market hub at each elevation. Contractors using SP15 experience the highest combined unit price of all spot trading hubs used in the analysis.

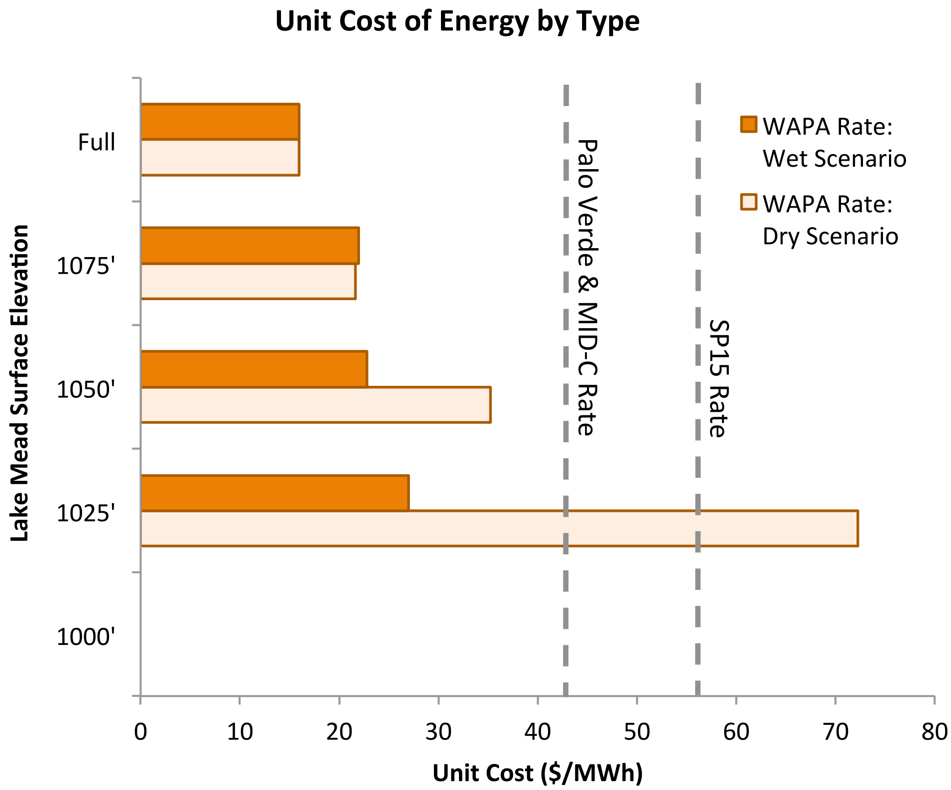

Figure 15: Unit Price of Energy by Source. Spot Market (black dashed lines) is constant through key elevations. WAPA (dark orange-wet scenario; light orange-dry scenario) increases with key elevation.

Costs (total and individual) and the combined unit price both peak at 1,000’ in wet and dry scenarios. However, the value changes between key elevations have a different shape in “wet” and “dry” scenarios (Figure 16 and Figure 17).

First, the magnitude of change in mean value of costs and range of costs increase at lower elevations. The mean value corresponds to the costs calculated with the baseline annual revenue requirement and baseline spot market rates. The range of costs includes potential costs calculated with all sensitivities. In the wet scenario, the change in costs between each key elevation increases as elevation decreases. For example, the difference in mean value between 1,075’ and 1,050’ is several times smaller than the difference between 1,025’ and 1,000’ (Figure 16). However, the range of costs is consistent from 1,075’-1,025’, with a sizable increase between 1,025’ and 1,000.

Conversely, in the dry scenario the change in mean value of costs between key elevations decreases at lower elevations. The difference in mean value between 1,075’ and 1,050’ values is larger than the difference between 1,050’ and 1,025’ (Figure 17). Furthermore, the change in range of costs between elevations appears to be more linear.

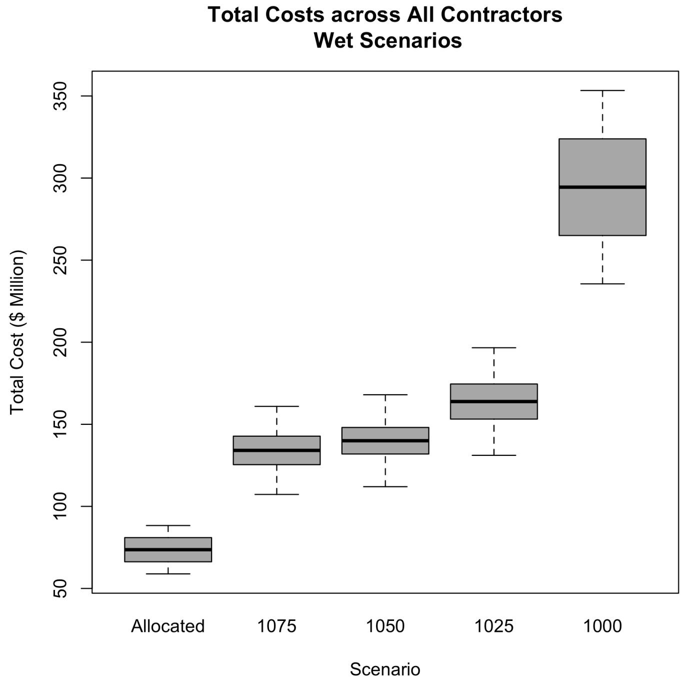

Figure 16: Annual Total Cost at each key elevation for the wet scenario (across all contractors).

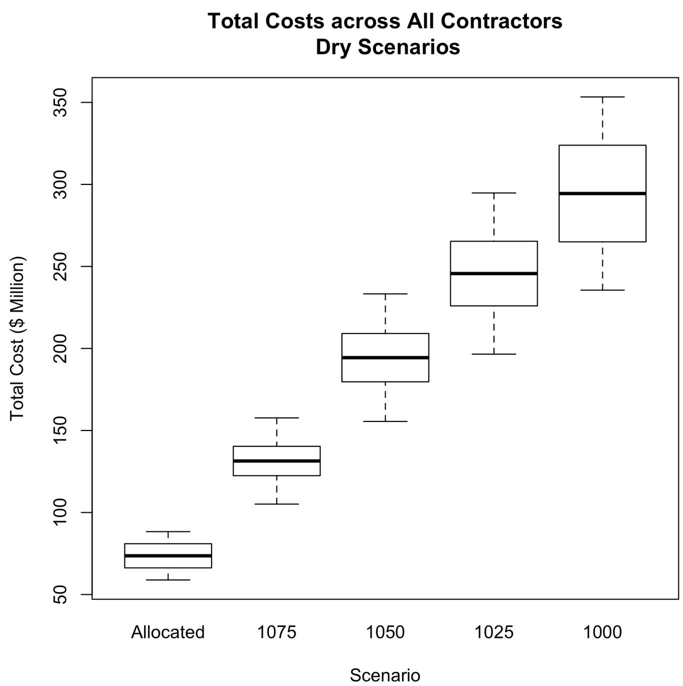

Figure 17: Annual Total Cost at each elevation for the dry scenario (across all contractors).

Discussion

The Hydropower Cost model developed for the analysis provides an approximation of the financial impact on each contractor and over all contractors at each key elevation (1,075', 1,050', 1,025', and 1,000'). Modeling the complexities of spot market pricing and hydropower generation within the scope of this project presented sources of uncertainty as illustrated by the sensitivity analyses. The sensitivity analyses for spot market prices and WAPA's annual revenue requirements, as well as the range of climatic scenarios at each key elevation, provide certainty bounds. The values estimated in this analysis establish a baseline scale, valuable for the planning process.

A contractor's cost of acquiring the amount of energy specified in their original WAPA contract (i.e. their full allocation) at each key elevation is the sum of costs for Hoover hydropower and costs for spot market energy. The differences in total costs (i.e. the sum of all contractors' costs) at each key elevation are driven primarily by the amount of hydropower produced at that elevation. As the conceptual model of hydropower generation illustrates (Figure 12), generation is a function of the starting reservoir level and precipitation/runoff conditions that characterize the following 12 months. The amount of hydropower produced at Hoover Powerplant determines the amount of supplemental energy needed from the spot market. Total cost of spot market energy changes at each elevation, causing the total cost of combined spot market and hydropower energy to change at each elevation. However, combined unit price at each elevation is more influenced by the WAPA unit price since it increases as reservoir levels decline. At lower elevations, contractors will require more supplemental energy, increasing their sensitivity to unit price changes, particularly increases.

Understanding the different controls on spot market unit price and WAPA unit price is crucial to understanding why individual and total costs will change as Lake Mead reservoir levels decline through the key elevations. The spot market unit price is determined by outside market forces, and is assumed to be independent of Lake Mead's surface elevation in our analysis. However, a contractor's expenditure on spot market energy increases with declining elevations as it needs to purchase a larger quantity of energy to make up for the larger shortfalls from Hoover Dam.

Conversely, WAPA's unit price of hydropower is a function of generation. Operating costs of Hoover Powerplant must be covered by hydropower revenue regardless of the amount of hydropower generated. Therefore, the unit price of hydropower will increase as generation decreases with reservoir level decline. However, because contractors pay the same percentage of the annual revenue requirement regardless of the amount of hydropower received, their total expenditure on hydropower will not change, regardless of Lake Mead's surface elevation (Figure 15 and Figure 18)

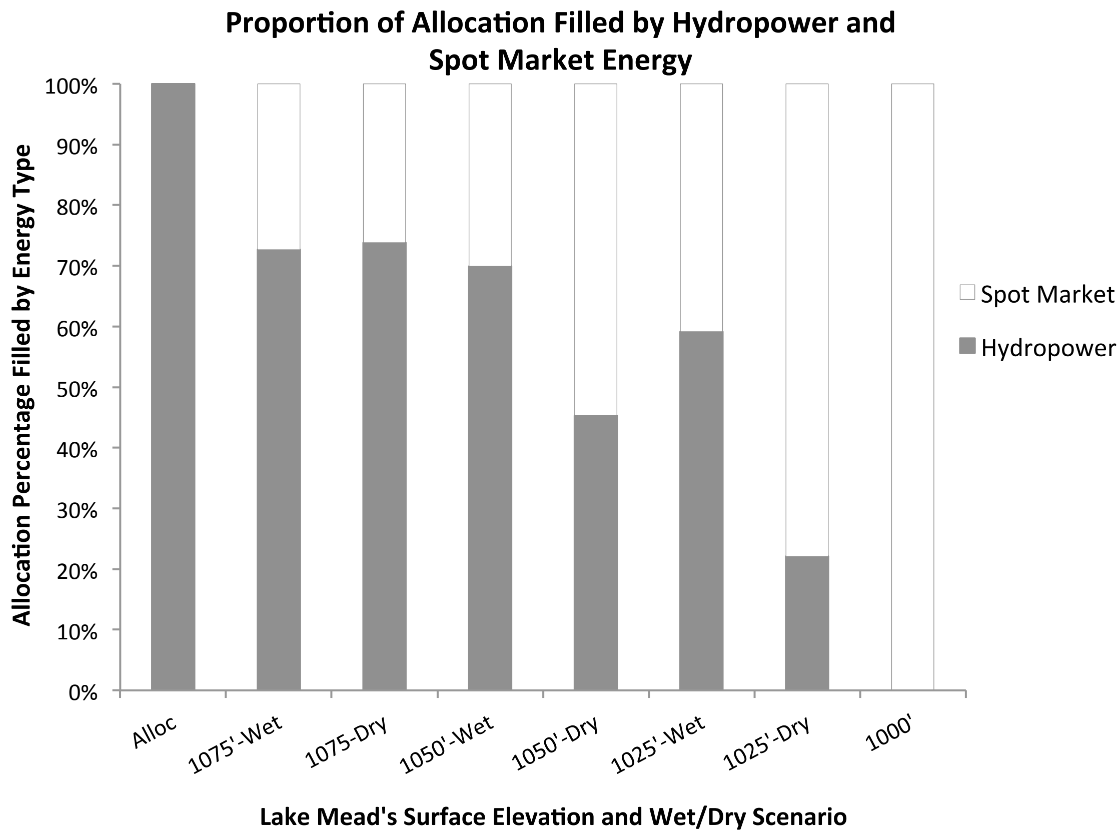

Figure 18: The proportion of energy provided by Hoover hydropower and the spot market for each generation scenario. Hoover hydropower (gray); and spot market energy (white). Hoover Powerplant cannot generate power at 1,000',

The combined unit price and percent change in costs is constant across contractors using the same spot market hub (Figure 14) because all contractors experience the same percentage of lost hydropower at each elevation. Therefore, all contractors are replacing lost hydropower with the same proportional amount of spot market energy. Each spot market trading hub has a different unit price. Since WAPA's unit price is the same for all contractors, the spot market rate deviations account for any differences in the combined unit price and percent change in costs between contractors.

This highlights the significance of the type of energy market contractors participate in to procure any supplemental energy. Hoover hydropower contractors participate in traditional markets in the Northwest and Southwest, and Independent System Operator markets in California CAISO. CAISO rates are determined by competitive market mechanisms, whereas traditional market rates are set by the cost of energy production. CAISO rates, such as those recorded at SP15, have historically been higher than those recorded at Palo Verde and COB (hubs located in the Southwest and Northwest markets) (Figure 19). Elevated CAISO rates are expected to continue in the near future (Figure 20). Contractors participating in CAISO markets may be disproportionately impacted financially in acquiring the amount of energy originally specified in their WAPA contractors if CAISO prices continue in the current trend.

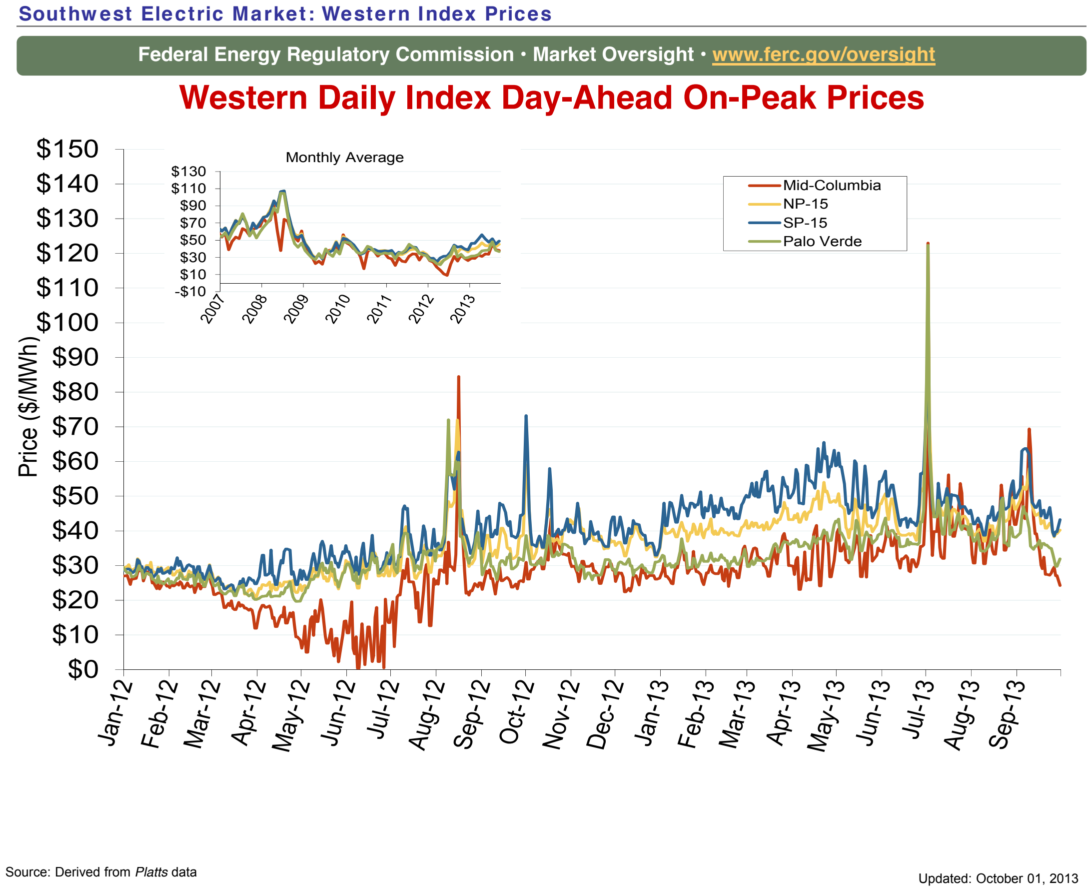

Figure 19: Average daily energy prices in at spot market hubs in western energy regions. Includes Palo Verde (Southwest, green) Mid-Columbia (Northwest, red), and NP15 and SP15 (CAISO, yellow and blue) (Federal Energy Regulatory Commission 2014)

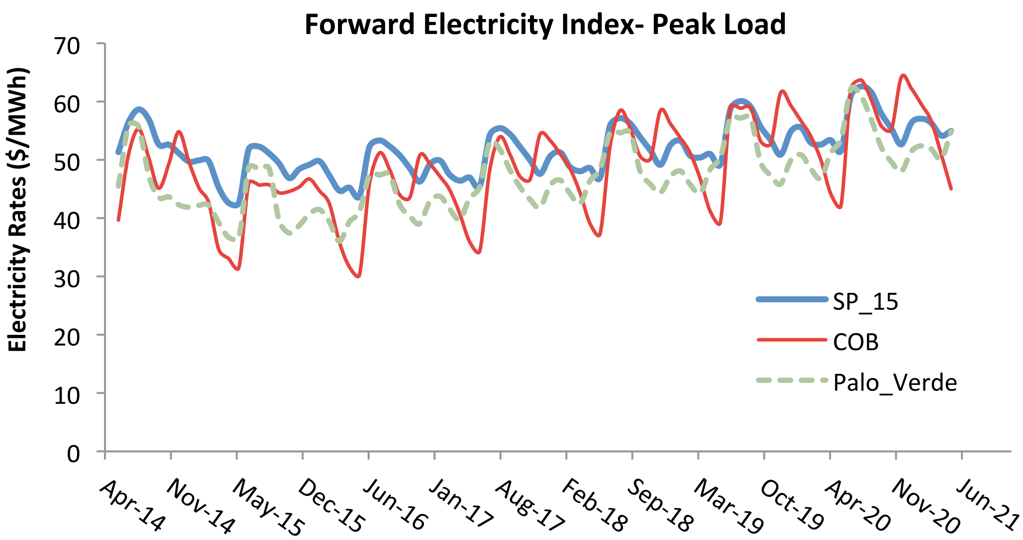

Figure 20: Forward Electricity Price Index for Peak Load. SP15 (blue) in CAISO market is predicted to have the highest prices until mid-2018 (OTC Global Holings 2014).

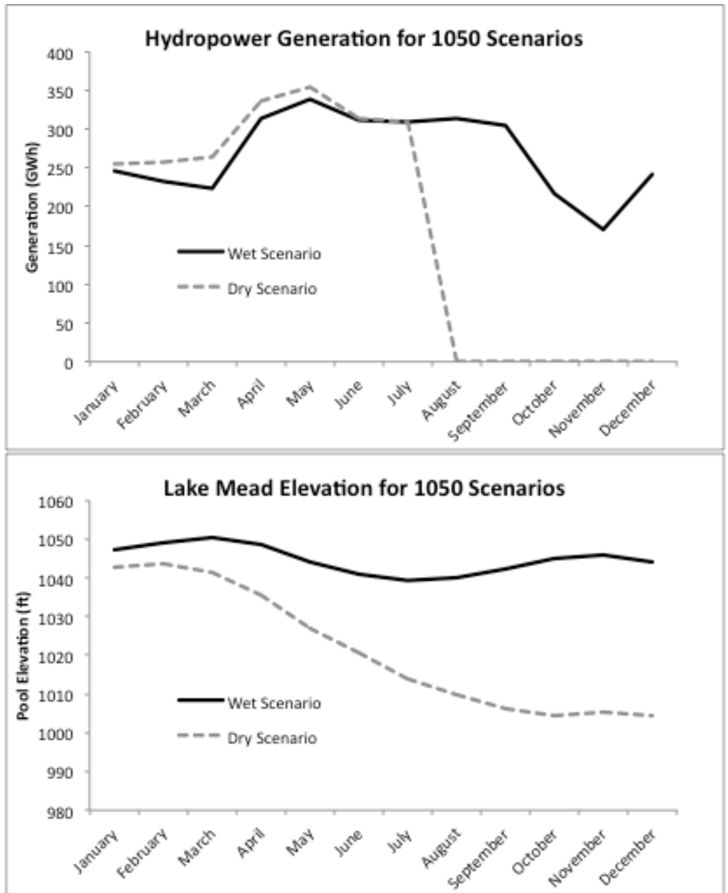

Figure 21: Hydropower generation and Surface elevation in Lake Mead for wet and dry scenarios at 1050'

The importance of climatic conditions in the economic viability of hydropower generation is illustrated through use of wet and dry scenarios to simulate the different trends in total costs and combined unit price value changes between elevations. The wet scenario, designed to mimic high precipitation and runoff inputs, represent stable, albeit lower reservoir levels. Conversely, the dry scenarios, designed to mimic low amounts of precipitation and runoff, represent reservoir levels still in decline (Figure 21).

Finally, wet and dry scenarios indicate the existence of threshold conditions in the Basin, beyond which it is not economically efficient to continue operating Hoover Powerplant. At 1,025' At this point contractors' shared costs of producing hydropower are greater than the cost of purchasing energy from the spot market. Contractors would financially benefit by switching entirely to spot market purchases, but are unable to do so because they are contractually bound to continue purchasing Hoover hydropower for the duration of their contract, until 2067 (Simonton 2015).

The threshold conditions are a function of the starting reservoir level, the ensuing climate regime, and spot market prices. In this analysis, the threshold occurs when Lake Mead starts at 1,025' in a year with low rainfall and runoff. At 1,025' in this scenario, the unit price of WAPA hydropower is $72/MWh, whereas the most expensive spot market unit price (SP15) is only $56/MWh (Figure 15). Where the threshold occurs is conditional, and will change annually dependent on variation in spot market prices and climatic conditions.

Furthermore, 1,000’ contractors are still contractually bound to pay their portion of Hoover Dam operations despite hydropower production no longer being physically possible. The unit price of hydropower is unique for each contractor and equals the total amount of a contractor’s annual financial responsibility delineated in its WAPA contract (i.e. the total cost of hydropower at each elevation--Table 6). Despite being bound to continued payments for hydropower, contractors must also purchase the full amount of its original allocation from the spot market for the price of $56/MWh in the case of SP15. Therefore, contractors total costs at 1,000 are total costs of hydropower plus the unit price of spot market energy multiplied by the amount of their original allocation.

Implications

To understand the implications of decreasing water levels in Lake Mead in terms of hydropower costs, one must look at the customers buying Hoover hydropower from the energy contractors. The energy contractors considered in this analysis are utility companies and executive agencies that buy spot market energy in order to serve their retail customers. Any costs borne by the energy contractors are automatically passed along to retail customers. It is the residents, municipal, and commercial operators in the towns reliant upon Hoover hydropower who will experience the biggest financial impact of diminishing flows in the Colorado River Basin.

The Arizona Power Authority (APA) and the Colorado River Commission of Nevada (CRC) are entities specifically formed to acquire and manage federal hydropower coming from Hoover Dam. Without hydropower production at the Hoover Powerplant, these entities will cease to exist. However, more importantly, the towns and irrigation districts reliant on Hoover hydropower will have to find another source.

For example, Lincoln County Power District No. 1 has contracts for a portion of the hydropower allocated to Nevada. Lincoln Power has relied on Hoover hydropower since 1937, and still almost exclusively relies on it as a power source. When Lincoln needs to supplemental energy they buy spot power through the Silver State Energy Association. The Lincoln Power District spends 50% of its annual operating budget on purchasing power, the single largest cost. In 2014, they purchased 14.3% of the power needs from the spot market (Luttrell 2014). As reservoir levels continue to fall, Lincoln will have purchase increasingly more energy from the spot market, forcing the utility to keep raising electricity rates unless they can find an additional low-cost stabilizing energy source.

Furthermore, Central Arizona Project (CAP) is APA’s largest customer for Hoover hydropower, contracting hydropower through the Central Arizona Water Conservation District (CAWCD). All energy bought by CAWCD is used to pump CAP’s share of water from the Basin uphill to users in central and southern Arizona in order to decrease groundwater overdraft in the state. Losing cheap hydropower from Hoover will increase CAP’s pumping costs, and the cost of CAP water in return. CAP customers claim they will switch back to groundwater pumping if water rates increase, even if just by a small amount. Rough calculations by CAP showed that even a 1 cent per kWh increase in CAP’s electricity costs would increase the cost of each AF of water by 3.5% (McNeill 2012). If CAP customers to switch back to groundwater pumping because of increased water rates, the stress on central Arizona’s groundwater supplies from water curtailments at each key elevation will be further exacerbated.

Similar to CAWCD, the Metropolitan Water District of Southern California (MWD) utilizes their full share of Hoover hydropower to move Colorado River water from Parker Dam through the Colorado Aqueduct to Southern California. If the price of Hoover hydropower increases, and the amount of energy each contractor receives from Hoover decreases, the cost of pumping Colorado River water to Southern

California will increase. MWD uses Colorado River to serve municipal water demand. It is possible that increases in pumping costs will increase consumer water rates in MWD's service area.

As pointed out in the Significance section, the rate of decline in Lake Mead's surface elevation accelerates as it continues to drop. The impact of decreased hydropower generation on contractor costs is contingent on their switching power in the electricity market. While out of the scope of this analysis, the findings raise questions about future energy acquisition behavior of contractors. Will contractors be able to successfully anticipate decreases in hydropower generation with enough time to procure alternative long-term power purchase arrangements? How cost-effective will supplemental long-term power purchase agreements be given climate variability within the Basin? While the hydropower cost model cannot answer these questions, the baseline analysis it provides will be a useful starting point for future investigations.

Recreation

Introduction

The Colorado River Basin is a playground for recreation enthusiasts. The expansive network of rivers, tributaries, mountains and canyons provide opportunities for hiking, camping, watersports, biking, fishing, hunting, wildlife watching and off-road vehicles. The extensive network of public land lures recreationists and supports local and regional economies. Lake Mead National Recreation Area is the sixth most visited National Park unit attracting almost 7 million visitors each year (Lake Mead National Recreation Area 2014).

Yearly recreational expenditures for the whole Colorado River Basin is estimated at $25.6 billion, ranking the Colorado River as the 155th company in the Fortune 500 (Southwick Associates 2012). Recreational visitation at Lake Mead accounts for one percent of those expenditures, with visitors spending $260 million annually in local communities which creates 3,000 jobs (Lake Mead National Recreation Area 2014). Additionally, Lake Mead is the most valuable water recreation area in the Colorado River according *Nature's Value in the Colorado River Basin*, contributing one-third of the total estimated annual water recreation and tourism value (Batker et al. 2014). Changes in Lake Mead elevations impact recreational opportunities and may have detrimental impacts to the local economy.

Recent studies have analyzed the contributions of Lake Mead recreation to the recreation economy, and the Interim Guideline EIS calculated the probability that access points would close, navigation hazards would occur and sport fishing populations would be impacted. But no analyses have determined the specific impacts at each curtailment elevation.

To understand the impact to recreation at Lake Mead National Recreation Area two questions were asked:

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

Recreation is an essential component of a sustainable future for the communities of the Colorado River Basin. The project will determine the potential changes in recreational use at the curtailment elevations in Lake Mead.

Methods

Lake Mead Elevation and Recreational Visitation Correlation

There are two commonly used approaches to determine changes in recreational visitation and the economic value of the recreation industry. User surveys conducted either on site or via phone can be used to assess both visitation and value of recreation at different sites (*Operation of Flaming Gorge Dam Final Environmental Impact Statement: Recreation Visitation and Valuation Analysis Technical Appendix* 2002). While these analyses often provide details on user values and characteristics, they also often ask theoretical questions that require the respondent to predict their future use based on hypothetical changes in reservoir elevation. These stated preference studies are useful but the use of revealed preference analyses, for example analysis of actual visitation and user demographics, provide a more robust foundation for understanding how individuals actual change behavior based on external factors. Since Lake Mead has not dropped to the key elevations, it would have been difficult to conduct a stated preference study about a hypothetical future event. Instead this project sought to statistically correlate recreational use data to Lake Mead elevation and use the correlation to predict visitation at low reservoir levels. A recent study conducted at Lake Mead and Lake Powell empirically correlated reservoir storage volume to recreational use over a 15 year time period during which reservoir levels dropped to 1082.1' (Neher, Duffield, and Patterson 2013). The Neher et al 2013 model was used to project recreational use at the key elevations – 1075', 1050', 1025' and 1000'. Since the model only correlates visitation for elevations as low as 1082', predictions for future lower elevations will be out-of-sample.

Neher et al (2013) correlated storage volume in Lake Mead and Lake Powell to recreational visitation. Lake Mead surface elevations and storage volume are collinear and can therefore be used interchangeably. Neher et al (2013) regressed recreational use on Lake Mead storage volume and monthly indicator variables (Mar-Nov). The months included as indicator variables were based on seasonal variation in recreational use at Lake Mead National Recreation Area. No external economic or social factors were included in the regression.

The Neher et al (2013) model was updated to include more recent data extending the model from 1996-2011 through September of 2014. Monthly recreational use data for Lake Mead National Recreation Area was obtained from the NPS Stats website (*NPS Stats* 2014). Since Lake Mead NRA includes Lake Mohave, only visitation data from Temple Bar, Northshore and Boulder Districts were included. Additionally, all non-recreational visitors were excluded from total monthly visitation. Lake Mead daily storage volume was obtained from the Bureau of Reclamations Lower Colorado River Operations office (*Lower Colorado River Operations* 2014). Monthly averages were based on end of day storage and elevation values

To determine if the revised Neher et al (2013) model would predict monthly visitation at Lake Mead, mean comparisons were performed for a) the whole time period – January 1996 through September 2014; b) the in-sample time period – January 1996 through December 2011; and c) the out-of sample time period – January 2012 through September 2014. Observed and projected monthly visitation were then graphed in excel for revised Neher et al. (2013) model extending through September 2014.

Finally, the revised Neher et al (2013) model was used to predict annual visitation at Lake Mead at each of the key elevations (1075', 1050', 1025' and 1000'). Since the recreation model used monthly Lake Mead volumes, recreational visitation was calculated using monthly reservoir elevations. For each key elevation the monthly reservoir elevations were drawn from the wet scenarios from the hydropower section to provide an upper bound of visitation (Figure 22). Monthly elevation were converted to monthly average storage volume using the US Bureau of Reclamations Lake Mead Area and Capacity Tables (*Lake Mead Area and Capacity Tables* 2011).

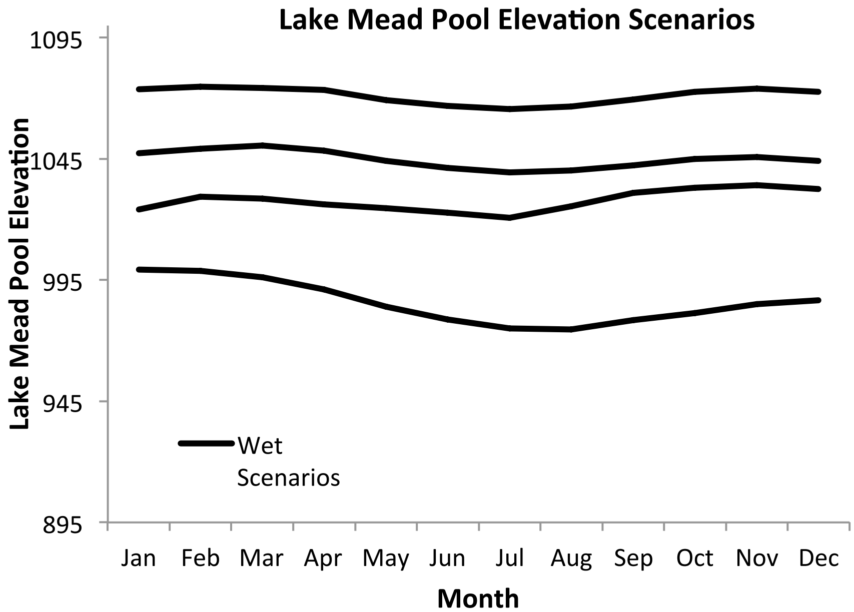

Figure 22: Lake Mead pool elevation scenarios from January through December. Scenarios start at key elevations (1075', 1050', 1025', and 1000') for wet climatic conditions.

Key Public Access Points and Lake Mead Elevation

As reservoir levels decline, access points for water-based recreation are impacted. Lake Mead National Recreation Area maintains a current list of the status of all access points in the National Recreation Area. The December 4th, 2014 status report was used to document the impact of lake elevation on accessibility.

Results and Discussion

Key findings from the recreation analysis include:

1. Recreational visitation is expected to decline from 7 million visitors to 4 million visitors at 1000'.
2. No access points are projected to be operable below 1050' without significant investment by the National Parks Service to move marinas or extend boat ramps.

With a projected loss of approximately half of the annual visitation, Lake Mead National Recreation Area could become economically unviable due to increase maintenance and infrastructure costs.

Lake Mead Storage Volume and Recreational Visitation Correlation

Predictions of recreational visitation from the revised Neher et al (2013) reproduce observed visitation through May 2011. After May 2011, predicted Lake Mead visitation is higher than observed visitation (Figure 23). Statistical analysis revealed that over the whole time period (Jan 1996 – Sep 2014) there was no significant difference between observed and predicted recreational visitation, but over recent years (Jan 2012 – Sept 2014), predicted visitation is significantly greater than observed visitation. This suggests the Neher et al (2013) model over predicts visitation at low lake elevations. The reservoir levels in 2012-2014 did not drop lower than the previous sample period (1996-2011) and the standard error between the observed and predicted visitation is not correlated to reservoir elevation. This suggests there are other factors influencing visitation decline in recent years such as the economy or media coverage of dropping reservoir levels. Given this error, any future predictions using the revised Neher et al (2013) model should be used as an upper bound of recreational use at lower Lake Mead elevations.

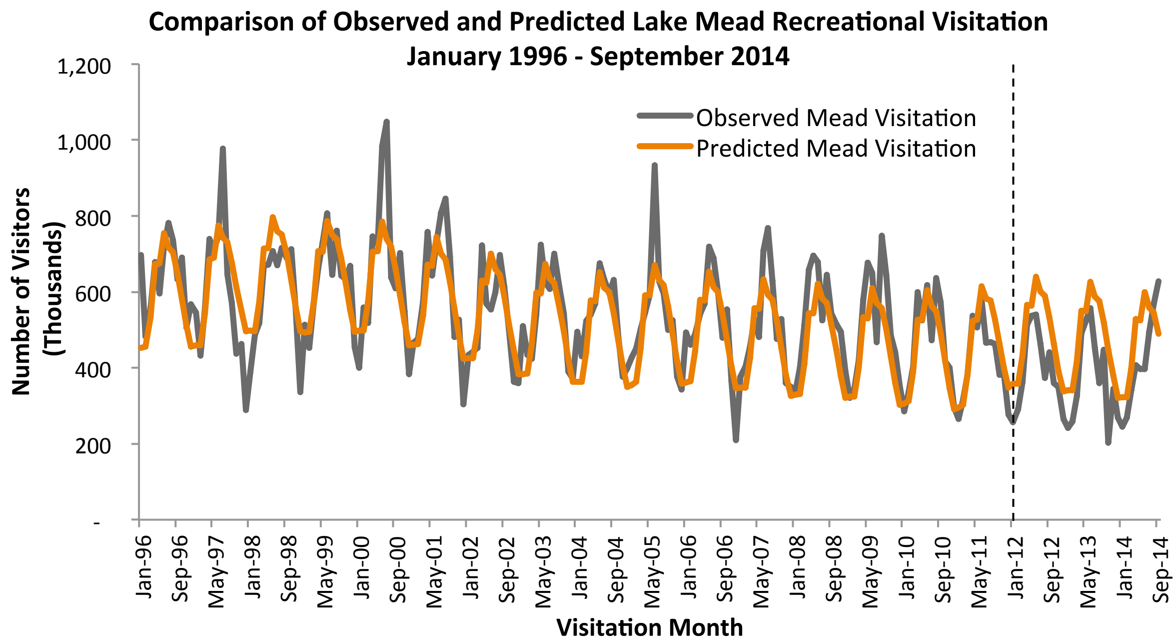

Figure 23: Observed (grey) and predicted (orange) Lake Mead recreational visitation January 1996 – September 2014. The revised Neher et al (2013) model correlated Lake Mead volume to recreational visitation from January 1996 through December 2011 (left of dashed line). The model was extended through September 2014 with more recent data (right of dashed line).

A summary of the revised Neher et al (2013) with the more recent data including the regression coefficients and statistics are summarized in (Table 8)

Table 8. Lake Mead estimated recreational visitation model using data from 1996 through September 2014, adapted from Neher et al. (2013). R-squared is 0.66 with a sample of 225.

Variable	Coefficient (Standard Error)	t value	Pr(>|t|)	
Intercept	149800 (23720)	6.318	1.51E-09	***
Lake Mead Volume	0.01388 (0.001206)	11.504	2.00E-16	***
March	78990 (23430)	3.372	0.000887	***
April	218000 (23430)	9.306	2.00E-16	***
May	222300 (23430)	9.485	2.00E-16	***
June	304300 (23440)	12.981	2.00E-16	***
July	267800 (23450)	11.42	2.00E-16	***
August	255300 (23450)	10.886	2.00E-16	***
September	199100 (23450)	8.489	3.49E-15	***
October	129200 (23910)	5.404	1.73E-07	***
November	59000 (23910)	2.467	0.014403	*

--- Significance codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.'

The revised Neher et al (2013) model was used to predict annual visitation using monthly reservoir levels from the wet scenarios for each of the key elevations (Figure 24). Model predictions were not adjusted. Projected recreational use doesn't drop below four million visitors per year even when Lake Mead is at 1000' and must be used as an upper bound in estimating visitation (Table 9).

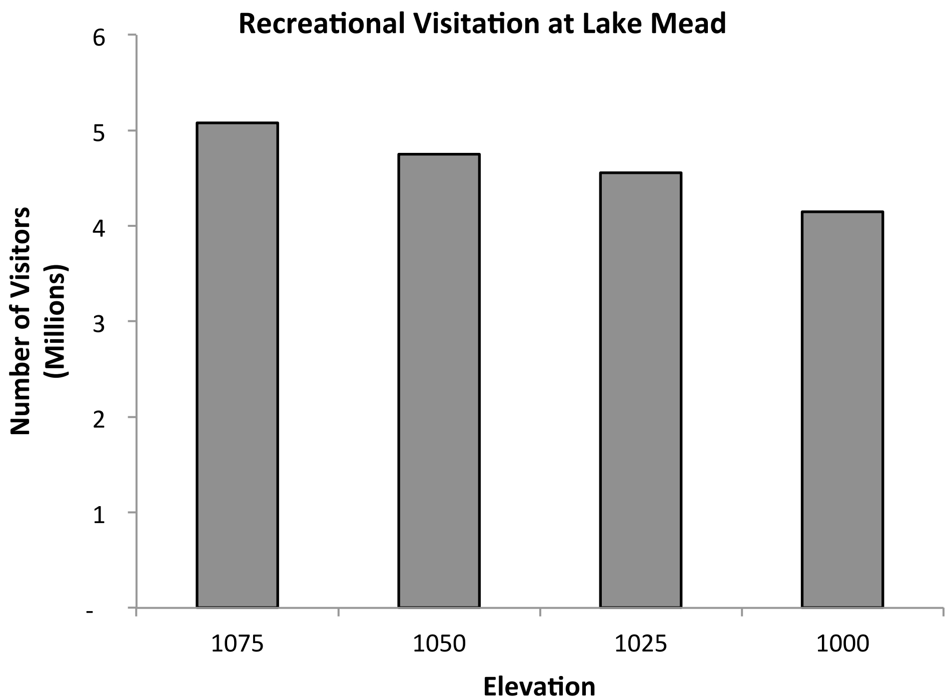

Figure 24: Predicted Lake Mead Visitation for each key elevation for the wet scenarios from the hydropower analysis.

Table 9: Predicted Recreational Visitation at Lake Mead based on storage volume by year with average monthly lake elevation.

Elevation	Predicted Visitation (Wet Scenario)
1,075	5,078,599
1,050	4,749,713
1,025	4,557,128
1,000	4,149,930

Recreational visitation at Lake Mead National Recreation Area has been declining since 1996. The regression analysis revised from Neher et al (2013) correlates declines in reservoir levels with declines in recreational use. In more recent years, since January 2012, declines in Lake Mead visitation may be due to factors other than lake elevation since the model statistically over predicts visitation. National economic conditions and negative media coverage could be deterring visitation at Lake Mead. Based on the model, predicted visitation for the key elevations doesn't drop below 4 million visitors a year. As stated previously, the visitation predictions are an upper bound for future low reservoir levels.

Declines in visitation will also impact the local economy. A variety of businesses depend on Lake Mead visitors including eight concessions operations, 125 small business and dozens of event planners in the local area. Jobs from Lake Mead recreational visitors exceed 3,000 and visitors spend $260 million in the local community. Each visitor spends around $95 (2013$) per visit (Duffield, Neher, and Patterson 2007), therefore, declines in visitation will negatively impact the local economy and reduce jobs. The total annual economic loss due to decreased visitation could be as great as $280,098,009 (calculated based on projected visitation at 1000’).

Key Public Access Points and Lake Mead Elevation

Lake Mead National Recreation Area has invested $36 million in improving access point around the reservoir as reservoir levels have declined. Lowering reservoir levels impact launch ramps, parking areas, utilities, docks, as well as on water navigational aids. Specifically, around 60 feet of new shoreline is created with a 2 foot elevation drop, which requires National Recreation Area staff to: remove debris from boat ramps, install pipe mat, extend cables and move anchors and courtesy docks, grade beaches, move land-based floating sanitation facilities, and mark new hazards. This not only impacts National Recreation Area staff, but also the eight concessions operations (Lake Mead National Recreation Area 2014). The current status of different ramps and marinas are detailed in Table 10.

Table 10: Minimum Lake Mead reservoir levels required for key shoreline public use facilities (Lake Mead National Recreation Area, 2014)

Location	Reference Value (feet msl)	Status	Date
Pearce Bay Boat Ramp and Ferry			
Government Wash Ramp		Closed	2001
Las Vegas Bay Marina		Moved	2002
Las Vegas Bay Ramp		Closed	2003
Lake Mead Marina		Moved	2007
Overton Beach Marina		Moved	2007
Overton Boat Ramp		Closed	2010
Echo Bay Boat Marina		Closed	2013
Echo Bay Main Ramp		Closed	2014
Callville Bay Main Ramp		Closed	2014
Hemenway Harbor Ramp	1082’ (temp)	Open	Completed 2014
Temple Bar Ramp	1080’ (temp)	Open	Completed 2014
South Cove Ramp	1080’ (temp)	Open	Completed 2014
Callville Bay Secondary Ramp	1079’	TBC	To be Completed 2015
Echo Bay Secondary Ramp	1078’	TBC	To be Completed 2015
Boulder Harbor	1060’	TBD	TBD

The model predictions for future visitation at Lake Mead do not account for potential impact of lowering reservoir levels on access points throughout the National Recreation Area. Every 10-foot drop in elevation corresponds to 300 feet of new shoreline. As reservoir levels decline access ramps and marinas have to be extended or moved. Between 2002 and 2012, the National Park Services invested $36 million to improve access as reservoir levels declined and they have budgeted an additional $5 million for additional improvements. Adapting to yearly changes in reservoir levels will continually require funding to adapt access points, but low water is proving to be a significant expense to the National Park Service. Additionally, based on planed improvements, all access points will be inoperable at reservoir level 1060’ without further modification (Figure 25).

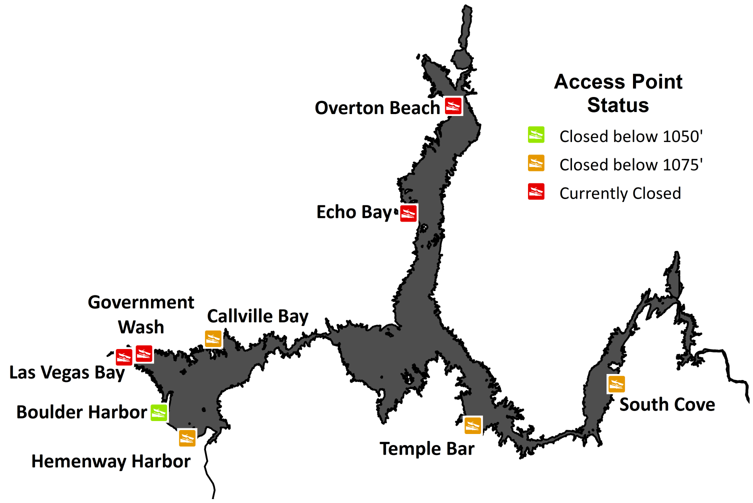

Figure 25: Predicted operability of access points on Lake Mead as reservoir levels decline.

Lowering reservoirs levels negatively impact visitation, reduce the number of accessible boat ramps and marinas and negatively impact the local economy overall. Decreased visitation will decrease revenues of Lake Mead National Recreation Area as costs of operations increase to accommodate low reservoir levels. There may be a threshold at which point the costs of operations at Lake Mead National Recreation Area will exceed the National Park Service revenues. Additionally, the local business that support the recreation economy may become less profitable and be forced to close due to declines in visitation. As reservoir levels decline to unprecedented levels, the recreation industry will have to adapt.

Across the Basin

Lake Mead National Recreation Area provides over one-third of the economic and tourism value in the Colorado River Basin due to its proximity to the major metropolitan center of Las Vegas. More than 125 small businesses depend on the recreation industry at Lake Mead and create 3,000 local jobs. As reservoir surface elevation drops, the recreational visitation was projected to drop to less than four million visitors, a loss in one million visitors between 1075’ and 1000’. The National Park Service has invested $36 million to date in moving marinas, and extending boat ramps. In 2015, the National Park Service plans to spend an additional $5 million. Despite this no access points are projected to be operable below 1050’ without additional investment. The loss in visitation combined with the continual maintenance investment required to maintain access points could make the National Recreation Area economically unviable in the future.

Environment

Introduction

The 1,450 miles of Colorado River originates in the Rocky Mountains, and flows through seven U.S. states, reaching the Sea of Cortez in Northern Mexico to form the Colorado River Delta (Triedman 2012). Decades of human development on the river have drastically changed the hydrology. The Colorado River ecosystem downstream of Hoover Dam is a now highly altered ecosystem (Adler 2007). Instead of natural river corridor, the system functions more as a water conveyance and delivery system than a river. Every drop of water is allocated to human needs leaving environmental concerns as the lowest priority in the river's operation. No instream flow requirements exist below Hoover Dam for beneficial use for the environment. The amount of water in the Lower Colorado River is determined by water needs of the Lower Basin states, and thus by the water released from the dams. As the surface elevation of Lake Mead drops, there may be impacts to the Lower Colorado River corridor downstream of Hoover Dam.

The Interim Guidelines Environmental Impact Statement discussed possible environmental impacts of the curtailments for each of the alternatives analyzed, assuming that the curtailments Interim Guideline are in effect between 2008 and 2016. It also assumed that Mexico would share the shortages proportionally (16%) with its delivery, higher than what's outlined in Minute 319 (13%). Probable reservoir level, water releases from dams, and consequential environmental impacts downstream of Lake Mead are modeled over the time frame of 2008 to 2060 on a probabilistic basis, given the curtailment operation and past hydrological fluctuations. However, it did not discuss the environmental impacts at each key elevation. Nor did it address potential environmental impacts on the Colorado River Delta, the economic impacts of salinity, or the impact to funding of key environmental programs.

To address these knowledge gaps, the following questions were asked:

1. How will water delivery curtailments impact ecosystem in the Lower Colorado River below Hoover Dam and the Colorado River Delta?
2. What are the impacts to water quality, specifically, salinity in the Lower Colorado River Basin?
3. How will funding to environmental programs be affected by reductions in hydropower revenues?

Through literature review, expert interview, and analyses based on results from Water Supply and Hydropower sections, key findings from this section include:

1. No direct relationship between Lake Mead water levels and downstream riparian ecosystem has been demonstrated in literature, and the effects are hard to predict. However, water security for one of the Lower Colorado River Multi-Species Conservation Program's restoration projects may be threatened if curtailments take place. For the Colorado River Delta, less agricultural runoff will be available during shortages, threatening the survival of the riparian zone and the off-channel wetlands.
2. Salinity in the Lower Colorado Basin will be maintained below the EPA-set salinity standards. Economic costs of salinity treatment will be higher, however.
3. Funding for Lower Colorado River Multi-Species Conservation Program will not be affected, while funding for the Salinity Control Program will be threatened as reservoir level declines and less hydropower is produced.

Effects on Ecosystems below Hoover Dam

Lower Colorado River Riparian Corridor within the US

Historically erratic and strong flows of the Colorado River created a rich ecosystem. Periodic flooding brought rich nutrients and accumulated organic sediments leading to diverse and lush vegetation. Native cottonwood and willows lined the Colorado River Corridor (Adler 2007). Riparian vegetation provides important feeding and breeding habitats for a wide variety of wildlife, especially in intensively farmed areas (Triedman, 2012).

The natural processes that formed the ecological diversity and stability have been significantly altered and degraded as a result of dams, diversions, invasive species, and flow depletion. The Colorado's once seasonal, erratic flows are now intercepted and controlled by the numerous dams sprinkled throughout the basin. Water discharged downstream of the dams is unnaturally clear and cold, changing hydrologic conditions that aquatic species had adapted to over a long evolutionary history (Triedman, 2012). Instream flows have declined drastically. Nutrient-rich sediment settles behind the dam. Plant and animals species relying on a healthy riparian zone to prosper are also threatened (Adler 2007).

Native riparian vegetation has been severely reduced. The once dominant, almost exclusive woody riparian tree species, native cottonwood and willows now collapsed to a 1% of the vegetation of the riparian zone above Morelos Dam (Glenn et al. 2008). These trees germinate during spring floods. Sediment deposited by flowing water provides areas for seedling recruitment. After germination, the young trees depend on shallow groundwater for continued growth. In the arid and semi-arid West, groundwater is fed by streamflow during dry seasons (Rood, Braatne, and Hughes 2003). Decreased river flow has lowered the groundwater table out of cottonwood and willow roots' shallow reach (Rood, Braatne, and Hughes 2003). Salinity increase in the river as a result of human uses further limits the growth the these salinity-sensitive species (Tomaso 1998).

Meanwhile, these new conditions favor non-native species proliferation. Invasive species such as Tamarisk and Ravenna Grass outcompeted native species and dominate the river corridor. Tamarisk's extensive root system helps it survive in limited groundwater conditions, outcompeting the drought-sensitive native willow and cottonwoods (Shafroth 2006). Tamarisk is also adapted to germinate and live in highly saline soils and to secrete salt and further increase salinity in the surrounding soil (Tomaso 1998).

Wildlife depends on riparian vegetation to forage and breed. The decline of endangered and threatened bird species population (e.g. Southwestern Willow Flycatcher and Yellowbilled Cockoo) are mainly attributed to the loss and degradation of the river's riparian cottonwood and willow ("Sonoran Yellow Warbler" 2014). However, some migratory avian species, having lost important migratory stopovers along the Colorado River Corridor, have adapted to the new hydrologic regime. Dams created more still water and vegetation for migratory birds. In Lake Mead National Recreation Area, many migratory bird species have prospered in the artificial lake (United States National Park Service 2014)(United States National Park Service, 2014b).

As hydrology of the river was altered, four out of fourteen native fish species in the Colorado River are on the Federal Endangered Species list: the Colorado pikeminnow (*Ptychocheilus lucius*), bonytail chub (*Gila elegans*), humpback chub (*Gila cypha*), and razorback sucker (*Xyrauchen texanus*). While each species has unique needs, they all are adapted to the river's natural silty conditions and varying water temperatures, and are dependent on hydrological patterns such as heavy spring flows, all of which have been significantly altered by human management (Triedman 2012). The cold and clear water coming out of the dam favor introduced fish species such as rainbow trout, which created a proliferous sports fishing industry at Lake Mead. Introduced species outcompete native fish species and have become a major contributor to the decline of native species (Defenders of Wildlife 2011).

Relationship to Lower Reservoir Level

As decades of human activities have highly altered the natural riparian corridor, it is difficult to differentiate the effects of declining reservoir level in Lake Mead on the ecosystem and that of ongoing anthropogenic developments. There is little evidence to show whether and how further decline in water levels will affect the ecosystem (Flessa 2015; Schmidt 2014). As curtailments occur, less water will be transported down the river corridor. However, the river still needs to fulfill its water delivery obligations to the Lower Basin states and Mexico, guaranteeing a fixed amount of water in the system. Delivery volumes (MAF), or the least amount of water that will pass through the river corridor between diversion points, were calculated based on the Interim Guideline and Minute 319, a binational agreement between the US and Mexico to share shortages. As shown in Table 11, the volumes of curtailments are small compared to the total delivery quantities. A large quantity of water will continue to pass through the water conveyance system. In addition, this range of reduction in flow is well covered by the Lower Colorado River Multi-Species Conservation Program, which will mitigates potential impacts of reduced flow (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007).

Table 11: Amount of water passing through the Lower Colorado River Corridor at each Key elevation in Lake Mead

	Hoover Dam to Parker Dam		**Parker Dam to Morelos Dam**		**Below Morelos Dam**	
Key elevation	**Delivery (maf)**	**% reduction**	**Delivery (maf)**	**% reduction**	**Delivery (maf)**	**% reduction**
Baseline	8.78	NA	7.8	NA	1.5	NA
1075'	8.41	4.21	7.7	1.28	1.45	3.33
1050'	8.305	5.41	7.65	1.92	1.425	5.00
1025'	8.175	6.89	7.55	3.21	1.375	8.33

Although the exact environmental impacts at each key elevation are unknown, the Interim Guidelines EIS predicted no or minor impacts on the environment as the probabilistic outcomes of the curtailment approach as a whole (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007). The Lake Mead National Recreation Area might be negatively affected as reservoir level drops. Shoreline vegetation will change composition as less water is available (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007). As migratory birds in the Lake Mead National Recreation area highly depend on shoreline vegetation, shoreline habitat change can affect bird populations. In Lake Mead, there would be no adverse effects on dissolved oxygen or the concentrations of phosphorus and other nutrients in Lake Mead even if it drops to 1000'. Additionally, the ability of Lake Mead to dilute contaminant loading from Las Vegas also would not be significantly affected down to 1000' (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007).

Water temperature also rises as lake levels drop due to a declining reservoir levels and global climate change (Backlund, Janetos, and Schimel 2008). Warmer water negatively affects introduced sports fish species that favor cooler waters, which has already greatly hindered sports fishing in the lake (Cook 2013) and can become worse as reservoir levels draw even lower. However, warmer water also allows for earlier reproduction and may be beneficial for introduced species (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007).

Along the riparian corridor, groundwater level is expected to decline no more than 0.5 feet between 2008 and 2060, which will put stress on the dwindling native vegetation but not to a significant degree (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007). It's expected to have minimal negative effects on the invasive species (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007). No environmental change is expected between Hoover Dam and Davis Dam, or between Lake Havasu and Parker Dam because Lake Mohave and Lake Havasu are operated to meet a monthly elevation targets. If the reservoir operations do not change, there will be no expected environmental changes within those two reaches (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007). Between Davis Dam and Lake Havasu, and between Parker and Imperial Dam, however, endangered fish species may be negatively impacted as dam releases decline. Spawning and rearing habitats of Razorback sucker and bonytail in those reaches will be adversely affected as river flow is reduced, although not to a significant degree (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007).

Water security for Lower Colorado River Multi-Species Conservation Program (LCR MSCP)

As reservoir level declines, water security to LCR MSCP restoration projects may be affected by water delivery curtailments. To balance lower basin water needs and conservation of critical habitat and endangered species to comply with the Endangered Species Act, the Bureau of Reclamation and agencies within the Lower Colorado River Basin developed and implemented the LCR MSCP in 2005, with help from the U.S. Fish and Wildlife Service ("LCR Multi-Species Conservation Program - History" 2014). The program is designed to restore riparian, marsh, and backwater habitats for at least 26 species of fish, bird, bats amphibians, insects, reptiles, rodents and plants. Threatened or endangered species include: bonytail chub, humpback chub, razorback sucker, Yuma clapper tail, desert tortoise, and the southwestern willow flycatcher ("LCR Multi-Species Conservation Program - History" 2014).

LCR MSCP emphasizes creating off-channel restoration sites for native vegetation (McClurg 2005). Restoring natural river flow is difficult due to the operation of the river, and there is no minimum in-streamflow requirement below Hoover Dam. Habitat creation mainly entails converting agricultural fields to natural habitat, but since the restoration sites are off-channel, nearly constant irrigation is required. Long-term vegetation survival and regeneration may occur without irrigation, but in the short-term irrigation is required. The MSCP acquires or leases water rights for their restoration sites. Therefore, water used for irrigating restoration sites is the only quantifiable required MSCP water. MSCP has been able to secure more than 84,000 AF of water per year for habitat restoration (Table 12) (Lower Colorado River Multi-Species Conservation Program 2010; 2011b; 2011a; 2012b; 2012c; 2012d; 2012a).

When curtailments occur, water rights to the Cibola Valley Conservation Area could be curtailed (

Table 12). The Conservation Area receives water from 4th priority Arizona Game and Fish Department and BOR as well as leased water from Mojave County Water Authority in Arizona (4th-6th priority). When these lower priority Arizona water right holders face curtailments during shortages, the Cibola Valley Conservation Area will lose this water source. However, as LCR MSCP covers flow reductions due to implementations of curtailments in the Basin, and BOR is committed to offset any negative impacts identified in the EIS, it's likely that BOR will find alternative water source to replenish the lost water sources (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007). The other restoration projects receive water from Federal Reserve water right holders (i.e. National Wildlife Refuges), or from high priority right holders in irrigation districts in California, whose water sources will be retained during shortages.

Table 12: Amount of water dedicated to habitat restoration by LCR MSCP (Lower Colorado River Multi-Species Conservation Program 2010; 2011b; 2011a; 2012b; 2012c; 2012d; 2012a).

Project	**Water Use (AF)**	**Water Source**	**Curtailment**
Cibola Valley Conservation and Wildlife Area	2400	Receives water from 4th priority Arizona Game and Fish Department and Bureau of Reclamation as well as leased water from Mojave County Water Authority, Arizona (4-6th priority).	Yes
Beal Lake Conservation District	1313	Receives water from Havasu National Wildlife Reserve that has a right of 37,337 AF of annual consumptive use	No
Cibola National Wildlife Refuge Unit 1	5400	Part of the Cibola National Wildlife refuge that has a right of 27,000 AF, 16,793 AF of which is consumptive use	No
Hart Mine Marsh	1843	Part of the Cibola National Wildlife refuge that has a right of 27,000 AF, 16,793 of which is consumptive use	No
Imperial Ponds Conservation Area	1133	Part of the Imperial National Wildlife refuge that has a right of 28,000 AF, 23,000 AF of which is consumptive use	No
Laguna Division Conservation Area	72,000	Water is available for the purpose of habitat restoration based on interpretation item numbers 10 and 11 of the LCR MSCP Water Accounting Agreement, which was signed in March 2010 (LCR MSCP)	No
Palo Verde Ecological Reserve	96	Water is purchased by California Department of Fish and Game from Palo Verde Irrigation District	No
TOTAL WATER USE	**84,185.00**		

Colorado River Delta in Mexico

Although there is not a clear linkage between Lake Mead levels and the lower Colorado River riparian ecosystem in the U.S., declining reservoir levels will influence the Colorado River Delta ecosystem, mainly through alternations in irrigation runoff. Historically the Delta received 14 million acre-feet of freshwater from Basin. This natural water input was almost entirely stopped after human development of the Colorado River basin, and the Delta has shrunk to 10% of its original size, now comprising of dispatched wetlands and riparian habitat (Cohn 2004; Zamora-Arroyo et al. 2005). Agricultural drainage from the U.S. or Mexico sustains the remaining Delta ecosystem (Flessa 2015; Zamora-Arroyo et al. 2005). Loss of irrigation runoff will be detrimental to those ecosystems.

In November 2012, the U.S. and Mexico sections of the International Boundary and Water Commissions signed *Minute 319 to the 1944 Treaty with Mexico in order to promote sustainable use of Colorado River for both countries*. This historic binational agreement allows the U.S. and Mexico to share shortage risks and surplus benefits (Table 11). As Mexico shares shortages with the U.S., less water is delivered down the river corridor per shortage sharing guideline. Irrigation runoff will decrease as a result, although the exact quantity in reduction cannot be calculated at the moment.

Delta habitats and agricultural runoff

The main water source feeding the remaining habitats in the Delta is irrigation return flow and is therefore not secure (Schuster and Colby 2013; Zamora-Arroyo et al. 2005). Waters delivered downstream from Morelos Dam is used for irrigation in Mexicali valley ("Colorado River Boundary Section" 2015; Schuster and Colby 2013). Shortage sharing, irrigation efficiency improvements, and agriculture to urban water transfer will decrease irrigation runoff (Schuster and Colby 2013; Zamora-Arroyo et al. 2005). Those habitats sustained by irrigation runoff will be in danger of drying out. Plant and animal species that rely on those habitats will diminish as a result. The main conservation sites that will be affected are the Riparian zone, Rio Hardy Corridor, and El Indio wetland.

The first 60 miles of Colorado River downstream from Morelos Dam forms the Riparian zone. This segment of the river is geomorphogically natural. Although confined between agricultural levees, the river channel is narrow and meanders freely (Zamora-Arroyo et al. 2005). The floodplain within the levees experienced periodic flooding during the high water years in 1980s and 1990s, which temporarily helped the Delta recover. These flood flows have not occurred during the recent drought (Cohn 2004). Nevertheless, the riparian zone below Morelos Dam has maintained a more natural ecosystem than the portion of Colorado River in the US. Ten percent of the flora here is made up by native trees (Glenn et al. 2008). Thirty percent of the riparian zone was characterized as cottonwood-willow habitat (i.e. greater than 10% of vegetation is comprised of cottonwood and willow), compared with only 5% above Morelos Dam (Zamora-Arroyo et al. 2005). Abundance of native trees and surface water positively correlate with diversity and abundance of bird species, both resident and migratory. All birds appear to favor cottonwood and willow dominated areas, with a diversity of understory vegetation types. In the absence of significant instream flow, agricultural drainage water in Mexico replenishes the shallow groundwater and sustains riparian vegetation (Zamora-Arroyo et al. 2005), although the exact quantity has not been recorded.

Similarly, two other important priority conservation areas, Rio Hardy Corridor and EI Indio wetland are also supported by irrigation return flow from Mexico. Rio Hardy River Corridor is supplied by 6,000 - 11,000 acre-feet of agricultural drainage water annually. As it is disconnected with the mainstem of the river, current flow of the river varies with irrigation patterns and the viability of the conservation area depends on the availability of irrigation runoff (Zamora-Arroyo et al. 2005). El Indio wetland, an off-channel wetland, is sustained only by irrigation runoff. It receives a monthly flow of 14-22 cfs of irrigation return water collected from most of the San Luis Valley (Zamora-Arroyo et al. 2005).

Loss of agricultural irrigation runoff during water shortages has been identified as one of the major threats to the survival of the current Delta ecosystem (Zamora-Arroyo et al. 2005). Although not discussed in the Water Supply section of the report, shortage sharing prompted by Minute 319 will reduce agricultural return flows that currently feed the remaining Delta habitats. The amount of curtailments to Mexico may seem small compared to the 1.5 million acre-feet allocation (Table 11). However, the fact that current agricultural demand of water already greatly exceeds supply, together with a growing demand of urban water uses, agricultural intensification, and irrigation efficiency improvements, will reduce irrigation water runoff (Schuster and Colby 2013; Zamora-Arroyo et al. 2005). As a result, the riparian zone and wetlands supported by agricultural runoff will lose their water inputs and dry out.

Effects on Salinity

Salinity is the most pressing water quality problem in the Basin, posing significant social and economic risks. Salt concentration in the basin naturally increases as flow decreases. Salinity control efforts are likely able to keep concentrations under EPA-set water quality standards, which comes with higher economic costs, however.

Salinity refers to the total dissolved solids of calcium, magnesium, sodium, sulfate and chloride. The Colorado River carries about nine million tons of salt per year past Hoover Dam and through the Lower Basin (Colorado River Basin Salinity Control Forum 2014). Half of the salt arriving at Hoover Dam originates from natural sources such as saline springs and rock weathering in the Upper Basin. Anthropogenic sources supply the other half mostly through agricultural return flows (Colorado River Basin Salinity Control Forum 2014). Salt concentration in irrigation return flow increases as additional salt is dissolved from saline soils and as water is lost through evapotranspiration. Municipal and industrial uses of water do not contribute to the salinity problem significantly and account for 4% of the total salt load in the river (Triedman 2012; Bureau of Reclamation 2013).

Diversions cause flows to cumulatively decrease down the course of the river. With less water volume to dilute the salt, more salt gets picked up along the way, increasing salinity from the headwaters to the extremities (Figure 26).

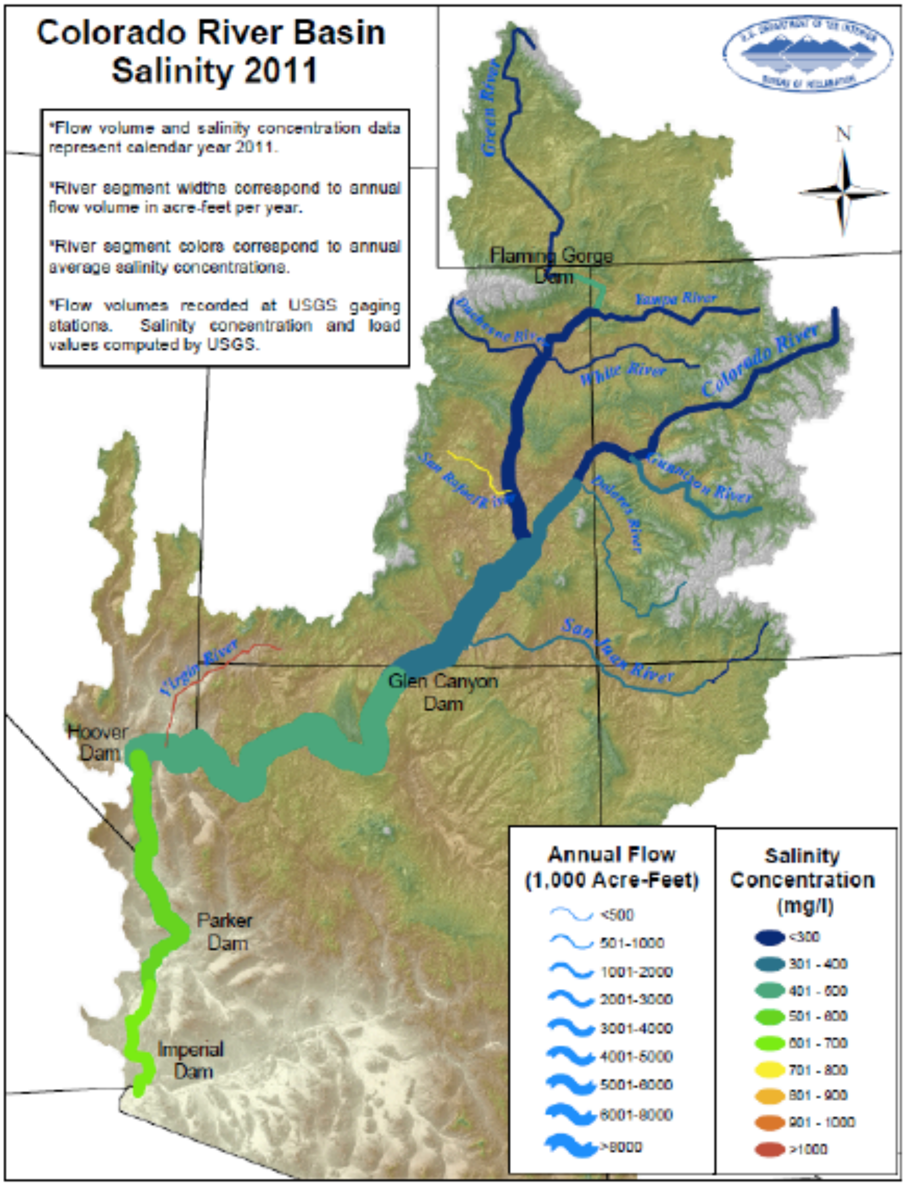

Figure 26: Generalized Flow and Salinity Concentration across the Colorado River Basin (Colorado River Basin Salinity Control Forum 2014).

High salinity causes significant economic damages to all Colorado River water users. High-value fruit and vegetables are sensitive to salinity changes in soil. Leaching is needed to maintain root zone salinity level in fields irrigated with Colorado River water (Oster, Hoffman, and Robinson 1984). Salt corrodes pipes for agricultural and municipal uses. Salinity remediation also increases water treatment costs for municipalities (Colorado River Basin Salinity Control Forum 2014). Salinity in the U.S. portion of the Colorado River Basin causes $500-$750 million in damages per year. Though not officially quantified, economic damages to Mexico may exceed $100 million a year (Bureau of Reclamation 2014a).

Different user groups experience the damages to different degrees. A model to estimate economic damages based on 2010 salinity levels showed that more than half of the damages are done due to a reduction in crop yield. Damages due to corrosion, plugging of pipes, and water fixtures in municipal and industry are also large (Figure 27).

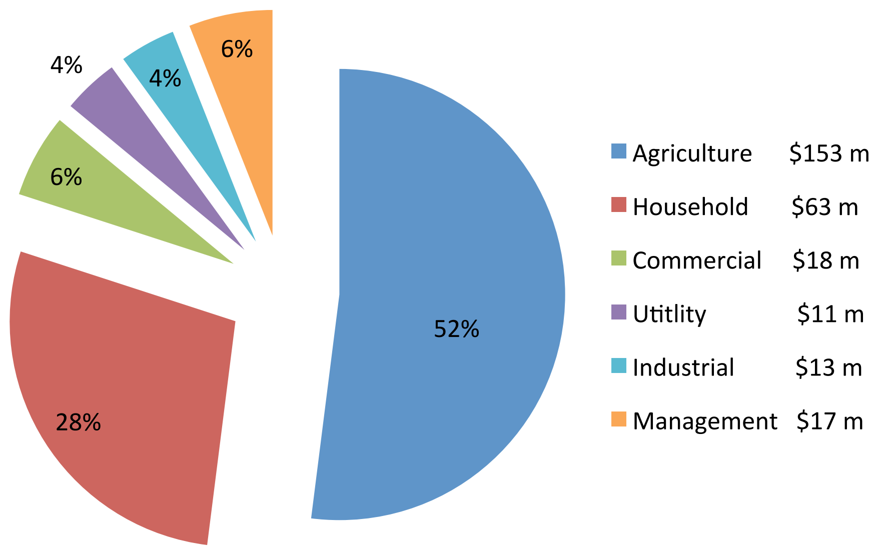

Figure 27: Breakdown of Salinity Damages in the seven Basin States based on 2010 salinity levels (Bureau of Reclamation 2013)

Salinity Control Program

In 1973, the U.S. and Mexico signed Minute No. 242 of the International Boundary and Water Commission, United States and Mexico. Under the agreement the U.S. is responsible to deliver water to Mexico with salinity levels no more than 115 ppm (plus or minus 30 ppm) greater than average annual salinity at Imperial Dam. To fulfill this obligation, the Colorado River Basin Salinity Control Act of 1974 authorized the Secretary of Interior and USDA to place salinity standards and proceed with a program to reduce salinity. The EPA has approved flow-weighted average annual salinity standards at three compact points: 723 ppm below Hoover Dam, 747 ppm at Parker Dam, and 879 ppm at Imperial Dam (Colorado River Basin Salinity Control Forum 2014).

The Act has two main components, Title I and Title II. Title I of the Act ensure that the U.S. complies with provisions of Minute 242 (*Colorado River Basin Salinity Control Act* 1974). The Act authorized the Secretary of Interior to build Coachella Canal lining, Protective and Regulatory pumping, Yuma Desalting Plant, and Wellton-Mohawk Irrigation and Drainage District, all administered by BOR (Colorado River Basin Salinity Control Forum 2014). Title I programs have continued to meet the requirement of Minute 242. However, these programs are capital intensive. For example, Yuma Desalting Plant cost $250 million to install and requires $25 million in annual operation and maintenance (Triedman 2012). It has been on standby since its installation, and is ready to operate if other salinity control strategies fell short.

Title II of the Act authorizes created salinity control programs in the U.S., which initiates projects mostly in the Upper Basin states, controlling salinity at the source with more cost-effective options. The programs are operated by Natural Resource Conservation Service (NRCS, of U.S. Department of Agriculture), Bureau of Reclamation (BOR, of Department of Interior), the Bureau of Land Management (BLM), and state programs (Colorado River Basin Salinity Control Forum, 2014). The Colorado River Basin Salinity Control Forum, in conjunction with the EPA, oversees the programs.

One of the best features of the Title II programs was the Basinwide Salinity Control Program, an integrated program with BOR and USDA. The program combined USDA's on-farm irrigation improvement expertise and BOR's off-farm improvements. Higher salinity reduction efficiency was achieved (Bureau of Reclamation 2013). In 1995, the Basinwide Program started a new way of implementing salinity control. It requests project applications, and funds competitively selected projects for up to 3 years with a maximum of $6 million each (Bureau of Reclamation 2012a). The cost-effectiveness of the Salinity Control Program is impressive. Salinity control costs $20-$100 per ton, while the benefits are estimated at $340 per ton (Bureau of Reclamation 2014a).

The Salinity Control Program reduces salinity by 1.3 million tons per year in the Colorado River (Bureau of Reclamation 2013; United States Department of Agriculture et al. 2011) and have been able to maintain the salinity levels at water quality standards in most years despite a growing water demand (Figure 28).

Relationship to lower reservoir level

A few factors influence salinity in the river system. Precipitation and irrigation dissolve salt from soil and carries it into the river system. During low flows, less salt is leached out from soil, effectively reducing the salt load going into the river. Due to drought and over-allocation of river water, the benefit of lower salinity load is counteracted by less dilution from reduced river flows. Overall, salinity in the basin fluctuates naturally with hydrologic cycles. Salinity increases in dryer years, and decreases in wetter years (Bureau of Reclamation 2013). In the highly developed Colorado River system, this natural fluctuation in salinity is dampened out by reservoirs. Reservoirs retain salinity and reduce its natural variability in the river. During spring runoff, the reservoirs retain the denser, highly saline water in the bottom while routing lower salinity overflow downstream (Bureau of Reclamation 2013).

Due to all the factors stated above, as well as salinity control efforts, salinity levels have not exceeded the EPA numeric standards on the Colorado River during this drought period since 2000 (Figure 28). Salinity concentration at all three compact points showed a downward trend since 2005, despite fluctuations in response to the variation in total Colorado River storage (Bureau of Reclamation 2013) and is not expected to exceed EPA-set Standards (*Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences* 2007).

Even though the Colorado's salinity can be maintained to the EPA standards, economic costs of salinity removal will rise substantially if prolonged drought continues and river levels continue to drop. Water treatment costs will rise as salinity increases with low flow. Utilization of recycled water for both municipal and agricultural use will also become more prevalent as water becomes scarcer (Jacobson 2014). In more extreme cases, if salinity control in the Upper Basin does not meet standards, forcing the Yuma desalting plant into operation, salinity management costs could double (Morford 2014).

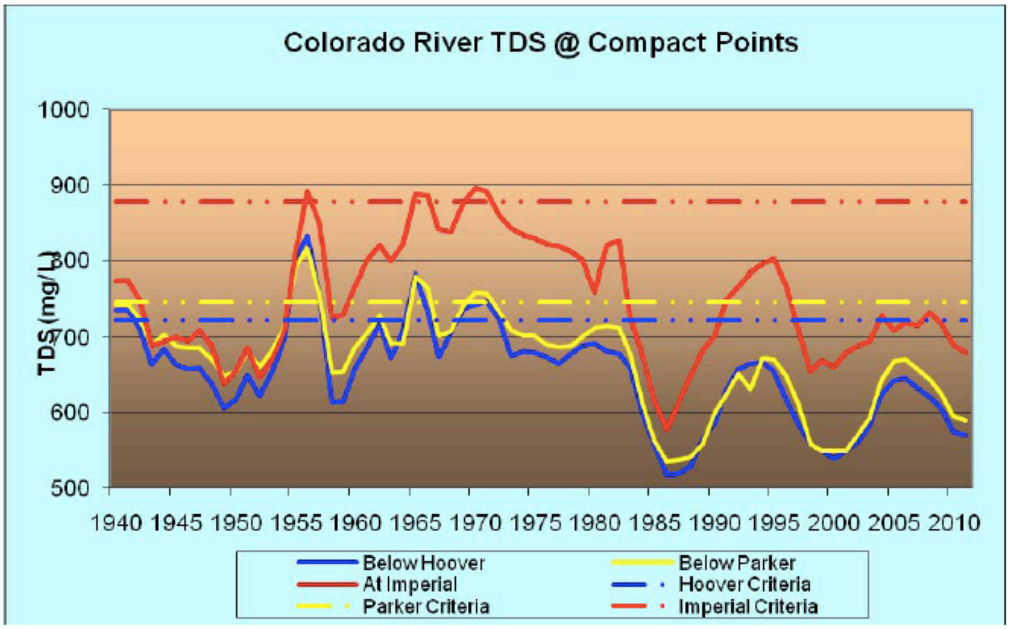

Figure 28: Colorado River Total Dissolved Solid (TDS) levels at Compact Points (Bureau of Reclamation 2013).

Key Environmental Programs and Funding Impacts

Hydropower revenue contributes to the funding to key environmental programs including the Lower Colorado River Multi-Species Collaborative Program (LCR MSCP) and the Salinity Control Program. As lake level declines and hydropower generation decreases, program funding impact depends on program funding mechanisms.

Funding impacts on LCR MSCP

Funding for LCR MSCP is not going to be affected by lower Lake Mead levels. Over its 50-year project life, the estimated program cost is $626 million (in 2002 dollars) with an established funding structure ("Steering Committee - Funding" 2014). An inflationary adjustment is built into funding agreements so cost in current dollars increases each year with projected inflation estimates (Bureau of Reclamation, 2005). The federal government bears 50% of the cost, plus any additional costs of LCR MSCP in excess of the program cost. Federal contributions come from a large pool of funding from Interior agencies and hydropower revenue managed by WAPA (Bureau of Reclamation 2005). The other 50% is shared among California (50%), Nevada (25%), and Arizona (25%). The states pay with quarterly deposits with BOR (Bureau of Reclamation 2005). BOR does not foresee additional increases in cost over and above the project budget adopted in 2005 (Fulp 2014).

Federal cost share is stable. Although hydropower revenue contributes to the federal pool of funding, hydropower contribution does not directly affect federal funding to the LCR MSCP. A decrease in hydropower revenue contribution is made up by other funding sources from the Interior agencies. The federal government has met, and is committed to continue meeting, the federal government's 50% funding obligation because species conservation is a priority in the Lower Basin (Fulp 2014). States are also expected to continue meeting their 50% cost share, as the cost of compliance with the Endangered Species Act is magnitudes higher if the states are not fully committed to the LCR MSCP (Fulp 2014). A summary of the funding structure is shown in (Table 13).

Table 13: Environmental programs funding structure comparison

Program	Total Costs	Agencies	Cost Share	Funding source	Stability
Salinity Control	$34 million/year	BOR, NCRS, BLM	Federal (70%)	Mixed	Decreasing over the years
			States (30%)	Upper Basin Fund (15%) All from hydropower (built-in rate)	Stable
				Lower Basin Development Fund (85%) All from hydropower ($0.0025/kMh)	Unstable
LCR MSCP	$810 million over 50 years	BOR	Federal (50%)	Mixed (partially from hydropower)	Stable
			States (50%)	Mixed	Stable

Funding impacts on Salinity Control Program

The Program has cost about $34 million per year between 1996 and 2011 (United States Department of Agriculture et al. 2011). Federal government covers 70% of the Salinity Control Program's total costs. Program budgets are proposed by agencies and approved yearly by the Congress. Each Program participant (BOR, NRCS, and BLM) is granted funding individually from its parent agency. Budget cuts and other competing BOR projects have made it increasingly difficult to appropriate federal funding to the Salinity Control Program recently (Jacobson 2014).

The Federal government requested 25% cost share from the states when the Salinity Control Act passed (*Colorado River Basin Salinity Control Act* 1974). In 1996, the states cost share was increased to 30%, but has not changed since. Since the Lower Basin states receive the most benefits from salinity control, they are responsible for 85% of state-shared costs, and the Upper Basin covers the other 15% (*Colorado River Basin Salinity Control Act* 1974; Colorado River Basin Salinity Control Forum 2005). Hydropower revenue provides state funding. Glen Canyon Dam and the Flaming Gorge Dam above Lake Mead contribute to the Upper Basin Fund. In the Lower Basin, Hoover Dam, Parker Dam and Davis Dam from Lake Mead and below make up the Lower Colorado River Basin Development Fund.

The Upper Basin Fund is managed by Western Area Power Association (WAPA), and generates approximately $180 million annually from hydropower production in the Upper Basin. About $2 million annually is spent on salinity control ("Upper Colorado River Basin Fund - Reclamation, Upper Colorado Region" 2014). Hydropower revenue contribution to Salinity Control Program is not expected to fall short in the near future. Although not discussed previously in the Hydropower Section of the report as the Upper Basin is out of the geographic scope of our project, WAPA sets firm power rates to pay for all the programs for which the Upper Basin Fund is responsible, including operation and maintenance of hydropower facilities, as well as environmental programs such as Salinity Control Program (Jacobson 2014).

The Lower Basin Development Fund (LB Fund), on the other hand, is more volatile. For every kWh sold from Hoover, Davis, and Parker dams, $0.0025 is dedicated to the salinity control account. Reduced river flows and water releases have lessened hydropower generation, reducing the amount of funding for salinity control. To date, the LB Fund met its cost-sharing obligations. As the Colorado River continues to decline, however, Lower Basin states are at risk of not being able to meet the cost-sharing obligations. The potential reduction in hydropower production by Davis and Parker dams are out of the scope of our project, but we can calculate the loss of funding due to reduced Hoover hydropower generation, using the hydropower generation model under the dry and wet scenarios at each key elevation from the Hydropower Section of the report. In general, funding gradually decreases as reservoir levels drop (Figure 29). Assuming there is no power generation at 1000', the available funding is reduced to zero. The Lower Basin States are considering how to restructure the funding mechanism to prevent shortfalls to the Salinity Control Program (Jacobson 2014). The summary of the funding structure for Salinity Control program is shown in Table 13.

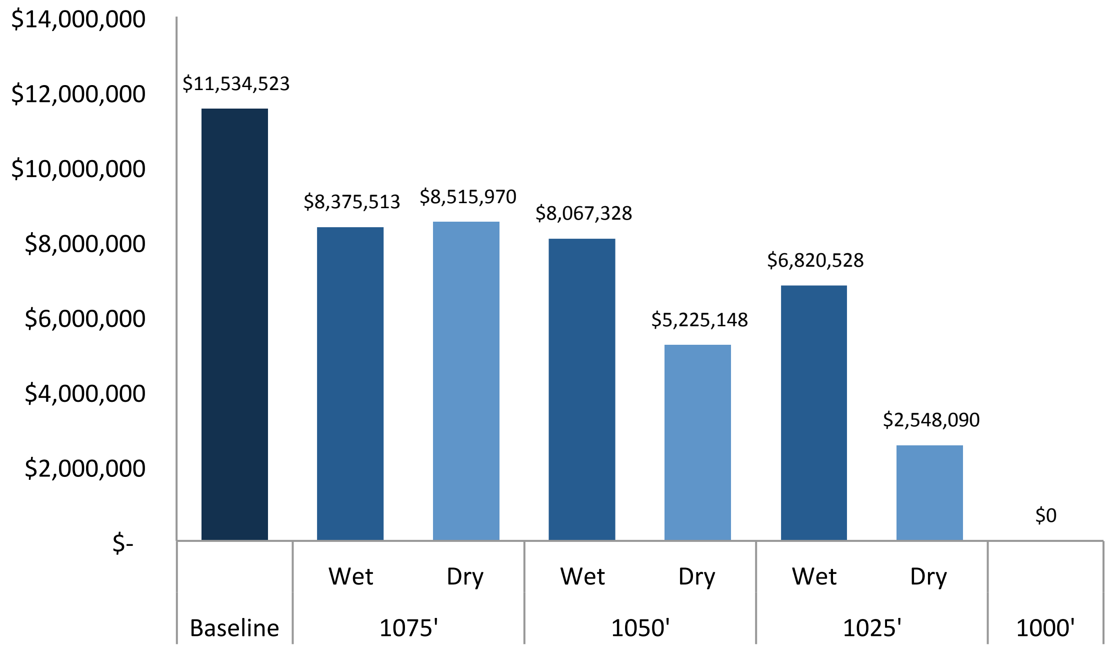

Figure 29: Hoover Dam hydropower's contribution to Salinity Control Program funding at each Key elevation under both Wet and Dry hydropower generation scenarios.

Anticipating future water development in the basins which will lead to more water treatment and recycling, an estimated of 31,000 tons of additional salinity needs to be removed each year to maintain the salinity standards. The Program has set the goal to remove 1.85 million tons of salt per year by 2030 and would require more funding (Bureau of Reclamation 2013). BOR alone would need $25 million more per year ($15.5 million federal appropriation and $7.5 million state cost-sharing) (Bureau of Reclamation 2013). This increase in funding is likely to be more difficult as reservoir levels continue to decline.

Across the Basin

It is difficult to isolate effects of declining Lake Mead levels on the ecosystem from that of ongoing human impacts such as damming and diversion. Although less water will move through the Lower Colorado River corridor at each key elevation due to curtailments, the amount of flow reduction is small compared to the water delivery requirements. There is little evidence showing future water shortages will significantly affect the downstream corridor ecosystem.

The link between reservoir levels and the Delta is clearer, through impacts on agricultural runoff. Irrigation runoff is the main source of water for the remaining Delta riparian zone and wetlands. As

Minute 319 allows Mexico to share the shortages with the U.S., less water is delivered to Mexicali agriculture. When agricultural runoff decrease, the wetland and riparian zone it supports will also dry out from reduced water source.

Salinity is likely to stay stable due to salinity control efforts and the retention function of the reservoirs. However, anticipating future projection of increased water demands in the basin, more water needs to be treated and recycled. Economic impacts of salinity removal will be higher.

Funding to key environmental programs will be impacted differently by the declining hydropower generation as reservoir levels decreases. LCR MSCP funding is not likely to be affected as the budget and funding structure are well established. The federal government and the Lower Basin states are expected to meet their obligations. Salinity Control Program funding, however, may be more volatile. Federal funding is getting harder to get approved, and state funding highly depend on hydropower revenue in the lower basin states. Without curtailments, Hoover Dam hydropower could contribute more than $11 million to the program funding. If Lake Mead levels continue to drop and hydropower production is compromised, less funding will be available for the program and will be reduced to zero at 1000’ under current funding agreement.

Conclusions

Water in Lake Mead is simultaneously used for water supply, hydropower production, recreational use, and riparian habitat. The impact of shortage curtailments in the Basin is predominantly discussed in terms of water supply impacts. However, this analysis demonstrates that water lost in Lake Mead at each successively lower elevation is accompanied by quantifiable physical and economic impacts for all four stakeholder groups: water supply deliveries to Lower Basin states, hydropower generation at Hoover Powerplant, recreation at Lake Mead National Recreation Area, and Lower Colorado River ecosystems. The associated economic consequences of low reservoir levels stem are not confined to water delivery curtailments, but also include increased energy costs for hydropower contractors, reduced recreation industry revenues, and funding reductions for the Colorado River Salinity Control Program. The Interim Guidelines curtailment elevations provided a framework for both qualitative and quantitative analysis of the impacts when Lake Mead reaches low surface elevations.

Though water delivery curtailments to Lower Basin states are distributed between Arizona and Nevada, in reality California and Central Arizona Project users are the most vulnerable geographic regions. Nevada only receives 4% of the curtailments, and is not vulnerable because SNWA's return flow credit program provides a sufficient buffer to keep Nevada's consumptive water use below their entitlement. Curtailments will reduce Nevada's entitlement to 93%, which is still above their 2013 consumptive use of 77%. Arizona Mainstem users are not considered vulnerable to curtailments because they only use 56% of their entitlement and will not share in shortages. Though California's deliveries are not curtailed, they are vulnerable because they use 100% of their entitlements and lose the ability to call on intentionally created surplus (ICS) water at 1,075'. The loss of this surplus water, which is used to make up for shortages in unreliable alternative water stores and supplies, makes the low priority municipal and industrial sector the most vulnerable within California. The Central Arizona Project (CAP) users currently receive Arizona's entire share of the other 96% of curtailments because of their 4th priority water right and junior status in relation to California user rights. Within CAP, excess water used to recharge groundwater will be curtailed first, followed by agricultural users. At current water use rates, curtailments will not affect municipal and industrial users, tribal NIA contracts, or long-term contracts.

The total cost of energy needed to fulfill Hoover's hydropower contracts will increase as reservoir levels decline. As generation at Hoover Powerplant declines, WAPA will increase the unit price of hydropower, which will be compounded by contractors need to purchase more supplemental energy from the higher price spot market. If generation is extremely low, WAPA's unit price can exceed the spot market unit price, making it financially inefficient for contractors to use Hoover's hydropower in their portfolio. Despite this, contractors are contractually bound to purchase the hydropower, even when the Powerplant cannot physically generate hydropower at 1,000'. As contractors' total energy costs increase, these costs will be passed onto retail customers. Municipal retail consumer electricity rates may rise as their utility companies replace lost hydropower with more expensive spot market energy. Additionally, water rate increases can be expected in southern California and central Arizona due to increased pumping costs. Energy is required to pump the three million acre feet of water delivered to consumers in southern California and central Arizona through the Central Arizona Project and the Colorado River Aqueduct. Cheap hydropower is used to move this water over 300 miles, but as hydropower generation declines, the water pumping costs will increase. The rising costs of Hoover hydropower will therefore have impacts to both energy and water retail customers in the Lower Basin states.

Recreational visitation is expected to decline from around seven million visitors per year to at most four million visitors per year if Lake Mead drops to 1000'. This loss in visitation will likely be higher due to the compounding effect of lost operable access points. Despite a $36 million investment and a projected future investment of $5 million, the National Park Service projects that no access points will be operable below 1060’. Reductions in visitation will impact the economic viability of Lake Mead National Recreation Area as recreational income declines and infrastructure investments increase. Additionally, more than 125 small businesses in the surrounding area that rely on Lake Mead’s recreation industry will also suffer financially

The major impact to the Lower Colorado River corridor will be indirect through reduction in environmental program funding. Key environmental programs in the Lower Basin are funded by hydropower revenue, which will be reduced as hydropower generation declines at lower reservoir levels. While the federal government has committed to funding the Lower Colorado River Multi-Species Conservation Program (LCRMSCP) regardless of hydropower generation capacity, it has not made the same commitment for the Colorado River Salinity Control Program. About a quarter of the Salinity Control Program’s budget comes from hydropower revenues, which will be reduced at lower reservoir levels. Additionally, while water delivery curtailments will directly reduce flows through the Lower Colorado River corridor, the magnitude of reductions is relatively small, and there is little evidence that the additional reductions will aggravate these already altered ecosystems. The off-channel restoration sites established by the LCR MSCP to mitigate habitat loss along the river corridor will cover these reductions in flow. Finally, the Colorado River Delta will be in danger of losing its primary water source, irrigation runoff, as less water is delivered to agricultural users in Mexico during curtailments.

To truly appreciate the implications of lowering reservoir levels in Lake Mead on these key stakeholder groups, it is important to recognize the interaction between each group’s uses of Colorado River water. Both the Central Arizona Project and Metropolitan Water District use cheap hydropower generated from Hoover Dam to pump Colorado River water to their respective service areas. Hydropower declines will increase pumping costs, which will likely result in increased water rates for their end users. Similarly, key environmental programs funded by hydropower revenues will lose this funding as generation declines at lower reservoir levels. Environmental stakeholders will also be impacted by water delivery curtailments to Lower Basin states. As water delivery is reduced, less water will flow through the Colorado River corridor below Hoover Dam, which sustains Lower Basin habitats as well as Colorado River Delta habitats. The interconnected nature of the consequences of lowering reservoir levels makes extreme low reservoir conditions all the more critical to understand and plan for as Lake Mead drops closer to the first curtailment elevation of 1,075’.

The physical and economic impacts of decreasing water levels in Lake Mead will continue to be problematic because currently the institutions governing water management in the Colorado River Basin propagate overuse of the Basin’s water. ICS water credits created in times of abundance accelerate the decline of reservoir levels in drier years as Lower Basin states use them to supplement water needs, diverting more than their yearly entitlement. During persistent multi-year droughts, the use of ICS credits can cause surface levels at Lake Mead to remain at or just above Interim Guideline shortage elevations. Lower Basin states will continually fluctuate between being in, or on-the-brink, of shortage conditions. If this occurs, the impacts of low reservoir levels will become the norm and the impacts outlined in this analysis will need to be mitigated.

To mitigate the risk of curtailments the legal and policy frameworks in the Lower Basin are continually changing. Federal and state agencies, municipalities and agricultural groups recognize the risk of curtailments to water deliveries and are developing mitigation strategies to reduce the probability of curtailments. These strategies include local conservation measures, the ICS program, and new initiatives that have and are forming currently including the Colorado River System Conservation Program.

Additionally, some of these mitigation strategies also reduce the vulnerability of states and sectors to curtailments. While most mitigation strategies are driven by risk to water supplies, this analysis provides additional information about the impacts of low reservoir levels on other areas as well such as hydropower generation, recreation at Lake Mead and the environment. The impacts to areas other than water supply could motivate additional mitigations strategies. If low reservoir levels become the norm in the Colorado River Basin stakeholders will need to adapt to the impacts outlined in this report. This analysis doesn't project when Lake Mead will reach the curtailment elevations, but instead provides both quantitative and qualitative frameworks to support decision-making and as shortages occur and guide long-term adaptation strategies.

Bibliography

24-Month Study. 2014. Bureau of Reclamation.

Adler, Robert W. 2007. *Restoring Colorado River Ecosystems: A Troubled Sense of Immensity*. Washington, DC: Island Press.

"Agriculture." 2015. *Colorado River Water Users Association*. Accessed February 14. http://www.crwua.org/colorado-river/uses/agriculture.

Arizona Department of Water Resources. 2006. "Director's Shortage Sharing Workgroup Recommendation."

———. 2014a. "Overview of the Arizona Groundwater Management Code." Arizona Department of Water Resources. http://www.azwater.gov/AzDWR/WaterManagement/documents/Groundwater_Code.pdf.

———. 2014b. "Active Management Area Water Supply - Central Arizona Project Water." *Active Management Area Water Supply - Central Arizona Project Water*. March 27. http://www.azwater.gov/AzDWR/StatewidePlanning/WaterAtlas/ActiveManagementAreas/PlanningAreaOverview/WaterSupply.htm.

———. 2014c. "History of Water Management in Arizona." *History of Water Management in Arizona*. March 27. http://www.azwater.gov/AzDWR/PublicInformationOfficer/history.htm.

Arizona Department of Water Resources, Southern Nevada Water Authority, Arizona Water Banking Authority, and Colorado River Commission of Nevada. 2007. "Arizona-Nevada Shortage Sharing Agreement."

Arizona Power Authority. 2014. *Arizona Power Authority 2013 Annual Report: 55th Annual Report*. Pheonix Arizona. http://repository.asu.edu/attachments/141049/content/2013%20Annual%20Report.pdf.

Arizona Water Banking Authority, Arizona Department of Water Resources, and Central Arizona Project. 2014. "Recovery of Water Stored by the Arizona Water Banking Authority."

Backlund, Peter, Anthony Janetos, and David Schimel. 2008. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. U.S. Climate Change Science Program. http://books.google.com/books?hl=en&lr=&id=3ex349Qvie0C&oi=fnd&pg=PR9&dq=%22Agency+guidelines+as+the+basis+for+determining+that+this+product+conforms+with+Section+515.+For%22+%22by+the+U.S.+Climate+Change+Science%22+%22CCSP%E2%80%99s+guiding+vision+is+to+provide+the+Nation+and+the+global+community+with+the+science-based%22+&ots=vwukl1K1DT&sig=XViGHyjzz8OgP1KTKk7pQPSAXu4.

Batker, David, Zachary Christin, Corinne Cooley, William Graf, Kenneth Bruce Jones, John Loomis, and James Pittman. 2014. *Nature's Value in the Colorado River Basin*. Earth Economics.

Blue Ribbon Committee. 2010. "Metropolitan Water District: Energy for the Future." May 13. http://www.mwdh2o.com/BlueRibbon/pdfs/3c%20%20%20BRC%20Energy%20for%20the%20Future_Final.pdf.

Bonsor, Kevin. n.d. "How Hydropower Plants Work." *How Stuff Works*. science.howstuffworks.com/environmental/energy/hydropower-plant1.htm.

Boulder Canyon Project Act. 1928. http://www.usbr.gov/lc/region/g1000/pdfiles/bcpact.pdf.

"Boulder Canyon Project Power Repayment Study Executive Summary." n.d.

Burbank Water and Power. 2014. "Integrated Resource Plan 2014-2033: Phase One." PowerPoint, March 6. http://www.burbankwaterandpower.com/images/administrative/downloads/IRP_Board_Presentation.pdf.

———. 2014. “Where Does Burbank Power Come From?” Burbank Power and Water. Accessed July 20. http://www.burbankwaterandpower.com/images/electric/downloads/HooverDam-READMORE_Final.pdf#page=1&zoom=auto,-113,557.

Bureau of Reclamation. 2005. “Lower Colorado River Multi-Species Conservation Program Funding and Management Agreement.”

———. 2007a. *Lower Colorado Region Power Performance: For Fiscal Year 2007*. U.S. Department of Interior. http://www.usbr.gov/power/data/LC_Region_Databook_2007.pdf.

———. 2007b. “Shortage Allocation Model Documentation.” Bureau of Reclamation. http://www.usbr.gov/lc/region/programs/strategies/FEIS/AppG.pdf.

———. 2009. “Frequently Asked Questions - Tunnels, Towers, Penstocks and Spillways.” *Lower Colorado Region*. January. http://www.usbr.gov/lc/hooverdam/faqs/tunlfaqs.html.

———. 2011. *SECURE Water Act Section 9503(c) - Reclamation Climate Change and Water*.

———. 2012a. “Funding Opportunity Announcement No. 12SF40034 Basinwide & Basin States Salinity Control Programs 2012.”

———. 2012b. “Hoover Dam - Frequently Asked Questions and Answers: Lake Mead.” *Lower Colorado Region*. June. http://www.usbr.gov/lc/hooverdam/faqs/lakefaqs.html.

———. 2012c. “Colorado River Basin Water Supply and Demand Study: Appendix G2.”

———. 2012d. “Colorado River Basin Water Supply and Demand Study: Technical Report C - Water Demand Assessment.” http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20C%20-%20Water%20Demand%20Assessment/TR-C-Water_Demand_Assessmemt_FINAL.pdf.

———. 2013. “Quality of Water - Colorado River Basin - Progress Report No.24.”

———. 2014a. “Colorado River Basin Salinity Control Program.” *Usbr.gov*. http://www.usbr.gov/projects/Project.jsp?proj_Name=Colorado%20River%20Basin%20Salinity%20Control%20Project.

———. 2014b. “Listing of Individual Water Entitlements in the State of Arizona - Priority 1.” Bureau of Reclamation. http://www.usbr.gov/lc/region/g4000/contracts/entitlements/AZtable1.pdf.

———. 2014c. “Listings of Individual Water Entitlements in the State of Arizona - Fourth Priority.” Bureau of Reclamation. http://www.usbr.gov/lc/region/g4000/contracts/entitlements/AZtable4.pdf.

———. 2014d. “Listings of Individual Water Entitlements in the State of Arizona - Second and Third Priorities.” Bureau of Reclamation. http://www.usbr.gov/lc/region/g4000/contracts/entitlements/AZtable2and3.pdf.

———. 2014e. “Listings of Individual Water Entitlements in the State of California.” Bureau of Reclamation. http://www.usbr.gov/lc/region/g4000/contracts/entitlements/California.pdf.

———. 2014f. “Listings of Individual Water Entitlements in the State of Nevada.” Bureau of Reclamation. http://www.usbr.gov/lc/region/g4000/contracts/entitlements/Nevada.pdf.

———. 2014g. “Colorado River Accounting and Water Use Report Arizona, California and Nevada: Calendar Year 2013.” Bureau of Reclamation. http://www.usbr.gov/lc/region/g4000/4200Rpts/DecreeRpt/2013/2013.pdf.

———. 2014h. “Hoover Dam Data: Hydropower Generation and Water Release (1967-2014).”

———. 2014i. “Hoover Dam Data: Colorado River Simulation System Runs (Hydropower Generation, Water Release, Operating Head, Pool Elevation).”

———. 2015. “Lower Colorado River Water Delivery Contracts.” *Lower Colorado River Water Delivery Contracts*. February 13. http://www.usbr.gov/lc/region/g4000/wtrcontracts.html.

Buschatzke, Thomas. 2015. Arizona Department of Water Resources. Phone Interview.

Campbell, Paul. 1997. *Population Projections: States, 1995 - 2025*. Current Population Reports. Census Bureau. http://www.census.gov/prod/2/pop/p25/p25-1131.pdf.

Central Arizona Groundwater Replenishment District. 2014. “CAGRD 2015 Plan of Operation.” Central Arizona Groundwater Replenishment District.
Central Arizona Project. 2013. “Summary of the CAP Agricultural Water Incentive Pricing Program Arizona Municipal Water Users Association.” Central Arizona Project.
———. 2014a. “Excess Water Distribution Procedures.”
———. 2014b. “The State of the Colorado.”
Cohn, Jeffrey P. 2004. “Colorado River Delta.” *BioScience* 54 (5): 386–91.
Colorado River Basin Project Act. 1968. http://www.usbr.gov/lc/region/g1000/pdfiles/crbproj.pdf.
Colorado River Basin Salinity Control Act. 1974. http://www.usbr.gov/lc/region/pao/pdfiles/crbsalct.pdf.
Colorado River Basin Salinity Control Forum. 2005. *2005 Review: Water Quality Standards for Salinity Colorado River System*. Colorado River Basin Salinity Control Forum. http://water.epa.gov/scitech/swguidance/standards/wqslibrary/upload/2009_03_16_standards_wqslibrary_ca_CA-WQSS-0013_100105.pdf.
———. 2014. “2014 Review: Water Quality Standards for Salinity Colorado River System.” http://coloradoriversalinity.org/docs/2014%20Final%20REVIEW%20-%20complete.pdf.
Colorado River Basin Water Supply and Demand Study: Executive Summary. 2012. Bureau of Reclamation.
“Colorado River Boundary Section.” 2015. *International Boundary and Water Commission*. Accessed January 26. http://www.ibwc.state.gov/Water_Data/Colorado/Index.html.
Colorado River Commission of Nevada. 2012a. *Colorado River Commission of Nevada*. June 14. http://crc.nv.gov/index.asp.
———. 2012b. “Informational Public Workshop on Hoover Power Allocation Proceedings.” Las Vegas, NV, October 30.
“Colorado River Streamflow: The Lees Ferry Gaged Flow Record.” n.d. *TreeFlow: Streamflow Reconstructions from Tree Rings*. http://treeflow.info/lees/gage.html.
“Colorado River Water Users Association.” 2014. *Colorado River Water Users Association*. Accessed January 1. http://www.crwua.org/.
Cook, Terri. 2013. “Releasing a Flood of Controversy on the Colorado River | EARTH Magazine.” http://www.earthmagazine.org/article/releasing-flood-controversy-colorado-river.
Cooper, Keith, and Jonathan Sanchez. 2014. Hoover Dam and Powerplant Tour. Facility Tour.
Deaton, Ronald F. 2007. “Los Angeles Department of Water and Power Comments Regarding the Recommendations for the Market Advisory Committee for Designing a Greenhouse Gas Cap-and-Trade System for California,” June 21. http://www.climatechange.ca.gov/events/2007-06-12_mac_meeting/public_comments/LADWP%20LtrHickoxMAC6-07.doc.pdf.
Defenders of Wildlife. 2011. “Colorado River Basin Fish.” https://web.archive.org/web/20110601205039/http://www.defenders.org/wildlife_and_habitat/wildlife/colorado_river_basin_fish.php.
Department of Interior, Bureau of Reclamation. 2007. “Record of Decision: Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead.”
Duffield, John, Chris Neher, and David Patterson. 2007. “Economic Values of National Park System Resources Within the Colorado River Watershed: Phase II.” *Report Prepared for the National Park Service*. http://www.cfc.umt.edu/CESU/Reports/NPS/UMT/2005/Duffield_Colorado%20river_rpt.pdf.
Electric Power Supply Association. 2015. “What Is a Wholesale Electricity Market?” *Electricity Primer-Basics of Power and Competitive Markets*. https://www.epsa.org/industry/primer/?fa=wholesaleMarket.

Federal Energy Regulatory Commission. 2007. “Southwest Electric Market: Overview and Focal Points.” February 7. www.ferc.gov/market-oversight/mkt-electric/southwest/elec-sw-reg-des.pdf.
———. 2010. “Northwest Electric Market: Overview and Focal Points.” September 15. www.ferc.gov/market-oversight/mkt-electric/northwest/elec-nw-reg-des.pdf.
———. 2014. “Southwestern Daily Index Day-Ahead On-Peak Prices.” Federal Energy Regulatory Commission. *Southwest Electric Market: Southwestern Index Prices*. November. http://www.ferc.gov/market-oversight/mkt-electric/southwest/elec-sw-sw-pr.pdf.
Final EIS - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead - Chapter 4 Environmental Consequences. 2007. Bureau of Reclamation.
Flessa, Karl. 2015. University of Arizona. Phone Interview.
Fulp, Terrance. 2014. Bureau of Relamation. Phone Interview.
Glendale Water and Power. 2012. “Electric Utility Operating Statistics: FY 2011-12.” http://www.glendaleca.gov/home/showdocument?id=9873.
———. 2014. *2013-2014 Annual Report: Electric Utility Operating Statistics*. Annual Report. Glendale, CA: Glendale Water & Power. www.glendaleca.gov/home/showdowcument?id=19878.
Glenn, Edward P., Kate Hucklebridge, Osvel Hinojosa-Huerta, Pamela L. Nagler, and Jennifer Pitt. 2008. “Reconciling Environmental and Flood Control Goals on an Arid-Zone River: Case Study of the Limitrophe Region of the Lower Colorado River in the United States and Mexico.” *Environmental Management* 41 (3): 322–35. doi:10.1007/s00267-007-9056-4.
Hassencamp, William. 2014. Metropolitan Water District of Southern California. Phone.
Hecox, Walter, Brendan Boepple, and Matthew Gottfried, eds. 2012. “State of the Rockies Report Card: The Colorado River Basin, Agenda for Use, Restoration, and Sustainability for the Next Generation.” Colorado College State of the Rockies Project. http://www2.coloradocollege.edu/StateoftheRockies2/2012RC/2012ReportCard.pdf.
Hoover Coordinating Committee Meeting. 2014. Meeting Notes. Bureau of Reclamation.
Hoover Power Allocation Act. 2011. https://beta.congress.gov/bill/112th-congress/house-bill/470.
Illia, Tony. 2010. “Big Drop in Lake Mead Level Curbs Hoover Water, Power.” *ENR Southwest*, September 27. http://southwest.construction.com/southwest_contractor_news/2010/0927_LakeMeadLevel.asp.
Intercontinental Exchange. 2014. “Wholesale Electricity Market Data.” *Energy Information Association*. November 9. http://www.eia.gov/electricity/wholesale/index.cfm.
Jacobson, Kib. 2014. Bureau of Reclamation. Phone Interview.
James, Tim, Anthony Evans, Eva Madly, and Cary Kelly. 2014. *The Economic Importance of the Colorado River to the Basin Region*. L William Seidman Research Institute, W.P. Carey School of Business, Arizona State University.
Johnston, Louis, and Samuel H. Williamson. 2015. “What Was the U.S. GDP Then? Annual Observations in Table and Graphical Format 1790 to the Present.” *MeasuringWorth.com*. http://www.measuringworth.com/datasets/usgdp12/.
Kuhn, Eric. 2007. *The Colorado River: The Story of a Quest for Certainty on a Diminishing River*. Glenwood Springs, CO: Colorado River District. http://www.crwcd.org/media/uploads/How_Much_Water_05-15-07.pdf.
LADWP Eyes Renewables; Less Gas, Coal Use. 2008. Weekly Gas Market Report. Natural Gas Intelligence. http://www.naturalgasintel.com/articles/17635-ladwp-eyes-renewables-less-gas-coal-use.
Lake Mead Area and Capacity Tables. 2011. Bureau of Reclamation.
Lake Mead National Recreation Area. 2014. “Lake Mead Low Water Concerns.”

"LCR Multi-Species Conservation Program - History." 2014. *Lower Colorado River Multi-Species Conservation Program*. December 15. http://www.lcrmscp.gov/history.html.
Los Angeles Department of Water and Power. 2013. "Power." Company. *Los Angeles Department of Water and Power*. https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-power?_afrLoop=492104653963091&_afrWindowMode=0&_afrWindowId=1ar1qwxksv_244#%40%3F_afrWindowId%3D1ar1qwxksv_244%26_afrLoop%3D492104653963091%26_afrWindowMode%3D0%26_adf.ctrl-state%3D1ar1qwxksv_272.
———. 2014a. *Power System: Financial Statements and Required Supplementary Information June 30, 2013 and 2014 (With Independent Auditors' Report Thereon)*. file:///Users/juliamorton/Downloads/LADWP%20Power%202014%20FS.pdf.
———. 2014b. *2014 Power Integrated Resource Plan*. file:///Users/juliamorton/Downloads/2014%20Power%20Integrated%20Resource%20Plan.pdf.
Lower Colorado River Multi-Species Conservation Program. 2010. *Beal Riparian and Marsh Restoration 2010 Annual Report*.
———. 2011a. *Cibola Valley Conservation Area 2010 Annual Report*.
———. 2011b. *Cibola National Wildlife Refuge Unit 1 2010 Annual Report*.
———. 2012a. *Palo Verde Ecological Reserve 2011 Annual Report*.
———. 2012b. *Hart Mine Marsh 2011 Annual Report*.
———. 2012c. *Imperial Ponds Conservation Area 2008 Annual Report*.
———. 2012d. *Laguna Division Conservation Area Restoration Development and Monitoring Plan*.
Lower Colorado River Operations. 2014. Bureau of Reclamation. http://www.usbr.gov/lc/riverops.html.
Luttrell, DE. 2014. "2014 Summary of Activities." Lincoln County Power District No. 1. www.lcpd1.com/content/2014-summary-activities.
McClurg, Sue. 2005. *The Lower Colorado River MSCP: Protecting Endangered Species and Water Project Operations*. Water Education Foundation. http://www.water-ed.org/userfiles/rrsummer05.pdf.
McNeill, John R. 2012. "Statement of the Central Arizona Water Conservation District: DOE/Western Area Power Administration 'Defining the Future' Proceedings." ww2.wapa.gov/sites/western/about/Documents/Defining%20the%20future/JOTcomment62.pdf.
Metropolitan Water District of Southern California. 2014. "Regional Progress Report." Metropolitan Water District of Southern California. http://www.mwdh2o.com/mwdh2o/pages/yourwater/SB60/archive/SB60_2014.pdf.
Morford, Scott. 2014. "Salinity in the Colorado River Basin." https://watershed.ucdavis.edu/education/classes/files/content/page/6%20Morford-Colorado_Basin_Salinity.pdf.
National Park Service. 2015. "Storage Capacity of Lake Mead." *Lake Mead National Recreation Area*. March 15. http://www.nps.gov/lake/learn/nature/storage-capacity-of-lake-mead.htm.
National Research Council. 2007. *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability*. Washington D.C.: The National Academies Press. http://www.nap.edu/openbook.php?record_id=11857.
Neher, Chris J., John W. Duffield, and David A. Patterson. 2013. "Modeling the Influence of Water Levels on Recreational Use at Lakes Mead and Powell." *Lake and Reservoir Management* 29 (4): 233–46. doi:10.1080/10402381.2013.841784.
Nowak, Ken. 2014. Bureau of Reclamation. Email Correspondence.
NPS Stats. 2014. National Park Service. https://irma.nps.gov/Stats/Reports/Park.
Operation of Flaming Gorge Dam Final Environmental Impact Statement: Power System Analysis Technical Appendix. 2002. Environmental Impact Statement. Bureau of Reclamation. http://www.usbr.gov/uc/envdocs/eis/fgFEIS/appdx/5_power.pdf.

Operation of Flaming Gorge Dam Final Environmental Impact Statement: Recreation Visitation and Valuation Analysis Technical Appendix. 2002. Environmental Impact Statement. Bureau of Reclamation.

Oster, J. D., Glenn Hoffman, and Frank Robinson. 1984. “Management Alternatives: Crop, Water, and Soil.” *California Agriculture*.

OTC Global Holings. 2014. “OTCGH North American Electricity Forward Curves.” OTC Global Holdings, LP.

Pasadena Water & Power. 2014. *Pasadena Water & Power--2014 Annual Report*. Pasadena, CA: Pasadena Water & Power. file:///Users/juliamorton/Downloads/2014%20Annual%20Report%20-%20Revised%201-20-15.pdf.

———. 2015. “Power Content Label.” *CIty of Pasadena*. cityofpasadena.net/waterandpower/PCL/.

Pitt, Jennifer. 2014. “What the New York Times Misses About the Colorado River.” *Water Currents - National Geographic*. January 8. http://newswatch.nationalgeographic.com/2014/01/08/the-new-york-times-and-the-colorado-wheres-the-river/.

Rood, Stewart B., Jeffrey H. Braatne, and Francine MR Hughes. 2003. “Ecophysiology of Riparian Cottonwoods: Stream Flow Dependency, Water Relations and Restoration.” *Tree Physiology* 23 (16): 1113–24.

Schmidt, Jack. 2014. Utah State University. Phone Interview.

Schuster, Elizabeth, and Bonnie G. Colby. 2013. “Farm and Ecological Resilience to Water Supply Variability.” *Journal of Contemporary Water Research and Education*, no. 151: 70–83.

Senate Energy and Natural Resources Committee. 2013. *To Consider the Bureau of Reclamation’s Colorado River Basin Water Supply and Demand Study*. Washington D.C. http://www.energy.senate.gov/public/index.cfm/2013/7/water-and-power-subcommittee.

Shafroth, J.B. 2006. *Control of Tamarix in the Western United States: Implications for Water Salvage, Wildlife Use, and Riparian Restoration*. https://www.fort.usgs.gov/sites/default/files/products/publications/21653/21653.pdf.

Simonton, Michael. 2015. Western Area Power Administration. Email Correspondence.

“Sonoran Yellow Warbler.” 2014. *Lower Colorado River Multi-Species Conservation Program*. December 15. http://www.lcrmscp.gov/species/sonoran_yellow_warbler.html.

Southern California Public Power Authority. 2008. “About Us.” *Southern California Public Power Authority*. http://www.scppa.org/pages/misc/about.html.

Southern Nevada Water Authority. 2009. “Southern Nevada Water Authority, Water Resource Plan.” Southern Nevada Water Authority. http://www.snwa.com/assets/pdf/wr_plan.pdf.

———. 2015a. “SNWA - Return Flow Credits.” *SNWA - Return Flow Credits*. February 12. http://www.snwa.com/ws/reclaimed_returnflow.html.

———. 2015b. “Third Drinking Water Intake at Lake Mead.” *Third Drinking Water Intake at Lake Mead*. May 15. http://www.snwa.com/about/regional_intake3.html.

Southwick Associates. 2012. *Economic Contributions of Outdoor Recreation on the Colorado River & Its Tributaries*. http://protectflows.com/wp-content/uploads/2013/09/Colorado-River-Recreational-Economic-Impacts-Southwick-Associates-5-3-12_2.pdf.

“Steering Committee - Funding.” 2014. *Lower Colorado River Multi-Species Conservation Program*. December 15. http://www.lcrmscp.gov/steer_committee/funding.html.

The Division of Energy Market Oversight. 2012. *Energy Primer: A Handbook of Energy Market Basics*. Federal Energy Regulatory Commission.

Tomaso, Joseph. 1998. “Impact, Biology, and Ecology of the Saltcedar in the Southwestern United States.” *Weed Technology* 12 (2).

Triedman, Natalie. 2012. “Environment and Ecology of the Colorado River Basin.” In *The 2012 Colorado College State of the Rockies Report Card*, 88–107.

United States Department of Agriculture, Environmental Protection Agency, U.S. Fish and Wildlife Service, U.S. Geological Survey, Bureau of Land Management, and Bureau of Reclamation. 2011. *Colorado River Basin Salinity Control Program Federal Accomplishments Report for Fiscal Year 2011-SummaryTables*. https://www.usbr.gov/uc/progact/salinity/pdfs/FedAccompRep-2011-SummaryTables.pdf.

United States Department of Energy, and Western Area Power Administration. 2009. “Rate Schedule BCP-F8.”

United States National Park Service. 2014. “Lake Mead National Recreation Area: Invasive Species.” *National Park Service*. October. http://www.nps.gov/lake/naturescience/invasivespecies.htm.

“Upper Colorado River Basin Fund - Reclamation, Upper Colorado Region.” 2014. Accessed November 17. http://www.usbr.gov/uc/rm/crsp/bf.html.

US Department of Energy. 2013. *Effects of Climate Change on Federal Hydropower*. Congressional. Washington D.C.

U.S. Energy Information Administration (EIA). 2014. “Federal Power Marketing Administrations Operate across Much of the United States.” Accessed April 22. http://www.eia.gov/todayinenergy/detail.cfm?id=11651.

Vano, Julie A., Bradley Udall, Daniel R. Cayan, Jonathan T. Overpeck, Levi D. Brekke, Tapash Das, Holly C. Hartmann, et al. 2014. “Understanding Uncertainties in Future Colorado River Streamflow.” *Bulletin of the American Meteorological Society* 95 (1): 59–78. doi:10.1175/BAMS-D-12-00228.1.

Western Area Power Administration. 1984. “49 FR 50582: Conformed General Consolidated Power Marketing Criteria or Regulations for Boulder City Area Projects.” Federal Register Notice: 49-50582. https://ww2.wapa.gov/sites/western/about/Documents/Appendix%20D%20-%20Conformed%20Criteria.pdf.

———. 2012. “77 FR 35671: Conformed Power Marketing Criteria or Regulations for the Boulder Canyon Project.” Federal Register 77-35671. https://www.federalregister.gov/articles/2012/06/14/2012-14572/conformed-power-marketing-criteria-or-regulations-for-the-boulder-canyon-project#h-18.

———. 2014. “Power Marketing.” *Western Area Power Administration*. Accessed April 23. https://ww2.wapa.gov/sites/western/about/faqs/Pages/faqpm.aspx.

Zamora-Arroyo, Francisco, Steve Cornelius, Jennifer Pitt, Edward Glenn, Pamela L. Nagler, Marcia Moreno, Jacqueline Garcia, Osvel Hinojosa-Huerta, Meredith de la Garza, and Ivan Parra. 2005. *Conservation Priorities in the Colorado River Delta: Mexico and the United States*. Sonoran Institute, Environmental Defense, University of Arizona, Pronatura Noroeste Direccion de Conservation Sonora, Centro de Investigacion en Alimentacion y Desarrollo, and World Wildlife Fund-Gulf of California Program.

Zimmerman, Janet. 2010. “Colorado River Drought Threatens Power Production.” http://www.pe.com/local-news/topics/topics-environment-headlines/20101006-region-colorado-river-drought-threatens-power-production.ece.

Appendix A1: Water Supply Vulnerability Index

State	**California**		
Allocation	**4.4 MAF**		
Sector	**Agriculture**	**Municipal/Industrial**	**Tribal**
Percent Allocation Consumptively Using Statewide	**100%**		
	California is consumptively using their full apportionment of Colorado River water. The majority of Colorado River water is utilized by the large irrigation districts for agriculture. The remaining water is utilized by MWD for municipal and industrial water use. Every year, Palo Verde Irrigation District and Imperial Irrigation District transfer water to MWD through crop fallowing.		
State Priority	**HIGH**	**LOW**	**HIGH**
Basin Priority	*HIGH*	*HIGH*	*HIGH*
Priority of Water Right	All California water rights are considered senior to 4th priority water rights held in Arizona per the Colorado River Basin Project Act of 1968 that authorized the construction of the CAP. Within California, agricultural water rights are the highest non-Tribal water rights. The large irrigation districts hold PPRs and a total entitlement to the first 3.85 MAF of Colorado River water.	Within California, municipal and industrial Colorado River water rights are held by MWD. These rights are the most junior rights. MWD diversion rights are still held senior to Arizona 4th priority water rights. Additionally, MWD has first priority to any excess water that California is able to divert. This water is subject to availability and has been decreasing as Nevada and Arizona increase their consumptive use.	The Tribal water rights in California are all held as PPR rights and are comingled with other PPRs as the most senior rights in the state.

Developed Additional Water Storage and Supplies	**NO**	**YES (unreliable)**	**NO**
	The agriculture water users have little access to additional water supplies. The arid desert environment of these lands coupled with the quantity of water required for irrigation of crops and other uses makes the Colorado River the only viable source of water to support the industries and way of life. The other water source available to these sectors is deep groundwater that cannot serve as a replacement to Colorado River water. Additionally, the Coachella Valley Water District uses California State Water Project water to replenish their groundwater resources.	MET has limited groundwater and access to the California State Water Project to supplement its supply from the Colorado River. However, because of the large demand and the frequency of droughts in California these sources cannot reliably and sustainably meet the needs of MET without the Colorado River. California additionally has ICS water stored, however, the ability to utilize this water ceases at 1,075 feet.	The tribal lands that are utilizing Colorado River water have little access to additional water supplies. The arid desert environment of these lands coupled with the quantity of water required for irrigation of crops and other uses makes the Colorado River the only viable source of water to support the industries and way of life. The other water source available to these sectors is deep groundwater that cannot serve as a replacement to Colorado River water.
Percent change in projected overall water demand not constrained by Colorado River water supply *(Using scenario A for current growth trends from the Bureau of Reclamation's Colorado River Supply and Demand Study, Appendix C - Water Demand Projections)* *Projected demand values from the Basin Study are not constrained by availability of Colorado River water.*	**-2%**	**18%**	**No Change**
	California agriculture is projected to decrease from 710,000 acres to 690,000 acres by 2060 (Bureau of Reclamation, 2012c). The water delivered per acre is also projected to decrease by 1%. These changes result in a reduction of Agricultural water demand from 3,230,000 AF in 2015 to 3,159,000 AF in 2060, an overall 2% reduction in Colorado River water demand.	There are currently 20.4 million people in California who use Colorado River water. The Basin Study projects that by 2060 this population will increase to 27.6 million. While the per capita water use is projected to decrease by 12%, the overall municipal and industrial demand for Colorado River water is projected to increase 18% by 2060. It is important to note that this growth is projected to occur in the Coachella Valley, Imperial Valley and along the main stem river corridor with no net growth coming from MWD.	There is no projected change in tribal water demand in the state of California.

1,075 Feet Curtailed Allocations	4.4 MAF (no curtailment)		
Sector	Agriculture	Municipal/Industrial	Tribal
Percent of Water Right Available / Access to Water Right	100%	100%	100%
	ICS water not available during shortages	Looses ability to pull on excess water and ICS credits. This can be a significant impact, especially in CA drought years.	
1,050 Feet Curtailed Allocations	**4.4 MAF (no curtailment)**		
Percent of Water Right Available / Access to Water Right	100%	100%	100%
	ICS water not available during shortages	ICS water not available during shortages	
1,025 Feet Curtailed Allocations	**4.4 MAF (no curtailment)**		
Percent of Water Right Available / Access to Water Right	100%	100%	100%
	ICS water not available during shortages	ICS water not available during shortages	

State	**Arizona (Mainstem)**		
Allocation	**2.8 MAF**		
Sector	**Agriculture**	**Municipal/Industrial**	**Tribal**
Percent Allocation Consumptively Using Statewide	**56%** (balance goes to CAP)		
	Arizona's users along the main stem of the Colorado River currently consumptively use 56% of their Colorado River entitlements. This use is divided amongst agriculture, municipal/industrial and tribal water users with the largest portion of use in the Yuma-Mesa area. The portion of Arizona's Colorado River water apportionment that is not used along the main stem is diverted to the CAP bring the state wide consumption to the full 2.8 MAF.		
State Priority	**HIGH**	**HIGH**	**HIGH**
Basin Priority	*MEDIUM*	*MEDIUM*	*MEDIUM*
Priority of Water Right	Many of the large agricultural water rights holders in Arizona outside of the CAP are among the most senior rights, however, rights range from 1st to 6th priority.	Municipal and Industrial water rights outside the CAP represent the smallest portion of water. M&I rights range from 1st to 6th priority.	Many tribal rights are the most senior within Arizona, however tribal rights range from 1st to 4th priority.

Developed Additional Water Storage and Supplies	**NO** Rules and regulations drafted in the Arizona Groundwater Management Act of 1980 only apply to the Active Management Areas (AMAs) of Central Arizona. Therefore there are not the restrictions on groundwater pumping present for the Mainstem water users. However, because of the proximity to the Colorado River corridor, groundwater pumping by Mainstem users is typically considered to be diversions from the Colorado River because of the connectivity of the groundwater to the river.	**NO** Rules and regulations drafted in the Arizona Groundwater Management Act of 1980 only apply to the Active Management Areas (AMAs) of Central Arizona. Therefore there are not the restrictions on groundwater pumping present for the Mainstem water users. However, because of the proximity to the Colorado River corridor, groundwater pumping by Mainstem users is typically considered to be diversions from the Colorado River because of the connectivity of the groundwater to the river.	**NO** Rules and regulations drafted in the Arizona Groundwater Management Act of 1980 only apply to the Active Management Areas (AMAs) of Central Arizona. Therefore there are not the restrictions on groundwater pumping present for the Mainstem water users. However, because of the proximity to the Colorado River corridor, groundwater pumping by Mainstem users is typically considered to be diversions from the Colorado River because of the connectivity of the groundwater to the river.
Percent change in projected overall water demand not constrained by Colorado River water supply *(Using scenario A for current growth trends from the Bureau of Reclamation's Colorado River Supply and Demand Study, Appendix C - Water Demand Projections)* *Projected demand values from the Basin Study are not constrained by availability of Colorado River water. Therefore demand is projected to exceed Lower Basin state's apportionment quantities.*	**No Change** The there is no projected net change in agricultural water demand for the Mainstem Colorado River water users due to the high priority rights of agricultural users in the Mainstem region.	**86%** The per capita water use across Arizona Colorado River water users is predicted to decrease by 4% while the population is projected to increase by approximately 50%. In the Mainstem region, this translates to a predicted growth of 86% in the municipal/industrial water demand.	**1%** Tribal water demand in the Mainstem region is projected to grow by 1% between 2015 and 2060.

1,075 Feet Curtailed Allocations	2.48 MAF (no curtailment)		
Sector	**Agriculture**	**Municipal/Industrial**	**Tribal**
Percent of Water Right Available / Access to Water Right	100%	100%	100%
	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.
1,050 Feet Curtailed Allocations	**2.4 MAF (400,000 AF curtailment)**		
Percent of Water Right Available / Access to Water Right	100%	100%	100%
	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.
1,025 Feet Curtailed Allocations	**2.32 MAF (480,000 AF curtailment)**		
Percent of Water Right Available / Access to Water Right	100%	100%	100%
	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.	4th priority Mainstem water users could be impacted by curtailments if water use increases to the full 4th priority entitlement of 164,652 AF.

State	Arizona (Central Arizona Project)			
Allocation	Balance of unused Arizona's Colorado River Water apportionment. (Roughly 1,500,000 AF)			
Sector	Excess Water	Agriculture	Municipal/Industrial	Tribal
Percent Allocation Consumptively Using Statewide	100%			
	The Central Arizona Project has a water right to the balance of Arizona's Colorado River water apportionment not used by higher priority main stem users. For this reason, the amount of water available to CAP is dependent on the demand of the main stem users and that CAP diversions always brings Arizona's state wide water consumption to the full 2.8 MAF apportionment. Water within the CAP is distributed between municipal/industrial, tribal and agricultural use. In addition to these sectors, the CAP also uses excess water for groundwater recharge and replenishment as well as federal firming.			
State Priority	LOW	LOW	MEDIUM	MEDIUM
Basin Priority	*LOW*	*LOW*	*LOW*	*LOW*
Priority of Water Right	Excess water is the lowest priority water use in the CAP. Excess water used for groundwater replenishment, recharge and firming receives water after the Agricultural Settlement Pool is fulfilled. This is the first portion of water eliminated by a curtailment call.	Non-Indian agriculture in the CAP is considered excess water and is satisfied through the Agricultural Settlement Pool. Currently, the Agricultural Settlement Pool has first priority to the first 400,000 AF of excess CAP water. This sector will be impacted by the first curtailments called during a shortage after the additional excess water is eliminated.	Municipal/industrial water right holders in the CAP are equal to Tribal rights as high priority users. Municipal and industrial water rights holders have long-term contracts as well as NIA contracts. The NIA contracts would be curtailed before long term contracts but only after all excess water is eliminated.	Tribal water right holders in the CAP are equal to municipal/industrial rights as high priority users. Tribal water rights holders have long-term contracts as well as NIA contracts. The NIA contracts would be curtailed before long-term contracts but only after all excess water is eliminated.

Developed Additional Water Storage and Supplies	**NO**	**YES (unreliable)**	**YES (reliable)**	**NO**
	For groundwater recharge there can be considered to be no additional water resources. However, to meet groundwater replenishment obligations, the CAGRD has a diversified water portfolio to compensate for the declining reliability of excess Colorado River water.	As part of Arizona's Ground Water Management Act of 1980, agricultural users have the ability to pump groundwater. However, barriers such as high cost to drill new wells or repair existing unmaintained wells due to dependence on river water and dropping groundwater levels make accessing this water difficult. For this reason the agricultural users in the state of Arizona are considered to have access to additional yet unreliable groundwater resources.	Municipal and industrial water users in Arizona are considered to have access to reliable alternative groundwater resources. The Groundwater Management Act of 1980 prevented the mining of groundwater to save it for municipal and industrial use in instances of extreme drought. As part of this process, the Joint Recovery Plan was created to govern how groundwater would be extracted in such cases. There is not enough groundwater to provide a permanent sustainable substitute to Colorado River water, only enough to serve as a buffer to get through drought years until there is enough Colorado River water to meet demand again.	Tribal lands have the expressed right to extract groundwater under the Winters doctrine. Additionally the Federal Government uses excess CAP water to firm tribal water rights, providing a reliable resource for tribes to fall back on in a time of shortage.
Percent change in projected overall water demand not constrained by Colorado River water supply *(Using scenario A for current growth trends from the Bureau of Reclamation's Colorado River Supply and Demand Study, Appendix C - Water Demand Projections) Projected demand values from the Basin Study are not constrained by availability of Colorado River water.*	**NA**	**-100%**	**92%**	**48%**
		Agricultural water use demand for Colorado River water in Central Arizona is projected to reduce to 0 by 2060. This is due to decline of the Agricultural Settlement Pool and its eventual elimination in 2030. This will force farmers to rely solely on groundwater for irrigation and could potentially lead to agricultural land conversion to urban land.	Municipal and industrial use in Central Arizona represents the largest area of growth in Colorado River water demand. Projected population growth in the urban areas of Phoenix, Tucson, Scottsdale, etc. as well as potential conversion of agricultural land to urban land lead to a predicted growth in Colorado River water demand by 92% in 2060.	Tribal water demand in Central Arizona is predicted to increase by 48% in 2060. This is largely due to the Arizona Water Settlement Act allowing tribes to realize their water rights and increase their Colorado River water use.

1,075 Feet Curtailed Allocations	Balance of unused Arizona's Colorado River Water apportionment with 320,000 AF of curtailment. (Roughly 1,180,000 AF)			
Sector	Excess	Agriculture	Municipal/Industrial	Tribal
Percent of Water Right Available / Access to Water Right	0%	53%	100%	100%
	Excess water is completely eliminated at the first round of curtailments.	After excess water is eliminated, the Agricultural Settlement Pool is curtailed to reach the full shortage. The amount curtailed depends on the amount of excess water and higher priority user demand.	At current water use there is no impact to contracted deliveries at this stage. NIA contracts are the first to be curtailed if water demand continues to increase, reducing available excess water.	No impact at this stage
1,050 Feet Curtailed Allocations	Roughly 1,100,000 (400,000 AF curtailment)			
Percent of Water Right Available / Access to Water Right	0%	33%	100%	100%
	Same as previous elevation	Same as previous elevation	Same as previous elevation	No impact at this stage
1,025 Feet Curtailed Allocations	Roughly 1,020,000 (480,000 AF curtailment)			
Percent of Water Right Available / Access to Water Right	0%	13%	100%	100%
	Same as previous elevation	Same as previous elevation	Same as previous elevation	No impact at this stage

State	Southern Nevada		
Allocation	300,000 AF		
Sector	Agriculture	Municipal/Industrial	Tribal
Percent Allocation Consumptively Using Statewide	77%		
	Because of Southern Nevada's proximity to Lake Mead, it is possible for them to return water to the reservoir and reduce their consumptive use. Through the "return flow credit program", Southern Nevada is able to treat their wastewater and then return that water to Lake Mead. This allows Southern Nevada to divert more than their 300,000 AF apportionment while keeping their consumptive use below their 300,000 AF. The current consumptive use is approximately 77% of their total apportionment.		
State Priority	NA	HIGH	HIGH
Basin Priority		*MEDIUM/HIGH*	*MEDIUM/HIGH*
Priority of Water Right		Municipal and industrial water use comprises the majority of the water use in Nevada and as such can be considered to have high priority. While Nevada's rights are not explicitly junior to California's, Nevada receives curtailments when California does not, giving Nevada a medium/high priority overall. All curtailments will be applied to municipal/industrial water users.	Tribal water rights in Nevada hold highest priority in the state.

Developed Additional Water Storage and Supplies	**NA**	**YES (reliable)**	**NO**
		SNWA has been recharging a groundwater basin in Las Vegas with excess Colorado River water. This groundwater basin can serve as a buffer to get through drought years but cannot replace the Colorado River water. Therefore, SNWA has a variety of Intentionally Created Surplus water credits built up as well as agreements with both California and Arizona to store water on their behalf. Additionally, SNWA is also pursuing groundwater resources in other less inhabited regions of Nevada. The combination of these resources can serve as a reliable supplemental water resource to Colorado River water for municipal and industrial water uses in Nevada.	Tribal water use in Nevada however, is considered to have no access to these alternative water resources. The very limited groundwater resources available to the tribal land in Nevada cannot serve as a reliable alternative to Colorado River water.
Percent change in projected overall water demand not constrained by Colorado River water supply *(Using scenario A for current growth trends from the Bureau of Reclamation's Colorado River Supply and Demand Study, Appendix C - Water Demand Projections)* *Projected demand values from the Basin Study are not constrained by availability of Colorado River water. Therefore demand is projected to exceed Lower Basin state's apportionment quantities.*	**NA**	**75%**	**No Change**
	There is no agriculture or predicted agricultural use of Colorado River water in Nevada.	The Bureau or Reclamation's Colorado River Basin Supply and Demand Study projects a growth of the Nevada population using Colorado River water from the current 2.6 million to 4.4 million in 2060. However, the per capita water use is predicted to decline by 20%. This leads to a net increase in municipal and industrial water demand from 289,000 AF in 2015 to 506,000 AF in 2060, a 75% increase.	There is no predicted change in tribal water demand in the state if Nevada.

1,075 Feet Curtailed Allocations	**287,000 AF (13,000 AF curtailment)**		
Sector	**Agriculture**	**Municipal/Industrial**	**Tribal**
Percent of Water Right Available / Access to Water Right	NA	96%	100%
		Curtailments directly apply to the Municipal and industrial users within the SNWA. However, while these users do not currently utilize this quantity of apportionment they may not be impacted by curtailments	
1,050 Feet Curtailed Allocations	**283,000 AF (17,000 AF curtailment)**		
Percent of Water Right Available / Access to Water Right	NA	94%	100%
		Curtailments directly apply to the Municipal and industrial users within the SNWA. However, while these users do not currently utilize this quantity of apportionment they may not be impacted by curtailments	
1,025 Feet Curtailed Allocations	**280,000 AF (20,000 AF curtailment)**		
Percent of Water Right Available / Access to Water Right	NA	93%	100%
		Curtailments directly apply to the Municipal and industrial users within the SNWA. However, while these users do not currently utilize this quantity of apportionment they may not be impacted by curtailments	

Appendix B1: Hoover Contractors

Metropolitan Water District of Southern California & Southern California Edison Company

The Metropolitan Water District of Southern California (MWD) utilizes all hydropower from Hoover Dam to move water from the Colorado River Basin to Southern California through the Colorado River Aqueduct. MWD is responsible for meeting all energy requirements for the Colorado River Aqueduct, and does so through their own Hoover allocation, a purchase agreement for Southern California Edison Company's Hoover allocation, hydropower from Parker Dam, and power exchanges with the Department of Water Resources. Currently, 50% of the Colorado River Aqueduct's pumping needs are met by their own Hoover allocation (Blue Ribbon Committee 2010).

Los Angeles Department of Water and Power

The Los Angeles Department of Water and Power (LADWP) is the largest municipal utility in the nation and the third largest utility in California. LADWP delivers 23.5 million MWh per year to 1.5 million customers in Los Angeles and 5,000 customers in the Owens Valley. LADWP is a vertically integrated utility, meaning that they own and operate a majority of their generation, transmission, and distribution systems (Los Angeles Department of Water and Power 2013).

LADWP's energy portfolio includes: natural gas, coal, nuclear, hydropower (large and small), wind, solar, geothermal, and biogas/biomass. They own and operate four natural gas electricity generating plants, one large hydroelectric pumped-storage plant, and a handful of solar, geothermal, and biomass projects. They also have entitlements from Navajo Generating Station (coal), Palo Verde Nuclear Generating Station, and Hoover Powerplant (Los Angeles Department of Water and Power 2014b).

Because LADWP is vertically integrated, they rarely purchase energy from the spot market. However, when it is economically viable to purchase energy from the spot market they participate exclusively in traditional spot markets with bilateral sales. Despite their proximity to CAISO, LADWP does not participate in CAISO markets because of issues with the ISO's regulatory and credit management practices and reciprocity requirements (Deaton 2007). Furthermore, because they own their own transmission lines and act as a balancing authority in the region, it is less economically viable for them to participate in CAISO's market than in traditional markets such as in the Southwest or Northwest region (*LADWP Eyes Renewables; Less Gas, Coal Use* 2008). As such, the hubs most utilized by LADWP are California-Oregon Border (COB), Palo Verde, and Mead (Los Angeles Department of Water and Power 2014a) .

During FY 2013-2014 LADWP spent \$1.5 billion on fuel and purchased power, and \$1 billon on operations and maintenance. Of the \$1.5 billion \$436 million was spent on fuel for generation, and \$977 million on purchased energy (Los Angeles Department of Water and Power 2013). Of the \$977 million, 17.3 million was spent on hydropower from Hoover Powerplant (Los Angeles Department of Water and Power 2014a).

Burbank

The city of Burbank, CA, located in Southern California, has been receiving power from Hoover Powerplant since 1936. The hydropower from Hoover dam is primarily used for reserve power, a backup in case a problem arises somewhere else in the system (Burbank Water and Power 2014). Burbank's customer base is approximately 24% residential, and 76% businesses.

Burbank is a vertically integrated utility. In 2007 they became the first US city to commit to using 33% renewable energy by 2020. In 2014, their energy portfolio consisted of: natural gas (30%), coal (29%), renewables (25%), nuclear (6%), hydroelectric (2%), and other (8%) (Burbank Water and Power 2014). Hoover Dam is included in the hydroelectric category, but does not count towards compliance with California's Renewable Energy Standards (33% by 2020).

Pasadena

As Pasadena's municipal electric utility, Pasadena Water and Power (PWP) manages Pasadena's Hoover hydropower allocation. They serve 140,000 customers over 23 square miles. In 2014 PWP delivered 1.15 million MWh's of electricity to their customers. Pasadena is part of the Southern California Public Power Authority, and participates in CAISO for necessary supplemental energy purchases (Pasadena Water & Power 2014).

In 2013, PWP's power portfolio included: coal (52%), renewables (27%), large hydroelectric (5%), natural gas (5%), nuclear (7%), and other (4%) (Pasadena Water & Power 2015). Pasadena owns minimal power generation facilities, but does own and operate a transmission area within the CAISO region. PWP purchases power for pumping water, as well as for residential and commercial uses. In 2014, PWP generated 75,000 MWh's, and purchased 1,130,00 MWh's of electricity (Pasadena Water & Power 2014).

Glendale

Glendale Water & Power (GWP) administers the city of Glendale's Hoover hydropower allocations. GWP serves 85,358 customers, and is part of the Southern California Public Power Authority. In 2014, Glendale sold 1,742,551 MWh to: residential (20%), commercial (19%), industrial (21%), spot (19%), other utilities (20%), and streetlighting (1%) (Glendale Water and Power 2012).

Glendale's portfolio includes natural gas, coal, hydropower, nuclear, and renewable energy, and is both self-supplied, and purchased on from other resources. GWP supplies 9% (127,663 MWh) of their power through facilities they own and operate. Approximately 39% (737,897 MWh) of the power is supplied by facilities jointly governed with other organizations, such as the Palo Verde Nuclear Generating Station, and the Tieton Hydropower Project. The remaining 52% (999,932 MWh) of their power needs are purchased through the Portland General Electric Contract or other market purchases (Glendale Water and Power 2014).

Boulder City, NV

Boulder City, NV has its own designated hydropower allocation through the Hoover Power Allocation Act of 2011. However, its allocation is administered through the Colorado River Commission of Nevada. Also the home of Hoover Dam, Boulder City serves 6,800 customers, and receives approximately 60% of their power from Hoover Dam (Colorado River Commission of Nevada 2012b).

Arizona Power Authority

The Arizona Power Authority (APA) was created in 1944 by the Arizona state legislature, in order to market Arizona's share of hydropower from Hoover Dam. APA sells spot power to 39 customers, including water, electrical, and irrigation districts, as well as cities. APA operates as a non-profit by crediting customers at the end of the operating year for any revenue in excess of expenses incurred (Arizona Power Authority 2014).

When APA's full Hoover allocation is unavailable, it will purchase supplemental energy, but passes on any extra expenses incurred entirely to the customer. APA is required to pay an extra 0.45 cents per kWh repay CAP expenses.

Colorado River Commission of Nevada

The Colorado River Commissions of Nevada (CRC) was created by state legal authority in 1935 to acquire, manage, and protect Nevada's Colorado River water resources—including water, hydropower, and the environment. CRC currently serves rural utilities, municipal utilities, and industries through contracts with: Southern Nevada Water Authority, Overton Power District No. 5, Lincoln County Power District No. 1, Valley Electrical Association, the City of Boulder City, and industries in the Basic Management Industrial Complex in Henderson, NV (Colorado River Commission of Nevada 2012a).

CRC sells power to its customers at cost, plus administrative fees. Any other charges include transmission, distribution, and ancillary services (Colorado River Commission of Nevada 2012b). They also manage power allocations from Parker and Davis Dam's, the Colorado River Storage Project, and the Salt Lake City Area Integrated Project. Hoover hydropower shortfalls are supplements from additional purchased power contracts. The Commission has recognized that issue of dropping reservoir levels in terms of their ability to provide to power their customers. CRC also participates in environmental programs in the Lower Basin such as the Lower Colorado River Multi-Species Conservation Program and the Salinity Control Forum (Colorado River Commission of Nevada 2012a).

Schedule B-Southern California Public Power Authority cities

All of the Schedule B contractors added in the 2011 Act (Anaheim, Azusa, Banning, Riverside, Vernon, Colton) are part of the Southern California Public Power Authority (SCPPA). Burbank, LADWP, Glendale, and Pasadena, who had contracts under the original Boulder Canyon Act are also part of the SCPPA. The SCPPA is a collective of eleven municipal utilities and one irrigation district, that was formed to provide the financial backing needed to acquire the generation and transmission resources needed for the members (Table 1). SCPPA also advocates for its members at a state and national level, and coordinates cost reduction and efficiency improvements for its members (Southern California Public Power Authority 2008).

Table 1: Schedule B contractors and their service bases

SCPPA Member	Annual Customer Base	Additional Notes
Anaheim (Anaheim Public Utilities)	113,434	Only municipal electric utility in Orange County. Own/operates facilities with 248 MW capacity power.
Azusa	15,276	
Banning (City of Banning Electric Utility)	11,800	Energy portfolio includes coal: nuclear, hydropower, and two geothermal plants in Imperial Valley which serves 20% of its customers
Colton (Colton Electric Utility)	18,715	Largest municipal electric utility in San Bernardino County
Vernon (Vernon Utilities Department)	1,888	Participating Transmission Owner in CAISO
Riverside (Riverside Public Utilities)	106,335	82 square mile service area

Appendix B2: Hydropower Cost Model Data

Table 2: Allocation and proportion data used in the Hydropower Cost Model

Contractor	Summer allocation (MWh)	Winter allocation (MWh)	Total Allocation (Pc) (MWh)	Percentage of total power allocated (%) in HPAA 2011	Summer percentage of Pc (%)	Winter percentage of Pc (%)	Monthly Summer Proportion	Monthly Winter Proportion	Assigned Spot Market Hub
Metropolitan Water District of Southern CA	859,163	368,212	1,227,375	26.60	70.00	30.00	0.02660	0.01596	SP15
City of Los Angeles	464,108	199,175	663,283	14.38	69.97	30.03	0.01437	0.00863	Palo
Southern California Edison Company	166,712	71,448	238,160	5.16	70.00	30.00	0.00516	0.00310	SP15
City of Glendale	47,777	19,297	67,074	1.45	71.23	28.77	0.00148	0.00084	SP15
City of Pasadena	39,021	17,594	56,615	1.23	68.92	31.08	0.00121	0.00076	SP15
City of Burbank	17,674	7,596	25,270	0.55	69.94	30.06	0.00055	0.00033	SP15
Arizona Power Authority	570,182	244,907	815,089	17.67	69.95	30.05	0.01765	0.01062	Palo
Colorado River Commission of Nevada	703,182	301,907	1,005,089	21.78	69.96	30.04	0.02177	0.01309	MidC
Boulder City	53,200	22,800	76,000	1.65	70.00	30.00	0.00165	0.00099	Palo
City of Anaheim	34,442	14,958	49,400	1.07	69.72	30.28	0.00107	0.00065	SP15
City of Azusa	3,312	1,438	4,750	0.10	69.73	30.27	0.00010	0.00006	SP15
City of Banning	1,324	576	1,900	0.04	69.68	30.32	0.00004	0.00002	SP15
City of Colton	2,650	1,150	3,800	0.08	69.74	30.26	0.00008	0.00005	SP15
City of Riverside	25,832	11,219	37,051	0.80	69.72	30.28	0.00080	0.00049	SP15
City of Vernon	18,546	8,054	26,600	0.58	69.72	30.28	0.00057	0.00035	SP15
Schedule D	248,377	67,975	316,352	6.86	78.51	21.49	0.00769	0.00295	Palo

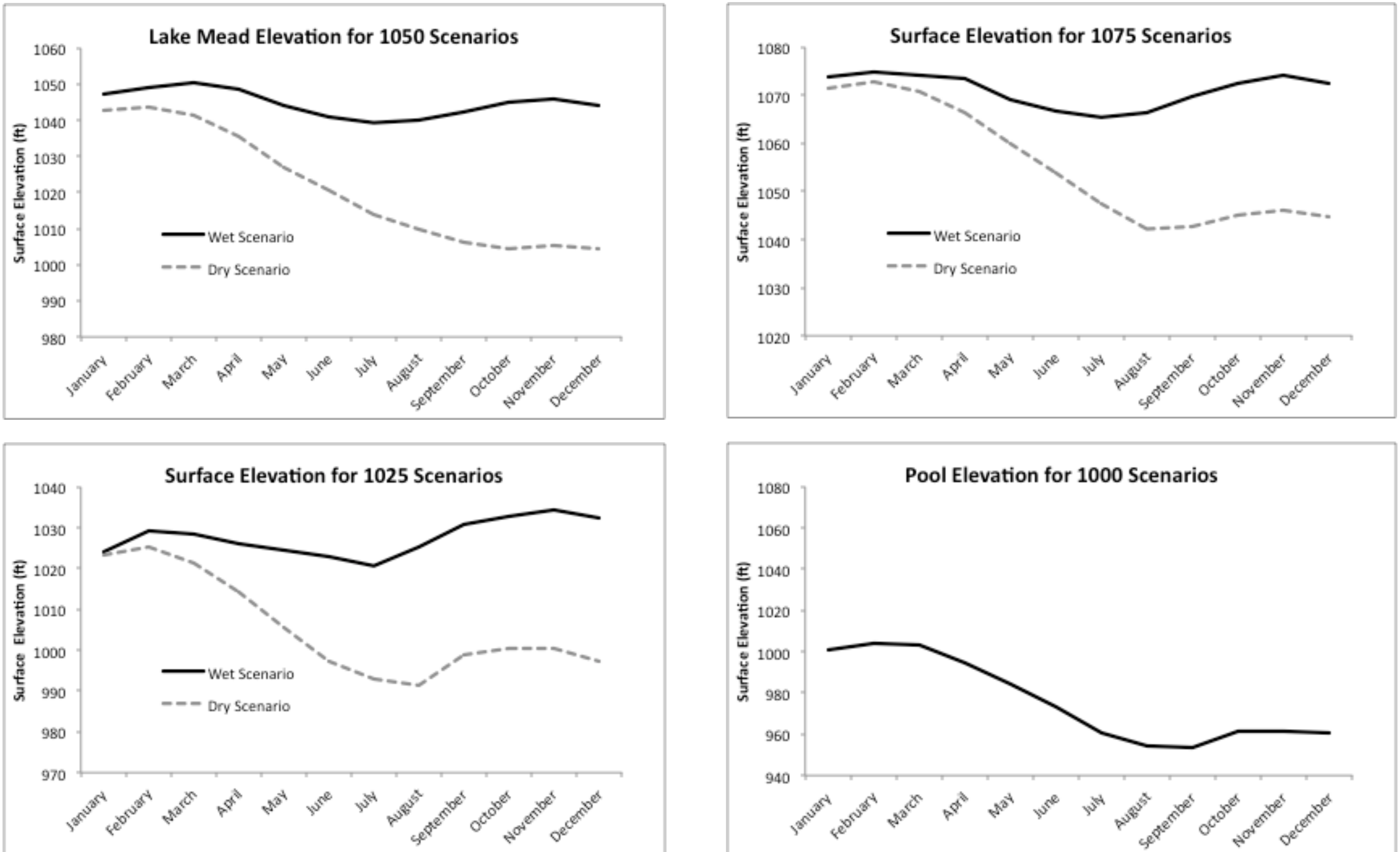

Figure 1. Surface Elevation of Lake Mead in each key elevation generation scenario.

Table 3: Monthly Spot Market Prices used in the Hydropower Cost Model

Month	SP15	Palo Verde	Mid-Columbia
January	$52.75	$35.93	$32.81
February	$53.21	$36.16	$33.06
March	$58.91	$38.30	$37.26
April	$64.63	$43.03	$37.00
May	$58.91	$43.78	$38.68
June	$54.60	$45.76	$39.02
July	$58.34	$53.86	$52.18
August	$52.45	$44.03	$46.34
September	$55.17	$41.42	$42.77
October	$48.85	$38.86	$42.15
November	$50.48	$37.05	$43.15
December	$60.31	$51.90	$64.93

Table 4: Hydropower generation from the generation scenarios used in the hydropower cost model.

Hoover Hydropower Generation								
	Full	*1,075'*		*1,050'*		*1,025'*		*1,'000*
Month	**Allocation**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet/Dry**
Jan	271,661	271,661	271,539	246,469	256,001	216,233	223,312	-
Feb	271,661	254,112	249,461	232,972	256,617	179,741	217,459	-
Mar	465,072	276,683	285,280	223,982	264,975	231,498	270,229	-
Apr	465,072	291,159	349,737	313,168	335,542	278,320	308,236	-
May	465,072	358,391	362,049	338,988	353,385	285,299	-	-
Jun	465,072	317,064	326,268	312,457	313,389	262,596	-	-
Jul	465,072	318,617	331,837	310,440	310,150	271,738	-	-
Aug	465,072	332,082	339,104	314,351	$-	254,958	-	-
Sep	465,072	319,996	314,857	304,817	-	231,001	-	-
Oct	271,661	213,775	209,810	217,309	-	186,174	-	-
Nov	271,661	160,329	145,604	170,522	-	128,792	-	-
Dec	271,661	236,336	220,842	241,456	-	201,861	-	-