Optimizing for Water Equity in the Colorado River Basin

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract— **The Colorado River Basin is experiencing water shortages of increasing severity and frequency. Due to the scale of the Colorado River Basin, its multitude of end users, and ecosystems dependent on its consistent water supply, these water shortages present a dire problem. If the Colorado River ran dry it would lead to a loss of $1.4 trillion in economic activity [1] not to mention the fatal impact on wildlife, Western populations, and environmental systems within its watershed. Our work focuses on optimizing Lake Mead reservoir operations to support the Lower Colorado River Basin. We produce alternative reservoir operating rules to address historic and present environmental justice issues. Our final results will be fundamentally driven by the hydrological budget of the river system and by human and environmental needs both now and in the future. We couple the Borg multi-objective optimization algorithm with the RiverWare river model, a decision support system, to design operating rules that prioritize flows to Native American reservations and tribal groups and Mexico. Our work distinguishes itself from past optimization applications by explicitly considering climate change scenarios and potential impacts on water justice issues faced by Native American tribal communities. Our results aid in identifying promising reservoir management alternatives at Lake Mead for controlling droughts both now and under future possible climate conditions. This work can inform the redesign of the Basin's operating policies after the current Interim Guidelines expire at the end of 2025.**

I. Introduction

The Colorado River Basin is home to over 40 million people as well as 5.5 million agricultural acres, 29 federally recognized indigenous tribes [2], 9 national parks and 7 wildlife refuges [3]. Its drainage basin includes all of Arizona, parts of Wyoming, Nevada, Colorado, New Mexico, Utah, and California [4]. The basin has been in a dry period since 2000 [3], which has only been exacerbated by growing water stressors from population growth and increasing evaporation from global warming. These dual pressures have depleted reservoir storage capacity, causing water managers to question current reservoir operating practices.

Most recently, the US Bureau of Reclamation declared the first ever Level 1 shortage condition at Lake Mead [5], a reservoir fed by the Hoover Dam. Lake Mead has been operating below capacity for years, threatening economic livelihood, storage potential, water security, hydropower generation and ecosystem health. This impact of climate change in the basin will require flexibility in operations at Lake Mead, as future conditions remain largely unknown.

The Colorado River Basin's water allocations are governed by the "Law of the River," a series of compacts, treaties, Supreme Court decrees, contracts, and records of decision [3]. Because of this collection of documents, water apportionments between states and users cannot be altered, but individual reservoir operating rules that influence user shortage frequency and severity can be optimized for future climate change scenarios. Operating policies determine release timing, volume and whether supply will be reduced or increased (during times of shortage or surplus) rather than total water allocation. All of the water in the basin has been allocated. It is extremely difficult to determine the probability of supply scenarios in the Colorado River Basin due to diverse stakeholder groups and interests, a wide range of drought and inflow conditions and ever-changing water demand, creating "deep uncertainty" [6]. With problems of deep uncertainty, it is appropriate to select the most *robust* solution, one that is applicable over a wide range of future scenarios rather than an optimal solution for a "best guess" projection [7].

Like all users in the basin, Native American water allocation is generally divided into municipal and industrial or agricultural, and water can be used on reservations for applications beyond these descriptors. The native use of water varies greatly, with the use of most priority being the meeting of basic household needs. Beyond this, uses vary from cultural to ceremonial to environmental. The Havasupai tribe prioritizes environmental maintenance of Havasu Canyon, the Hopi tribe cites the water and wildlife as being essential for ceremonies, and the Ute Mountain tribe relies on their allocation for agriculture so they can support their families economically. Native American groups are allocated about 20% of total flows in the Basin [2], however reservoir operating rules can exacerbate shortage frequencies and durations. By minimizing the severity of these shortages, a reduction of times of intense water scarcity can be achieved without changing the total amount of water allocated to a tribe. The USBR administered the 2007 Colorado River Interim Guidelines for Lower Basin Strategies for Coordinated Operations of Lake Powell and Lake Mead [8], a collection of strategies for coordinated management aimed at addressing shortage reductions at Lake Mead and Lake Powell. Expiring in 2026, its replacement policies must address deep uncertainty, as well as considerations for water equity throughout the Basin-wide water planning process.

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II. Problem Statement

To improve equity in the basin, this project aims to optimize reservoir operating policies in Lake Mead by coupling a RiverWare reservoir model of the Basin with Borg, a multi-objective optimization algorithm [9], to reduce the frequency and severity of indigenous water shortages in the face of drought and climate change. The model balances industrial water use, ecological impacts, economics and equity of allocation to redress water justice inequalities in the region. To address climate change, we optimize alternative reservoir operating rules to minimize simulated shortage magnitude and frequency between years 2020 and 2060 for our selected water users over an average of 8 possible future climate scenarios. This seeks to find reservoir operating rules that are robust across a wide range of projected climate change scenarios

III. Methods

A. *Study Area and Data*

Due to logistics and limitations of the modeling software, the scope was narrowed to focus on Lake Mead's operating policies rather than the entire basin. However, Upper and Lower Basin tribal users were considered as they were part of the watersheds draining into or receiving from Lake Mead. The study is entirely bound by the hydrological budget of the river systems around Lake Mead, specifically projected precipitation and flows that are predicted to be different from historic recorded flows as a result of the extended western drought and climate change. There will be no consideration of alternative dam systems, aqueduct and canal designs, stormwater management systems, or additional infrastructural water management. Data inputs, operating conditions, model licenses and formulation files for the Lake Mead operating system were supplied by the USBR.

B. *Model Description*

This project was completed using a modified version of the Colorado River Simulation System (CRSS), a river and reservoir modeling tool developed by the USBR in RiverWare for long term (decades) water supply planning [3]. With CRSS, researchers can project future water supply scenarios by simulating different operating policies, hydrologic inflows, and demand conditions for drought contingency planning. It uses a large set of inputs representing possible future hydrologic conditions to simulate a set of output time series of water supplied to different users. CRSS simulates water supply scenarios using a mass balance calculation, tracking inflows, storage and outflows in the system. The simulation is controlled by rulesets, or policies, that regulate when and where water is stored and released.

There are three characteristics of water supply: reliability, resilience, and vulnerability. The inverse, framed in terms of shortage, is frequency, duration, and intensity [10]. CRSS determines shortage by calculating the difference between supply and demand. According to the Colorado River Compact, Lake Mead should release 7.5 million acre-ft (maf) of water per year to the Lower Basin. Under the Interim Guidelines, <7.5 maf is released per year when the reservoir elevation falls below certain levels, resulting in shortage to downstream users [8]. The shortages below 7.5 maf that are delivered, and the elevation levels at which such shortages are triggered, formulate a reservoir operating policy. Results from the simulation of such policies inform water planners of the timing and severity of shortage conditions for different users under different operating rules.

C. *Optimization*

Real-world water resources systems have multiple conflicting objectives rather than one. Addressing the deep uncertainty of the Colorado River Basin's future state requires the consideration of many reservoir operating rules [6], climate scenarios and end user objectives - calling for the use of Multi objective evolutionary algorithms (MOEAs). Evolutionary algorithms employ a "search and destroy" method similar to natural selection, eliminating poor decision variables and refining good decision variables, exploring the bigger decision space and exploiting the local decision space to find the best "Pareto set" [11]. A Pareto set is a set of alternative operating rules that are "non-dominated," meaning no solution outperforms another on all objectives. For this study, the best solutions are the most robust (rather than "optimal") set of operating rules, defined as those achieving the best average performance across the 8 possible future hydrologic traces. We apply the Borg MOEA, a free and open source algorithm.

Coupling Borg optimization with RiverWare, we input decision variables describing Lake Mead operations (elevation levels and associated shortage volumes) and objectives describing shortage frequency and intensity for different end users to determine Pareto-optimal solutions. The Borg MOEA is executed through the command line with a software wrapper, running the CRSS RiverWare model through a loop, searching for solutions.

The Lake Mead optimization model was designed to discover operating policies which are determined by three kinds of variables with upper and lower limits provided by the model: water surplus distance, shortage elevation, and shortage volume. Water surplus distance describes the elevation at which *more* than 7.5 million-acre feet (maf)/year is released from Lake Mead, while shortage elevation and shortage volume describe the elevation at which *less* than 7.5 maf/year is released from Lake Mead and how much less, respectively. Operating policies are unique combinations of each of these variables. Within RiverWare, water users are assigned different priority levels that determine their susceptibility to shortage. A priority level of 1 indicates that that user will be in the first group of users to receive flows in the case where one group must have a shortage. A priority level of 4 means that a group will be the last to receive water when systematically allocated. These settings exist in the RiverWare system and are not changed when altering the model to our project.

The existing Lake Mead model is primarily designed to improve the 2007 Interim Guidelines for shortage reduction and water security [12]. This is done by simulating alternative values of the above decision variables over 8 possible future hydrologic traces and computing simulated performance on conflicting system objectives. We define 10 system objectives in Table I. This combination of minimizing shortage frequency and magnitude can help to provide the most tolerable drought management in a changing climate. The first four objectives were implemented to improve water equity for tribal water users. Running the model with solely tribal user objectives yielded 1 optimum result while placing the rest of the Lower Basin's water users at a severe disadvantage. Because of this, we created two broad objectives to minimize shortage frequency and volume for all Lower Basin users. Objectives MexShortV and MexShortF minimize magnitude and frequency of shortages received by Mexico to prioritize meeting the needs of these users, as well as incorporating environmental flows reaching the Colorado River Delta. The last two objectives address maintaining adequate water supply in Lower Basin reservoirs to avoid deteriorating storage capacity potential.

TABLE I. MODEL OBJECTIVES IN CONTEXT

Objectives	Description
Upper Basin (UB) Tribal Shortage Volume (UBShortVT)	Minimizes the average shortage volume amount annually for UB tribal users
UB Tribal Shortage Frequency (UBShortFT)	Minimizes the percentage of time that UB tribal users are in shortage condition annually
Lower Basin (LB) Tribal Shortage Volume (LBShortVT)	Minimizes the average shortage volume amount annually for LB tribal users
LB Tribal Shortage Frequency (LBShortFT)	Minimizes the percentage of time that LB tribal users are in shortage condition annually
LB Shortage Volume (LBShortV)	Minimizes the average shortage volume amount annually for all LB users
LB Shortage Frequency (LBShortf)	Minimizes the percentage of time that all LB users are in shortage condition annually
Mexico Shortage Volume (MexShortV)	Minimizes the average shortage volume amount annually for flows to Mexico
Mexico Shortage Frequency (MexShortF)	Minimizes the percentage of time that all flows to Mexico are in shortage condition annually
Combined Reservoir Storage Volume (CRSV)	Maximize amount of water in Lakes Mead and Powell
Lake Mead 1000 (Mead1000)	Minimizes the percentage of time that Lake Mead is below 1000 feet annually

In Table 1 above, the Upper and Lower Basin tribal objectives were determined using the geographic locations of the Native American reservations and assigned to groups accordingly.

IV. RESULTS

The optimization was run for 1145 evaluations of different policies and output 137 non-dominated solutions. To visualize the performance of the non-dominated policies, we created a parallel coordinate chart of 20 of the 137 solutions across the objectives (Fig. 1). To identify which 20 to compare, we increased the "epsilon values" used to determine the non-dominated policies. The epsilon values represent how much better an objective value has to be to warrant choosing that policy over another. In mathematical terms, changing the epsilon values of each objective limited the number of solutions on the Pareto front so that we had a smaller set of non-dominated policies from which to choose. Tribal water equity objectives were excluded from Fig. 1 due to uniformity across all policies.

The model sought to minimize all of the objectives. Each line on the plot represents a different policy and each objective is oriented on the x-axis. The height of the line with respect to the objectives shows their relative performance. All of the axes are oriented so that down is the favorable direction, so an ideal solution would be a straight line across the bottom of the graph. Instead, the lines cross showing that there are tradeoffs in performance of each policy for each objective. There was no one policy which dominated all the other policies over every objective. We observed that the values for all of the tribal objectives experienced no change regardless of the policy, so we have not included those objectives in the plot. We can conclude from this that the tribal objectives are unaffected by the different policies. As a result, we removed the tribal objectives from the rest of our analysis, knowing that the policy which best addressed the other objectives would result in acceptable values for the tribal objectives.

In the chart, trade-offs between objectives are visualized by the lines of different policies crossing. This makes sense intellectually because one policy is better and thus has a lower value for the first objective, but is worse and has a higher value for the second objective, necessitating an intersection. Policies which do not experience trade-offs across two objectives do not see their lines cross over those two objectives. The chart shows that the objectives of Mexico Shortage Frequency and Mexico Shortage Volume experience no trade-offs because none of the lines representing different policies cross in the chart. However, the Mead 1000 and Lower Basin Shortage Frequency objectives consistently experience tradeoffs as seen by the policy lines crossing in the chart. The policies which best address the needs of various user groups, regardless of tradeoffs, are displayed in Figure 2 below alongside the Current Operating Policy for comparison.

Figure 1. Parallel axis plot of model objectives for 20 non-dominated operating policies.

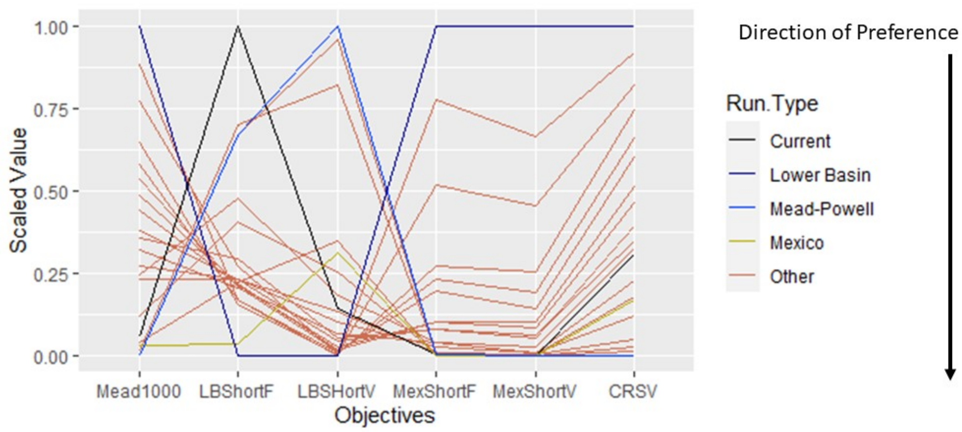
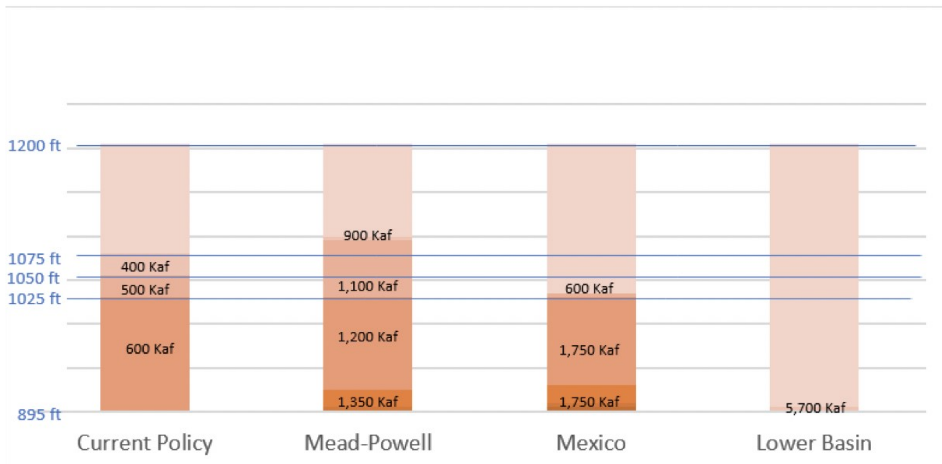


Figure 2. Shortage tier elevations and associated volume reductions for select model solutions.



One policy, labeled "Mexico" on the above chart, was found to be optimal for minimizing the Water Shortage Volumes and the Water Shortage Frequencies to Mexico. A separate policy, labeled "Mead-Powell", was optimal for minimizing the amount of time which Lake Mead was below 1000 feet annually and maximized the Average Combined Storage or the amount of water in Lakes Mead and Powell. Finally, the policy labeled "Lower Basin" minimized the shortage and frequency of shortages to all non-tribal Lower Basin water users. For comparison we also graphed the performance of the current reservoir operating policy, labeled "Current", to show how well our recommended policies performed relative to the existing policy.

The decision variables of these solutions are shown in Fig. 2 along with the results from the currently existing operating policy for comparison. Each bar represents a different policy and the y-axis shows different elevation levels of water in Lake Mead. The associated shortage volumes, or amount that would need to be reduced from the 7.5 maf/year release, are directly written on the color-blocked tiers. Elevations of particular interest are noted in blue.

We also sought to find a compromise policy that was not necessarily the best for either the flows to Mexico or the reservoir water levels, but which would balance all objectives. In order to find this moderate policy, we took several steps. First, we normalized the objective values for each non-dominated policy between (0,1) by subtracting the minimum value of each objective and dividing by the range of the values in that objective. We then squared each of those values. Finally, for each policy we summed the squared values of all objectives and evaluated which policy had the lowest sum and was thus the best compromise. Upon finishing this analysis, the best compromise was the same policy which optimized flows to Mexico.

V. Discussion

Original iterations of the optimization were done using main objectives of Lower and Upper Basin tribal users, flows to Mexico and other major descriptors of the basin. Across all of the policy iterations for this set of objectives, tribal water shortage frequency and volume remain unchanged. This indicates that regardless of the policy selected, all tribal users within the model will receive the same allocation of water. There is however variation in these allocations across different climate scenarios, the non-dominated policies show the mean of these scenarios. The lack of variation in the tribal users' average shortage is encouraging, as it shows that it is possible to reduce the water shortage frequency and volumes for Native Americans while still fulfilling other objectives, such as flow to Mexico. It is, however, disappointing that these stable values do call for some water shortages to the tribes in some climate scenarios. Although the shortages are temporally short and small in magnitude, we had hoped that the optimization would find even one policy which would result in no shortages for the tribes, particularly given the relatively small volume of water which the tribal users require annually.

A likely contributing factor to the stability of the shortage frequencies and volumes to tribal users is the relatively small volumes of water which they require relative to the overall Colorado River Basin. Additionally, tribal users have the most seniority in the system and are priority 1 for shortage prevention. However, despite this benefit, even these most senior users are facing shortages in the more severe climate scenarios, a concerning situation for the future of the basin in the face of climate change. Both Upper and Lower Basin tribal users request and receive allocations of water which are multiple orders of magnitude smaller than other users and the overall flows through the Colorado River. Due to the small scale, it does not tax the overall water level to provide tribal users a stable allocation regardless of the policy scenario. .

The rest of the users considered in this model experience significant fluctuations in water allocations depending on which policy is adopted. This is to be expected because water, like any other natural resource, has limited quantities available, and thus allocating more water to one user necessarily requires allocating less to another user. There is no easy solution to balance these tradeoffs in a way that will make every water user happy. However, there are some solutions that are clearly unjust as they unreasonably favor one user group over all others. For example, the solution that was optimal for minimizing Lower Basin Shortages caused enormous water shortages both to Mexico and in the reservoirs themselves (Fig. 1). The operating policy itself called for taking no action to minimize outflows from Lake Mead until the water level dropped below 895 feet (Fig. 2). This policy, although beneficial for Lower Basin users in the short run, was clearly not a reasonable option as it would necessitate effectively draining Lake Mead and prioritizing short run usage above all else. The environmental and long-term costs to all users of this policy would be catastrophic and could accelerate an end to the Colorado River Basin as we know it.

The policy which optimized the water level in Lakes Mead and Powell resulted in more significant shortages to Mexico as well as significantly larger, more sustained shortages to the Lower Basin users. However, these tradeoffs, when compared to the significantly better water levels in the reservoirs, could be justified. This policy is certainly feasible, but would face long odds of being accepted and adopted given the legislative power of and emphasis on Lower Basin users. Policymakers would have to be convinced that the long-term wellbeing of not only the Colorado River Basin, but also Lower Basin users depends on sufficient amounts of water remaining in the reservoirs and the corresponding environmental benefits of such a result.

The policy which optimally minimized the water shortages to Mexico was more universally acceptable as it did not call for the absolute prioritization of one user group at the expense of all others. However, this strategy did result in some larger, more sustained shortages in the Lower Basin than the policy which was optimal for the Lower Basin, which is an undesirable tradeoff, but one that could be deemed necessary. This policy did, however, do better than the Current Policy with regards to Lower Basin Shortage Frequency with only a small sacrifice in Lower Basin Shortage Volume. Additionally, this policy resulted in more acceptable water levels in Lakes Mead and Powell relative to many policies, but still not levels which all stakeholders would be happy to accept.

Upon calculating the compromise policy, as described in the Results section, we found that it was in fact the same policy which optimized flows to Mexico. This policy is the most reasonable, actionable option as it effectively balances the objectives for all users which are neither phenomenal nor horrendous. This policy is made more desirable by the fact that it not only serves as a compromise between all the users, but actually optimizes the flows to Mexico. The tradeoffs in the allocation of water to users in the Colorado River Basin are very strong. So strong that there is no one solution which optimizes flows to one user group while matching the requested allocations of all other users. Frequently the mark of a good compromise is that no individual walks away completely satisfied, but also that no individual departs feeling completely neglected. Climate change is a powerful force, and one that will fundamentally change the way that humans can live and our approach to natural resources. These consequences are made vividly apparent in the case of water allocation in the Colorado River Basin. There is no solution to the problem of water shortages which does not require at least one stakeholder to make sacrifices. Ideally, there is a solution in which all stakeholders make moderate sacrifices for the greater good of society and ultimately the planet. Such a desire is best manifested in the operating policy which optimizes flows to Mexico while also serving as the best compromise for the users as a whole.

That being said, depending on the focus and incentives of the policymaker, they could opt for one of the more extreme policies which more significantly benefits one user group over the others. For example, if decision makers decide that maximizing water levels in the reservoirs is the best way to ensure that there is sufficient water flowing through the entire Colorado River and contributing to environmental health, they would select the strategy which optimally minimizes water shortages in the reservoirs. The same rule would apply if policymakers were compelled to maximize flows to Lower Basin users.

VI. Conclusion

This project provides a simplified example of the power of optimization to address deep uncertainty, such as implementing robust water management policies in the Colorado River Basin. With immense unpredictability in forecasting hydrological conditions due to climate change, MOEA optimization for long term planning models such as the coupled Borg-CRSS model can aid water managers with investigating the tradeoffs between different operating policies. There are multiple sources of uncertainty and error when modeling any natural system with either randomness of the system or incomplete understanding of the natural mechanisms of the system [3]. With the Colorado River Basin system, possible sources of uncertainty are incomprehension of the inputs, outputs, policies and stakeholders of the river and the physical or hydrological principles that govern its natural characteristics. Uncertainty and errors in our model may also stem from CRSS initialization, as the model initializes with end of month reservoir conditions; different initial conditions may yield different results. The CRSS model used here is more simplified than the one used by professionals, as its associated files used for the optimization were limited to Lake Mead's operations. Modeling Lake Mead and Lake Powell with a more complex CRSS model would increase accuracy and yield a greater set of policy results. Finally, model formulation is a source of error as the combination of objective functions used in the optimization drives the solution.

A similar project could investigate possible robust operating policies for different hydrological scenarios for an isolated Lake Powell system or a larger model including Lake Powell, Lake Mead and additional water infrastructure in the Colorado River Basin. Ultimately, coupling Borg with the CRSS-RiverWare model is an effective tool for long term water planning for cases with deep uncertainty; this approach can be applied outside of the Colorado River Basin to find more robust operating solutions for future hydrological and climate change scenarios.

Although we searched for a robust solution in terms of application to different climate scenarios, the understanding of how sensitive the model is, is unknown. In a new project, greater sensitivity or a wider range of climate scenarios may help create recommendations that are more encompassing of unpredictable climate events.

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