Adaptation to Climate Uncertainty in the Colorado River Basin Water Resources System

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March 5, 2020

Contents

Abstract

Management of water resources systems is increasingly relying on methods to adaptation operations to many socioeconomic and hydrologic uncertainties. Future hydrologic uncertainty due to climate change will have rising impacts in the Colorado River Basin, where adaptive management is becoming progressively more important. In this paper, we review literature which analyzes this uncertainty, coupled with our own brief analysis of climate projections for the Colorado River. We then review literature on assessing the vulnerability of the Colorado River Basin to climate uncertainty with both top-down and bottom-up approaches. This is followed by our own new study, in which we develop a simple simulation model of this highly engineered river system. Coupled this model with synthetic streamflows generated for Lee's Ferry we perform out own simple yet flexible vulnerability assessment of the system. Results indicate that many aspects of system operations, including reservoir levels and water supply, are vulnerable to drier streamflows and reduced snowpack. Further extensions of this analysis could give more insight into potential adaptations to operations of water resources infrastructure in the Colorado River Basin under climate change. Overall, this review of climate uncertainty and adaptation literature for the Colorado River Water Resources System, as well as a case study considering climate vulnerabilities, gives significant insight into the impact of climate change on this crucial water source.

1 Introduction

The Colorado River Basin, spanning the states of Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming, is a crucial aspect of life for both human civilization and the natural environment in the American Southwest. The Colorado River originates in the high peaks of the Rocky Mountains, spanning over 1400 miles through the basin in the United States and Mexico. The Basin supplies water to nearly 40 million people, 5.5 million of irrigated land, 22 federally recognized tribes, and generates more than 4200 megawatts of electricity (USBR, 2012). Thus, the Colorado River has often been referred to as the "lifeblood" of the Southwestern United States (Fleck, 2016).

The Colorado River has been managed to enhance its ability in enabling society to thrive in the Southwest. One milestone in the management of the River was the Colorado River Compact, which governs the water rights of the river among seven states and Mexico. Signed in 1922,t he compact allocates 7.5 million acre feet (MAF) the the states in the Upper Basin (Colorado, New Mexico, Utah, Wyoming, 7.5 MAF to states in the Lower Basin (Arizona, California, Nevada), and 1.5 MAF to Mexico (Norviel et al., 1922), with specific allotments (Table 1) being later established (Johnson, 1928; UCRBcommission, 1948). It should be noted that this compact resulted in over-allocation of the River's flow, as it was based off of an average annual flow of 16.5 MAF as seen in a few wet years before the compact was written (Adler, 2008), while the long term average annual flow of the River has been estimated to be closer to 15 MAF (Meko et al., 2007). This was one of the first instances in which management of the basin was planned without consideration of the potential future conditions of this coupled human-environmental system.

Party:	Arizona	California	Nevada	Colorado	New Mexico	Utah	Wyoming	Mexico
Allocation (MAF/year):	2.85	4.4	0.3	3.9	0.85	1.7	1.0	1.5

Table 1: Annual flow allocations established as part of the Colorado River Compact, Boulder Canyon Project (Lower Basin states), and Upper Colorado River Basin Compact (Upper Basin states)

Given the Compact and water users' desires to use their full river allotments, the Colorado River Water Resources System has been highly engineered over the 20th and 21th century. Over 13 dams have been constructed just along the main stem of the Colorado River for the purposes of water supply, irrigation, and hydroelectric power generation (Joyce, 1997). The largest an most influential of these include the Hoover and Glen Canyon Dams, impounding the major reservoirs of Lake Mead (29 MAF capacity) and Lake Powell (27 MAF capacity), respectively. Major conveyance structures in the Lower Basin serve to divert and transport Colorado River water over far distances for both municipal supply and irrigation. Some major conveyance infrastructure includes the Imperial Irrigation District operated All-American Canal, Metropolitan Water District of Southern California's Colorado River Aqueduct, and the Central Arizona Water Conservation District's Central Arizona Project. Given the many agencies that utilize the river, coordinated management of the river is crucial. However, the system has historically been operated based the assumption of stationary hydrology consistent with historical observations of flows and demands Wheeler et al. (2019). Changes in hydrology, land use, water supply, irrigation, and electricity demands have led to the necessity to find new strategies and policies for management of the Basin (Brown et al., 1990; USBR, 2012). As the Colorado River Water Resources System faces these many future uncertainties, vulnerability and adaptation assessments of this system have become increasingly crucial to achieve effective adaptive management in the Basin.

2 Literature Review

2.1 Climate Change Impacts and Uncertainty

Significant uncertainty exists for future hydrologic and atmospheric patterns in the Colorado River Basin. Uncertainty in changes in variables such as temperature, snowpack, precipitation and streamflow can be reduced through the use of climate projections. In this section, we present two studies aimed at mitigating uncertainty regarding these changes in the Colorado River Basin, followed by our own brief analysis. While uncertainty also exists in terms of demand, land use, and other socioeconomic and environmental factors, in this paper we focus solely on hydrologic and atmospheric changes, also considering their impacts on management.

Climate scenarios themselves exhibit high uncertainty, as there are significant variations in projection outputs when analyzed as an ensemble. To generate climate projections, various degrees of socioeconomic assumptions are first used to generate different greenhouse gas emission levels across scenarios, known as representative concentration pathways (RCPs). The several options of global circulation models (GCMs) and regional downscaling procedures exhibit differences in the representation of physical atmospheric phenomena. Concerning hydrologic variables, several methods and models are available for routing precipitation to obtain streamflow values, given differences in land use and hydrologic assumptions. These many factors cause uncertainty to propagate through the set of models and assumptions. This process has been termed the "cascade of uncertainty" (Wilby and Dessai, 2010), and explains the variability seen in climate projection ensembles.

The first study we consider (Ficklin et al., 2013) focuses on analyzing and mitigating this uncertainty. Using an ensemble of projections from the Coupled Model Intercomparison Project (CMIP) phases 3 and 5, Ficklin et al. consider only the highest emissions scenario (IPCC A2). They focus on the median and first and third quartiles of streamflow across the ensemble for full natural flow (FNF) at Lee's Ferry, the location on the Colorado River which marks the boundary between the Upper and Lower Basins. They report these values for the 2040-2069 and 2070-2099 time periods for both total annual streamflow as well as spring and summer season streamflow. Several conclusions are made given their results (see Table 4 in Ficklin et al. (2013)). They find that the median of the streamflow ensemble decreases to -23% of average by the end of century time period, with the lower 1st quartile reaching 50% of flow. This represents a realistic potential for significant loss of streamflow. Although the majority of scenarios in the ensemble show decreasing flows, the third quartile in both time periods shows a +15% flow increase, denoting that a small set of scenarios exhibit an increase in streamflow over the century. Displaying spring and summer values allows for an analysis of earlier snowmelt and snowpack loss through the century. In both climate projections and the past several decades, this has been widely determined to be a direct result of warming temperatures (Mote et al., 2005; Knowles et al., 2006; Stewart et al., 2005; Barnett et al., 2008; Kapnick and Hall, 2010; Donat et al., 2013; Belmecheri et al., 2016). Ficklin et al. show that the median of spring flows shifts downward from -36% to -44% and the of median summer flows also lowers from -46% to -55%. These changes are greater than those changes in the overall annual median streamflow, representing a shift of streamflow and snowmelt volumes earlier in the water year. These same trends are shown in the first and third quartiles, denoting that this shift is present throughout ensemble scenarios. Major takeaways from this study are the variability in streamflow changes that mostly trend downward but still have potential to increase, as well as the presence of a shift to earlier streamflow throughout the ensemble.

Udall and Overpeck perform a similar study using the CMIP3 and CMIP5 ensembles, but use both business as usual (high emissions, RCP 8.5) and somewhat reduced by mitigation (moderate emissions, RCP 4.5) scenarios (Udall and Overpeck, 2017). They groups scenarios by both emissions scenarios and temperature to show probability density functions of Lee's Ferry FNF (see Figure 4 in Udall and Overpeck (2017)). Interestingly, they show only reductions in flow at end of century for these scenarios, which differs from the previous study which showed a small fraction of scenarios increasing in streamflow. They present various mean streamflow reductions, varying from -10% to -55% based on their different groupings of scenarios (Udall and Overpeck, 2017). Overall, these two studies present several techniques which are useful in understanding and reducing the uncertainty in future streamflow projections. These

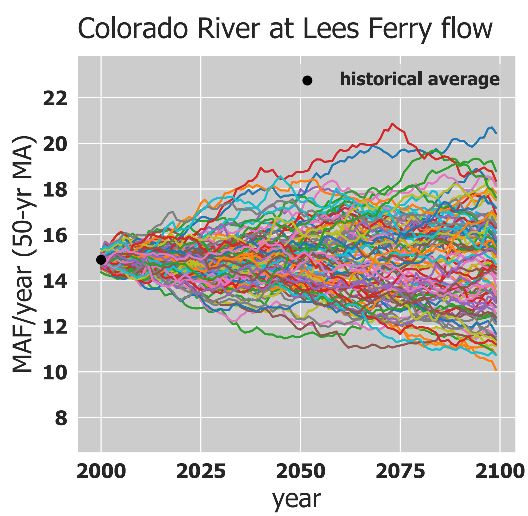


Figure 1: Projections of the 50-year moving average of total annual streamflow at Lee's Ferry. Data source: (Reclamation, 2014)

include including grouping scenarios by emission
and temperature increase levels, grouping of runoff values based on intra-annual timing, presenting mean streamflow values and probability density functions, and presenting median and quantile values.

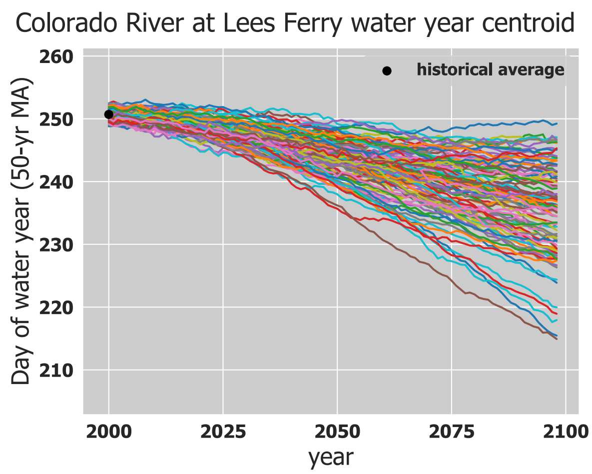


Figure 2: Projections of the 50-year moving average of water year cenroids at Lee's Ferry. For clarification, the water year begins on October 1st.Thus, day of water year 244 would represent June 1st. Data source: (Reclamation, 2014)

We consider an ensemble of 97 CMIP5 projections made publicly available by the United States Bureau of Reclamation (USBR) (Reclamation, 2014). These consist of various RCP levels run through 31 different global circulation models (GCMs), downscaled for the western United States region, and routed through the Variable Infiltration Capacity (VIC) model (Liang et al., 1994) to give future projections of FNF at various sites across the western United States. This climate scenario ensemble shows variability in both the magnitude and trends in total annual FNF at Lees Ferry and in a seasonal shift in streamflow due to rising temperatures. In Figure 1, we show similar results to Ficklin et al. (2013), presenting trends in Lee's Ferry FNF through a rolling average where each step in the timeseries represents the average of the past 50 years. The majority of scenarios show decreasing total annual streamflows through the century, while a small amount show some increase. While we do not present quantiles, the mean flow of the ensemble drops from to a 15MAF historical average to a 13.8MAF end of century average. To quantify intra-annual streamflow shifts due to earlier snowmelt and snowpack loss, we use the water year centroid (WYC) metric. The WYC is defined as the day of the water year (beginning on October 1st) at which 50% of the total annual flow has occurred. The WYC can also be viewed as the center of mass of the annual hydrograph (Herman and Giuliani, 2018). We show that every scenario in the ensemble shows lower average WYCs by the end of century, confirming this widely agreed upon impact of climate change. We calculate an average WYC shift of 18 years earlier in the year. In general out results from our brief analysis tends to agree with those from Ficklin et al. (2013) and Udall and Overpeck (2017). Overall, quantifying and narrowing uncertainty in climate projections can be an effective and necessary step in adaptation to climate change, including in the Colorado River Basin. Other examples of studies which examine uncertainties in projections of Colorado River streamflow include Dawadi and Ahmad (2012) and Vano et al. (2014).

2.2 Climate Adaptation Studies

Several options exist for water resources planning in the face of this climate uncertainty, utilizing both climate projections and statistical methods to represent uncertainty in future streamflows. The two main strategies consist of top-down and bottom-up methods. In a top-down study, any number of climate scenarios are downscaled, routed through a hydrologic model, and used as inputs to a reservoir model. Christensen et al. (2004) present an example of a top-down study for the Colorado River Basin. They run three downscaled business as usual climate scenarios through a reservoir model which consists of Lake Powell and Lake Mead, as well as four smaller reservoirs downstream of Lake Mead. They find that under the three scenarios, the probability of meeting lower basin supply target releases from Lake Powell (8.23 MAF/year) ranges from 60% to 70%. This is significantly lower than model output simulated with historical hydrology, which gives a probability above 90% that target releases will be met (see Figure 9 in Christensen et al. (2004)). In the same manner, they explore further probabilities of failure for other aspects of the system, including release targets to Mexico from Imperial Dam, Central Arizona Project shortages, and Metropolitan Water District shortages (Figures 10 and 11 in Christensen et al. (2004)). All of these show that the system is more vulnerable to shortages under the projected hydrologies than under historical hydrology. Overall, Christensen et al. show that using probability of failures may be an effective method to analyze system performance under climate change when a limited set of projections is available. Other top-down examples which use climate projections to simulate potential futures of Colorado River Basin include Rajagopalan et al. (2009) and Kopytkovskiy et al. (2015).

In contrast to top-down studies in which climate projections are used, bottom up studies perturb scenarios a priori with desired hydrologic and socioeconomic characteristics in order to analylze system performance under pre-specified states (Weaver et al., 2013). Hydrologic futures are often generated through synthetic weather and streamflows, in which hydrologic and atmospheric time series are generated with a statistical model based on historical record. In bottom-up studies, these synthetic time series can be perturbed to alter characteristic of synthetic time series, such as the mean or variance. We discuss two examples of bottom up studies for the Colorado River Basin, the first of which shows generation and use synthetic streamflows, and the second of which introduces Robust Decision Making. It should be noted that these two studies use The Colorado River Simulation System (CRSS,Schuster (1988)), a more complex model of the Colorado River Basin. This monthly time step planning model, developed by USBR, is the most detailed simulation model of the Colorado River Water Resources System available. On just the main stream of the Colorado River, it simulates 12 reservoirs and deliveries to over 500 individual water users.

In the first study, Barnett and Pierce (2008) simulate the CRSS using stationary synthetic time series generated with historical statistics (no climate change), and synthetic time series perturbed to give flow reduction levels of 10% and 20%. These synthetic scenarios are input to the model for each statistical perturbation up to the year 2060. The study, titled "When will Lake Mead go dry" focuses specifically on the probability of Lake Mead exhausting its storage to deadpool levels, which would denote vulnerabilities for both hydropower and water supply. The authors show that this probability rises logarithmically through time, reaching 90% probability of Lake Mead going to deadpool by 2060 with no climate change. Probabilities are higher through time for the reduced flow scenarios, approaching near 100% probability for the reservoir going dry by 2060 in the 20% reduced flow scenarios (Figure 6 in Barnett and Pierce (2008)). The authors extend their study from a vulnerability assessment to an adaptation study by incorporating management strategies in their simulations and analysis. These strategies include delivery cuts of either 10% or 25% the target release from Lake Mead when its storage drops below 15 MAF. They show that implementing these strategies can significantly lower the probability of Lake Mead dropping to deadpool over time for both natural stationary variability and reduced flow scenarios (see Figure 9 in Barnett and Pierce

(2008)). Overall, Barnett and Pierce present a well laid out example of using a bottom-up approach coupled with management alternatives for climate adaptation in the Colorado River Basin.

A commonly used formal method for bottom-up climate adaptation in water resources systems is robust decision-making (Lempert, 2002; Bryant and Lempert, 2010). In robust decision making, many scenarios are used to identify thresholds for vulnerabilities in a system. These are used to analyze potential robust management strategies and to evaluate their tradeoffs. Groves et al. (2013) provide a detailed example for the Colorado River basin, using the CRSS and synthetic generation. The authors perturb both synthetic temperature and precipitation time series to run a hydrologic model output through CRSS. They find a general vulnerability space for Lake Powell release deficits when precipitation drops below the historical average and temperature rises above two degrees Celsius (Figure 4.3 in Groves et al. (2013). They also analyze vulnerabilities to Lake Mead storage by developing vulnerability thresholds. These occur when the mean FNF of at Lee's Ferry drops below the historical average of 15 MAF/year and, to consider drought conditions, the mean of the driest year period drops below 13 MAF/year (Figure 4.4 in Groves et al. (2013)). They consider portfolios of management strategies which include increasing supply (e.g., ocean and groundwater desalination, wastewater reuse, and watershed management), and reducing demand (e.g., agricultural and urban conservation). They then analyze tradeoffs between these portfolios in terms of their robustness of limiting system failures in many vulnerable scenarios as well as potential for regret if they are implemented in scenarios which are not considered vulnerable. Overall, Groves et al. show that robust decision making can be an effective strategy for identifying vulnerabilities and proposing adaptations to uncertainty to improve the performance of the Colorado River Water Resources System under climate change.

3 Case Study

In this case study, we construct a simplified model of the Colorado River Water Resources System. We generate synthetic streamflows at Lee's Ferry to serve as model inputs. We use these to perform a bottom-up vulnerability assessment for the Colorado River Basin under climate change.

3.1 Simulation Model

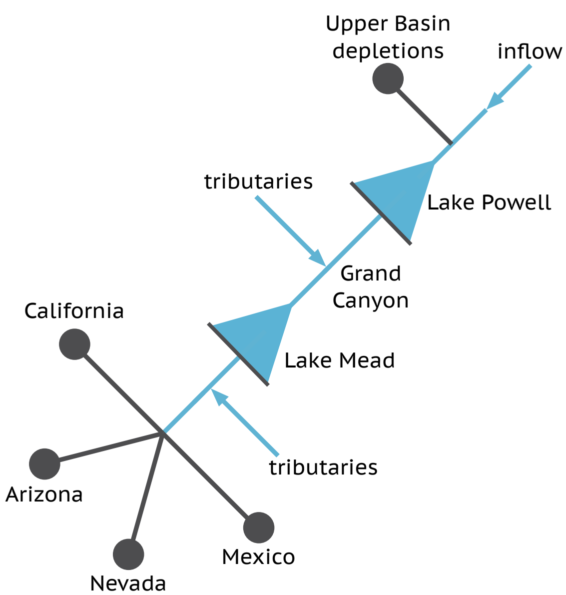


Figure 3: Schematic of the reservoir simulation model developed for this case study.

We construct a simple monthly time-step simulation model of the Colorado River Water Resources System. The model represents Lake Mead, Lake Powell, Upper Basin depletions, and deliveries to the Lower Basin states and Mexico (Figure 3). The main input to the model is the FNF at Lee's Ferry, which is used as the inflow to Lake Powell. Several operating rules, based loosely on those in CRSS and in agency documents, drive the system. The primary operating rule is that Lake Powell releases must be at or above 8.23 MAF/year. Releases only drop below this value if the storage in Lake Powell combined with its annual inflow is less that 8.23 MAF. The equalization of Lake Powell and Lake Mead is also simulated. This rule denotes that if Lake Powell storage is greater than that in Lake Mead, releases above the 8.23 MAF/year target occur in an attempt to equalize the storage in the two reservoirs. Upper Basin depletions are estimated to be 4.2 MAF/year (CRGI, 2012). For simplicity, this value is subtracted from the FNF at Lee's Ferry each year. Monthly demands for the Lower Basin states and Mexico are extrapolated from the Lower Basin Water Accounting Reports. These monthly demand values add up to give the annual allocations agreed upon in the Colorado River Compact. Lastly, drought curtailments in Lake Mead can occur based on its elevation. These are obtained from both those in CRSS and the 2007 Colorado River Interim Guidelines. The curtailment levels are described in Table 2.

Shortage tier	None	1	2	2'
Lake Mead Jan 1 Elevation	$\geq$ 1075'	$\geq$ 1050', <1075'	$\geq$ 1025', $<$ 1050'	<1025'
Total Reduction (MAF)	0	0.4	1.2	1.56
California Reduction (MAF)	0	0	0.72	0.94
Arizona Reduction (MAF)	0	0.32	0.4	0.48
Nevada Reduction (MAF)	0	0.013	0.017	0.02
Mexico Reduction (MAF)	0	0.05	0.07	0.125

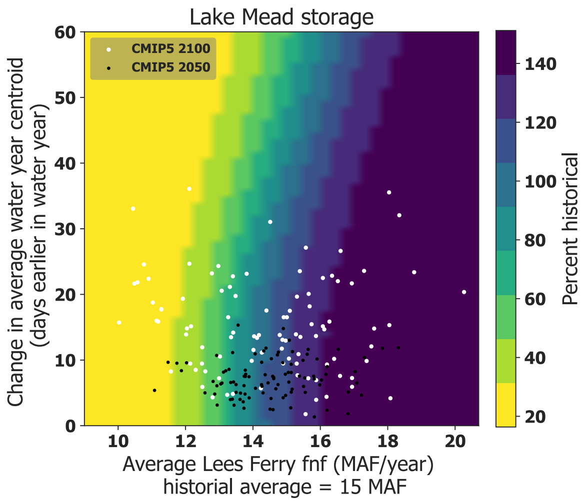
Table 2: Lake Mead release curtailments for each Lower Basin state and Mexico.

3.2 Synthetic Streamflows

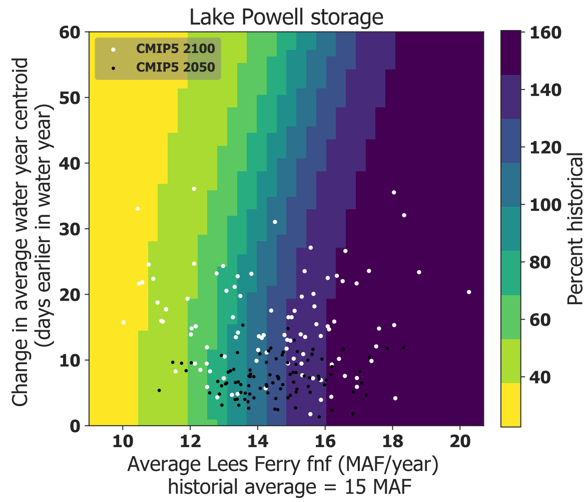
In a coupled top-down bottom-up approach, we develop synthetic streamflow for Lee's Ferry using both statistics from the historical record and those from climate projections. We initially use the auto-regressive Thomas-Fiering model (Thomas and Fiering, 1962) with monthly mean, variance, and auto-correlation values taken from the historical record of Lee's Ferry FNFs from 1950-2010. We analyze the range of changes streamflow projections to obtain reasonable functions for changes in the magnitudes of monthly means. The Thomas-Fiering model is perturbed with these changes in the mean, to create both "wetter" and "drier" scenarios. The second perturbation involves directly changing the water year centroid of streamflows to simulate earlier snowmelt and snowpack decline. Shifts in monthly mean streamflow in the climate projections are fit to triangular functions, similar to an analysis of projected snowpack in Rhoades et al. (2018). These functions are used to alter the water year centroid in the synthetic models, via functions which relate changes in inter-monthly mean streamflows. Synthetic streamflows are generated for shifts in mean annual streamflows from 9 to 21 MAF/year in steps of 0.3 MAF/year and for water year centroids from 0 to 60 days earlier in the water year than average, in daily steps. 1000 streamflow traces are generated for 2020-2100 for each combination of mean and water year centroid changes. This is able to expand these statistics to further ranges than occur in the climate projections. The model is then simulated with each of these sets as inputs.

3.3 Results

We analyze the system's response to these many futures in terms of Lake Powell and Lake Mead storage, Lake Powell releases, and supply to Lower Basin states via Lake Mead outflow. For reservoir storage results, end of water year storage in September is averaged over the 80 year timeseries for the 1000 synthetic traces for each of the streamflow futures. These are presented as percent of the average historical end of water year storage, rather than probabilities of failure that has been used in previous studies. Results are displayed in the form of a response surface which denotes these changes at various WYC shift and mean FNF levels. Results show that for both reservoirs, average storage changes over time are much more sensitive to changes in mean annual streamflow than to shifts in water year centroid (Figures 4a and 4b). However, average storages do tend to lower as the seasonal shift in streamflows become more severe. In general, a transition zone is seen for each reservoir, where percent historical falls between extreme high and low values. This transition zone moves slightly diagonally across the heatmap response surfaces, denoting sensitivities in system performance to both the mean streamflow (highly sensitive) and streamflow shifts (less sensitive).



(a) Lake Mead



(b) Lake Powell

Figure 4: Response surface denoting average end-of-water-year storage values in (a) Lake Mead and (b) Lake Powell.

We focus on the extreme values on the lower side of the transition zone, where average levels reach - 50% of historical average. Without a streamflow shift, Lake Mead reaches extreme low storage values just above 12 MAF/year annual flow (Figure 4a). With higher streamflow shifts, this can approach extreme low values just below 14 MAF/year annual flow. Many of the climate scenarios (represented by the black and white points) fall in these ranges by both years 2050 and 2100, denoting that these changes may be realistic and a significant chance for this vulnerability exists. The same patterns are seen for Lake Powell storage, which reaches extremely vulnerable states by a mean of 12 MAF/year FNF without a streamflow shift (Figure 4b). This is exacerbated in futures where the water year centroid shifts earlier. This again occurs in areas where climate projections fall. Therefore, significantly low storage in Lake Powell may be a realistic vulnerability.

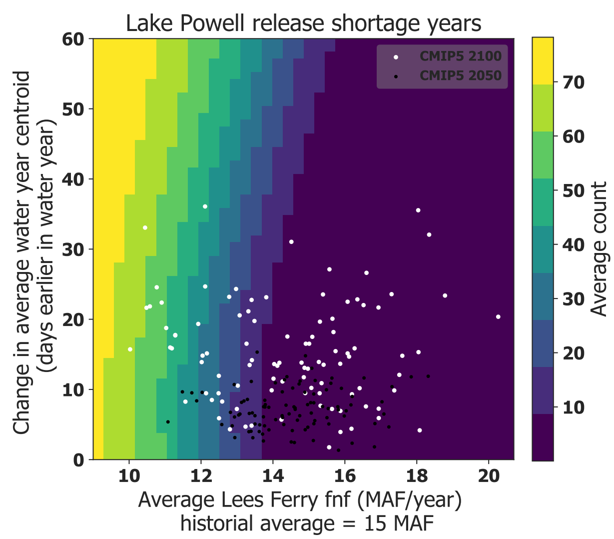


Figure 5: Response surfaces for average number of Lake Powell release shortage years.

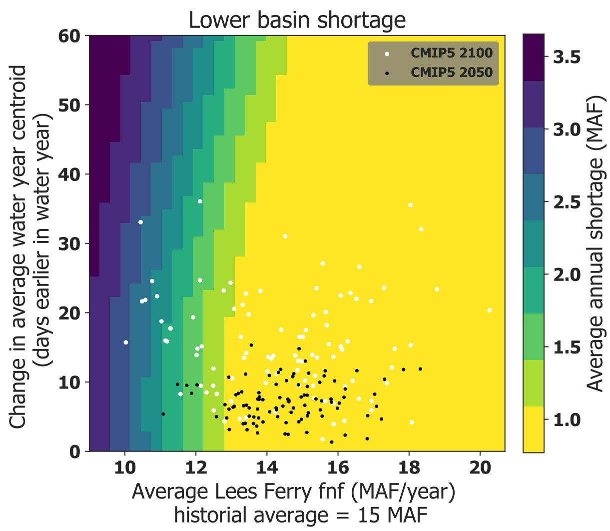


Figure 6: Response surfaces for average annual Lower Basin shortages from Lake Mead.

We next analyze the effect of these changes on the average number of years per scenario when Lake Powell does not release the required 8.23 MAF target (Figure 5). Without a shift in WYC, this average will remain below 10 years until 14 MAF/year. While no vulnerability threshold is defined, meeting this release is an important requirement for the system. Therefore, even relatively small fractions of years where the release is not met may be significant. Unlike other response surfaces displayed, the transition zone for this requirement does not begin until the average FNF drops 1 MAF below historical average. Thus, increases in shortage years for the Lake Powell requirement may not occur until the system is significantly stressed. However, once these decreases streamflow values are hit, vulnerabilities increase very quickly. As has been shown in the other analysis of system operations, WYC shifts have an increasing detrimental impact on this aspect of system performance as well.

Lastly, we examine the effects of hydrologic perturbations on supply to the Lower Basin as a whole, another aspect of the system which could be vulnerable to climate uncertainty. Here, the transition zone does not begin until 13 MAF/year. While the transition zone does move quickly once it is encountered, there is a maximum average shortage of 3.7 MAF/year, about half of the Lower Basin's allotment. This does not occur until a significant decrease in the mean FNF to 10 MAF/year, and still 11 MAF/year with a 60 day WYC shift. Therefore, it can be concluded that meeting the demands and allocations of the Lower Basin states is likely one of the more robust aspects of the system to hydrologic changes.

4 Discussion and Conclusions

Overall, we have analyzed and performed several methods for analysis of climate uncertainty and adaptation to climate change in the Colorado River Basin. For water resources planning in the face of this uncertainty, studies should focus on understanding a breaking down uncertainty in order to implement and test management options. We have shown, both through a review of the literature and our own brief analysis, that reducing the uncertainty in climate projections though several statistical analysis is an important step for this type of planning. The choice of whether to use these climate projections in testing management options is one of significance. We conclude through our analysis that they should be coupled with a bottom-up approach to determine hydrologic states in which system failures become more prevalent. To determine realistic potential for characteristics to occur in the future, the states of climate projections must be analysed in conjunction with the bottom up approach.

Even without further developing details in the simulation model, our brief study could be extended in several ways, inspired by both reviewed literature and complexity of the Colorado River Water Resources System. There are a few other system performance objectives which could be analyzed in model output. A clear one that is missing from this analysis is the deliveries to each individual state in the Lower Basin and Mexico. Response surfaces for each of these could be displayed and analyzed in order to observe the differences in vulnerabilities across parties of Colorado River Compact. Furthermore, different simple management alternatives could be implemented in the model and tested in an adaptation study. These could include alterations to the drought contingency plans used to curtail Lake Mead releases, increasing supply to Lower Basin states (ie. assuming desalination and water reuse), reducing their demands, and changes to Upper Basin depletions. The robustness of these actions across the response surface could be analyzed, similar to the analysis used in robust decision making. The basic study implemented in this paper has potential to be a step to easily perform more complicated climate adaptations studies for the Colorado River Basin without the use of complex models.

Given its significance and importance to the American Southwest, the Colorado River Basin will have to adapt to continuous changes in hydrology and human society throughout the 21st century. Effective adaptive planning will always be crucial in order to keep this system effective when faced with these many changes. This review and study gives insight into some of the strategies that may be useful for attaining these objectives in the face of long term climate change. In reality, water resources systems are constantly adapting to changes, and implementing formal strategies for doing so is the most effective way to achieve successful system performance from these adaptations.

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