M3 Challenge Fifth Place (Exemplary Team Prize) - $5,000
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Summary

The 26.2 million acre-feet of water in Lake Powell, the major reservoir in the Colorado River Basin maintained by the Glen Canyon Dam, is critical to the western United States in times of drought, irrigating crop fields, satisfying municipal and industrial water needs, powering towns and cities through hydropower.

The 1922 Colorado River Compact stipulates the allocation of 7,500,000 acre-feet of water per annum each to the Upper Basin and the Lower Basin. Now, in the middle of a historical drought whose end is unknown, the inflow of the reservoir is impacted and the reservoir water levels are fluctuating, drawing concern to the economic ramifications should the compact's regulations be maintained. Further legislation on managing the outflow would have to depend on a model estimating the percent capacity of the reservoir in the near future.

Therefore, we constructed a model for the capacity of the reservoir in 2015, based on the three potential inflow rates, at 39%, 83%, and 137% of the average inflow rate of 12 million acre-feet. The rates of inflow at Lake Powell have upper and lower bound predictions. These predictions can be used to determine scenarios on the extremes, yielding practical outcomes from using the highest and lowest predicted inflow rates. From these outcomes, we conclude that in the most likely scenario, about 70% of the time the reservoir will increase in percent capacity over the next 5 years, and that 30% of the time the reservoir will decrease in percent capacity over the same time period. We also adjusted our model to fit other inflow rates. The results of our model imply that economic-wise, for every foot drop in water elevation, there is a loss of 5.7 megawatts of power. There does not seem to be a shortage for water usage from the seven states supplied by Lake Powell.

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Background

Nearly a decade into an unprecedented drought, Lake Powell, situated roughly between the Upper and Lower Colorado River Basin and gated by the Glen Canyon Dam, has reservoir elevations fluctuating. As the principal water storage unit of the Colorado River Storage Project (CRSP) with the second highest concrete arch dam in the United States, the reservoir sustains the West with its water and its dams' hydroelectric power. Lake Powell with the Colorado River irrigates over 3.5 million acres of farmland and provides water to 27 million people in seven states, and the Glen Canyon Dam produces, along with the Hoover Dam further downriver, nearly 10 billion kilowatt-hours of power per year [CRSP Glen Canyon Unit].

(source: http://crc.nv.gov/map99.gif)

Figure 1 Colorado River Basin

Because the Lower River Basin's water resources depend predominantly on Lake Powell, the Colorado River Compact was implemented in 1922 to stipulate the water allocation. It designated a minimum of 7,500,000 acre-feet of water per annum each to the Upper Basin and the Lower Basin, but the compact was drawn in a period of higher than typical rainfall [Norviel, McClure, Carpenter, et al.].

The current bout of drought, whose end is unknown, has drawn scrutiny to this regulation. How exactly will reservoir levels persist, and what adjustments are necessarily to satisfy the Lower Basin's water and power needs while at the same time maintaining an operational minimum? Determining the percent of Lake Powell's capacity over the near future will be the first step to help legislators gauge the economic impact of the drought and aid them in revising regulations of the dam.

Global Assumptions

For the next five years,

- Legislation governing the operation of the dam will not be revised, and no new regulations will be implemented.
- No dams or reservoirs upriver of the Glen Canyon Dam, in the Colorado River, Escalante River, or San Juan River which feed into Lake Powell, will adjust their output significantly.
- Typical weather conditions will continue, and no natural disasters will occur.
- Absorption by rock and runoff due to seepage are minimal with respect to the overall capacity of the dam, and are assumed to be constant and can be disregarded.
- Amount of water that evaporates is constant and minimal enough to be disregarded.

A. Modeling the Changes in Reservoir Capacity

Model Assumptions

- Drought conditions will persist over the next five years.
- The predictions for the rates of inflow (39–137% of average) do not change.
- The restrictions on rates of outflow remain in place. Regulations pursuant to the 2007 Environmental Impact Statement dictate that, at the very minimum, 7.46 million acre feet (maf) of water be released from Glen Canyon Dam each year; 17.13 maf is the upper limit [Executive Summary]. 8.23 maf per year is the general rate of outflow given that no additional action needs to be taken. With these restrictions, the capacity of Lake Powell can be calculated using a sum of net water flow for each year.
- Since the inflow is defined to be just the amount of water that flows into Lake Powell, and not the amount that passes through the Glen Canyon Dam, the water lost to evaporation and seepage must be considered. This amount is assumed to be constant over the five year period and is estimated to be 860,000 acre feet per year [Glen Canyon Institute].

Creation and Interpretation of the Model

Despite the existence of upper and lower bounds for inflow rates, it is clear the inflow rates by year will vary. Hence the model for the percentage of capacity of the reservoir at the end of the five year period is the sum of each year's net flow rate added to the initial quantity in the reservoir. The net flow rate is the difference between the inflow and the outflow rates. This is represented symbolically below:

$$C = 14.4 + \sum_{n=1}^{n=5} (12.0 I_n - 8.23),$$

where C is the capacity of the reservoir in millions of acre feet (maf), n indentifies the year number after 2010, 14.4 is the initial amount of water in maf at the year $n = 0$, which is 2010, I_n is the percentage of the average inflow rate for a specific year n, and 8.23 is the outflow rate under conditions where there is no need for alternative actions. 12.0 maf is the average inflow rate.

According to the graphs.water-data.com database, for the last several years, the output value of Lake Powell has been the minimum output of 8.23 maf. In addition, every year, some water is lost due to evaporation and seepage [Lake Powell Water Graphs], which is estimated to be roughly 0.86 maf per annum. This total came to 9.09 maf.

Table of Predicted Reservoir Capacities in Acre-Feet Over Five years For Three Inflow Rates			
	Reservoir Capacity in Acre-Feet		
Year	With High Inflow (137% of average inflow)	With Most Likely Inflow (83% of average inflow)	With Low Inflow (39% of average inflow)
2010	14.4	14.4	14.4
2011	21.75	15.27	9.99
2012	29.1	16.14	5.58
2013	36.45	17.01	1.17
2014	43.8	17.88	-3.24
2015	50.85, or 212% of the average capacity	18.75, or 78% of the average capacity	-7.65, or -32% of the average capacity

Figure 2: Table of Predicted Percent Capacities Based on the Model

The table above only provides the scenarios where the rate of inflow is at extremes for the entire course of the five year period. However, this is unrealistic. Since the year-to-year fluctuation of the capacity is uncertain and the pattern of the water level in Lake Powell is non-deterministic, a stochastic process is used; in other words, scenarios were created with variable inflow within the range of possible rates of inflow.

Because we know that the inflow will vary from 39% to 137% with 83% being the most likely, a distribution is used based on information provided in the *Annual Operating Plan for Colorado River Reservoirs 2010*. It is given from the operating plan that in 50% of the predicted scenarios the inflow rate exceeds 83%, the “minimum” of 39% is given from 90% of the predicted scenarios having an inflow rate exceeding 39%, and the “maximum” of 137% is given from 10% of the predicted scenarios having an inflow rate exceeding 137%. Hence, a distribution is created by creating a library of 10,000 values following the distribution organized as follows: 1,000 randomly generated numbers from 0.00 to 0.39, 4,000 randomly generated numbers from 0.40 to 0.83, 4,000 randomly generated numbers from 0.84 to 1.37, and 1,000 randomly generated numbers from 1.38 to 1.76. Using a Monte Carlo simulation algorithm, given the aforementioned parameters, rates of inflow for individual years are calculated and plugged into the equation for I_n:

$$C = 14.4 + \sum_{n=1}^{n=5} (12.0 I_n - 8.23),$$

where I_n represents the randomly generated double mentioned before. Using this equation and iterating this test 10,000 times (thus 10,000 scenarios), the mean and quartiles are found.

The simulation was run 50,000 times to simulate possible rates of inflow for 50,000 independent years. Therefore, only 10,000 values resulted for the final capacity of the reservoir since each value is a sum of five different, randomly selected years. The graphs on the next page show these distributions.

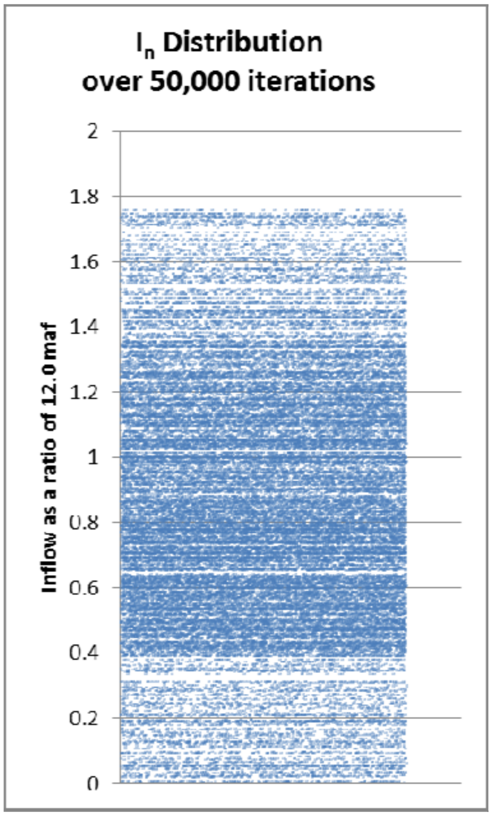

Figure 3: Inflow Rate Distribution Reservoir Capacity Projections

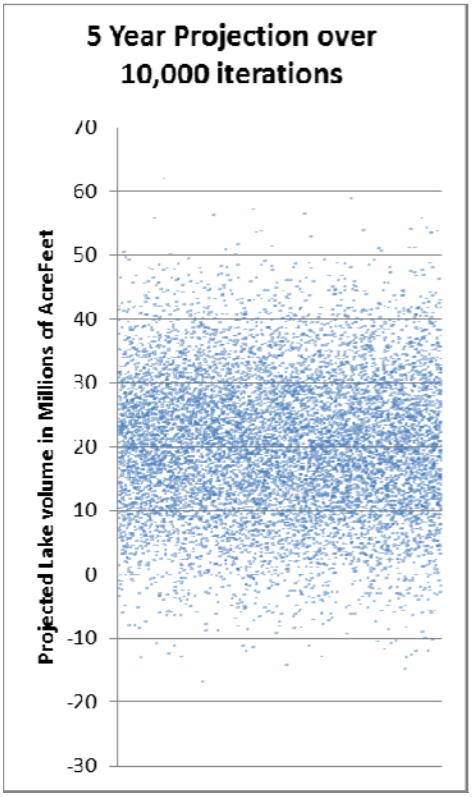

Figure 4: Reservoir Capacity Projections

- The inflow rate distribution has a mean of 0.853, or 85.3% of average flow rate, and a standard deviation of 0.394, or 39.4% of average flow rate.

- The five year projected reservoir capacity has a mean of 20.150 maf and standard deviation of 10.815 maf.

These data provide a better picture of the possibilities for how the reservoir will change over five years. Since the range of inflow rates is so highly variable, it is not surprising that the standard deviation for the possible reservoir capacity is so high. With a mean projected capacity of 20.150 maf, and a maximum capacity of 24.0 maf, the mean percentage capacity of the reservoir following 10,000 iterations of the simulation is therefore 83.96%. This turns out to be an increase over the current percentage capacity of 60%.

Low Inflow Conditions:

However, the above scenario is only the "most likely." Given the worst possible conditions of drought, inflow would be at 39% of the average flow rate. As shown previously, if this condition were extant, the percentage capacity after five years would be negative. This is physically impossible and thus warrants a change in the outflow. The Colorado River Compact, along with the Environmental Impact Statement of 2007, allows for the outflow rate to change if action must be taken. The lowest outflow rate legally allowed even after action is taken is 7.46 maf per year. With this figure, the percentage capacity at the end of five years with the driest possible conditions
is calculated as follows:

$$C = 14.4 + 5\left(12.0(0.39) - 7.46\right).$$

This formula will yield 0.5 maf left in the reservoir at the end of five years. This is 2.083% of the capacity of the reservoir. Under these conditions, Lake Powell will be nearly completely empty, but the outflow rate to the Lower Basin, most importantly to Hoover Dam, will still continue, albeit at a lower rate of 7.46 maf per year.

The two variables have an r-squared value of 0.9804, which indicates an extremely strong relationship between them. The equation relating the two is

$$y = 1.0497x + 509.95.$$

The graph below illustrates this.

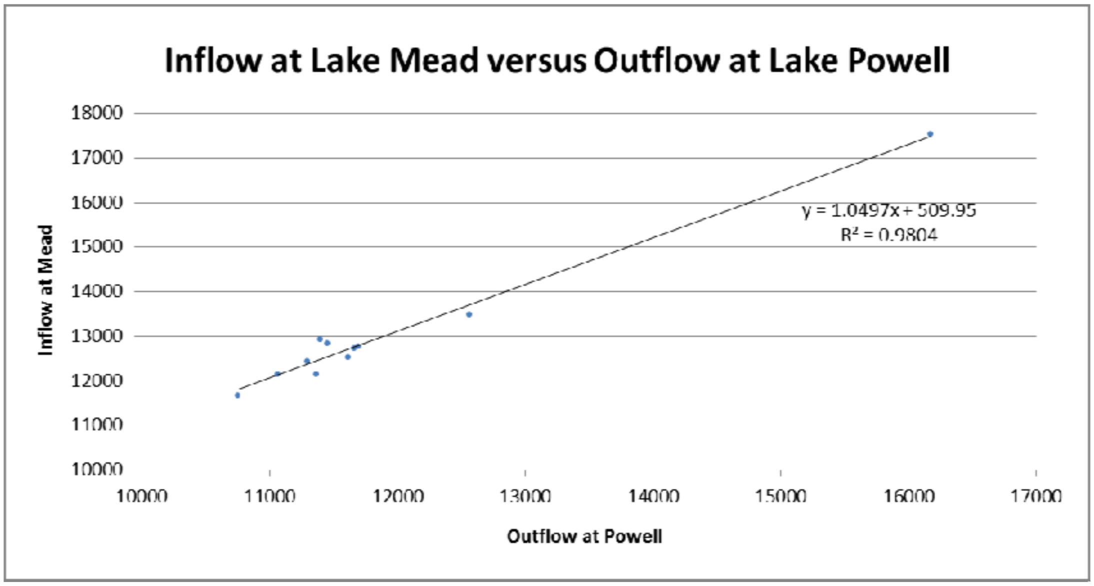

Figure 5: Inflow at Lake Mead versus Outflow at Lake Powell

Hence, substituting in a flow rate of 7.46 maf per year yields a predicted inflow at Lake Mead. First, 7.46 maf per year must be converted back to cubic feet per second. 7.46 maf is equal to 10304.34 ft^3/s. Thus the predicted inflow at Lake Mead is $y = 1.0497(10304.34) + 509.95$, which equals 11326.41 ft^3/s. It is known that the average inflow at Lake Mead from 1999 to 2009 is 13441.56 ft^3/s. It seems that there is a significant difference between these two values.

Knowing the predicted inflow at Lake Mead, we can predict the water elevation at the Lake. For every foot of elevation lost at Lake Mead, there is a drop of 5.7 megawatts of power at the Hoover Dam (Walton). This drop in power would have a significant impact on the economy of the Lower Basin.

High Inflow Conditions:

Under conditions where the inflow is a sustainted rate of 137% of the average for the entire duration of the five year period, then it is possible that the reservoir at Lake Powell will overflow if the outflow rate is not adjusted. Given that the outflow can legally increase up to 17.13 maf, an outflow rate lower than 17.13 can be calculated using an equality. Using an equation similar to the one used to calculate capacity in low inflow situations, the equality is

$$24 = 14.4 + 5\left(12.0(1.37) - O_p\right),$$

indicating that, to prevent overflow, a rate of outflow O_p must be great enough to at least remove enough water to keep the percent capacity of the reservoir at 100%. Following calculations, the rate of outflow is shown to be at least 15.12 maf per year to prevent overflow under high inflow conditions.

Economical Ramifications of Our Model

Knowing the predicted inflow at Lake Mead, we can predict the water elevation at the Lake. For every foot of elevation lost at Lake Mead, there is a drop of 5.7 megawatts of power at the Hoover Dam (Walton). This drop in power has a significant impact on the economy of the Lower Basin.

The three major uses of the outflow from Lake Powell are power generation, municipal and industrial water supply, and irrigation.

Power Generation

Water Use

The Colorado River is essential to providing water for the Lower Basin. The river not only supports 18 million people, but it is also involved in the irrigation of one million acres of farmland. The irrigation of this farmland is important in providing money for local economies. Without water from the Colorado River, several areas of the Lower Basin would not have access to enough water to support its people or properly grow crops. As of now, the water in the Lower Basin is apportioned in the following manner: the Lower Basin has 7.5 maf, and of that amount, 2.8 maf are given to Arizona, 4.4 maf are given to California, and 0.3 maf are given to Nevada [Dwyer, 2008]. All three of these states have experienced massive growth in recent years, so getting water to these areas is of great importance.

In southern Nevada, the recent drought has caused problems, especially because of Nevada's rapid population growth and the extreme upkeep that Las Vegas needs to maintain tourism. From 2002 to 2009, however, the South Nevada Water Authority has managed to reduce South Nevada's use of water from 314 gallons per capita per day (GPCD) to 240 GPCD. They are also attempting to reduce the GPCD to 199 by 2035. The renewed interest in decreasing water use is especially important considering the decline of water in the Colorado River. Reducing the need for water is crucial to solving the problem of the Lower Basin's loss of available water.

In the event that Lake Powell gets 137% of the average yearly inflow for five years, the water supply for the Lower Basin states would increase, since the amount of water to spare is enough to support a healthy surplus for the Lower Basin states to use. This may cause overdependence on a surplus in the future, though, so it would be best to continue trying to conserve water, even with a large amount of readily available water.

If only 39% of the average yearly inflow to Lake Powell occurs over five years, the Lower Basin states have a severe issue, because Lake Powell would run out of water within that time. The results would be disastrous, because no water flowing from Lake Powell means that entire cities would be without water. If this trend begins, it would be best to begin a large conservation effort immediately, to try to avoid a total crisis. Using less water in this situation might allow Lake Powell time to start filling up.

The most likely case, however, is 83% of the average inflow over five years. This would mean that the minimum legal amount of water could be given to the Lower Basin states without depleting the supply of Lake Powell. Difficulties arise, however, because the smaller surplus of water makes it more difficult to operate cities in the Lower Basin states. California, for example, needed a surplus of 4.4 maf to maintain itself before 2001. Guidelines were set up to allow

California a large portion of surplus water, so this drought may cause issues with California's maintenance. Fortunately, the same guidelines stipulated that California had to attempt to create conservation methods so as to not depend on the Colorado River's surplus, ensuring that the impact of a lack of surplus on California will not be devastating.

B. How Changes in Assumed Flow Rates Affect the Model

Our model in section A was developed using a library of 10,000 values in the following distribution:

	Levels of Fraction of Average Flow			
	0.00–0.39	0.40–0.83	0.84–1.37	1.38–1.76
# of randomly generated numbers	1000	4000	4000	1000

To see how changes in the assumed likelihood of flow rates affect our model, we adjusted the distribution of the library of values to simulate a situation with lower typical rate of inflow:

	Levels of Fraction of Average Flow			
	0.00–0.39	0.40–0.83	0.84–1.37	1.38–1.76
# of randomly generated numbers	4000	4000	1000	1000

We also ran another simulation with a distribution of the library of values that emulates a higher typical rate of inflow:

	Levels of Fraction of Average Flow			
	0.00–0.39	0.40–0.83	0.84–1.37	1.38–1.76
# of randomly generated numbers	1000	1000	4000	4000

When these parameters are implemented and each simulation is repeated five times, the results obtained are as follows, where Increasing Scenario indicates the number of runs in each trial that resulted in an average volume at the end of five years that is greater than the initial capacity of 14.4 acre-feet; the Decreasing Scenario indicates those that were less than the initial capacity. Constant Scenarios designate the number of runs that resulted in the same volume of Lake Powell as initially.

Trial #	Average volume at the end of 5 years (in acre-feet)	Increasing Scenarios	Decreasing Scenarios	Constant Scenarios
1	3.668	166	834	0
2	4.156	180	820	0
3	4.135	187	813	0
4	4.110	202	798	0
5	4.563	200	800	0

Figure 6: Table of Simulated Capacity for a Lower Typical Inflow

Tiral #	Average volume at the end of 5 years (in acre-feet)	Increasing Scenarios	Decreasing Scenarios	Constant Scenarios
1	37.564	968	32	0
2	37.602	962	38	0
3	37.950	962	38	0
4	37.866	964	36	0
5	37.622	964	36	0

Figure 7: Table of Simulated Capacity of a Higher Typical Inflow

Positive and negative shifts of the mean can greatly change the overall capacity of Lake Powell, which will in turn significantly impact the water supply in the Lower Basin. Even when the outflow of the lake was slightly increased from 8.23 to 9.09 maf, this resulted in an decrease in capacity of Lake Powell by about 4 maf.

C. Recommendations on Reductions of River Water Removal Upriver

In order to reduce the amount of water removed from the Colorado River before it reaches Lake Powell, water can be stored in headwater reservoirs to minimize the water loss due to evaporation. Excess water can also accessed through a banking system that would allow states to buy excess water from adjacent states or market their water as well [U. S. Geological Survey].

The states of the Upper Basin can increase the inflow into Lake Powell by economizing the water they use for themselves so as to not deplete any surpluses. The Lower Basin states are continually expanding, while the Upper States are not experiencing high levels of growth [Upper Colorado Basin]. This means that the Lower Basin states need a lot more water to maintain themselves than the Upper Basin states do, especially since the Lower Basin states experience much less annual rainfall than the Upper Basin states. Even though a light drought wouldn't deplete Lake Powell, it is still a good idea to get more water flowing to the Lower Basin states, because of legal obligations and environmental concerns. 90% of Colorado's water comes from the Colorado River, so any reductions in Colorado's water usage would most likely have a very positive impact on the Lake Powell Reservoir [Alternative Water Sources]. Other states that don't depend as much on the Colorado River may have an easier time with reducing the amount of river water they use.

A simple way to reduce water usage from the Colorado River is to look for alternative water sources. The large amount of water that becomes contaminated after being used in showers and washing machines can be reclaimed, as can wastewater. Desalinization may be a good option for Utah, because water from Utah's Great Salt Lake can be altered into fresh water. Desalinization is expensive, however, so this option is quite limited. Rainwater can be harvested for use in a few specific areas of the Upper Basin, reducing river water consumption in those areas.

Releasing Public Service Announcements about how to reduce water usage is a good way to educate citizens about their impact on the supply of water in Lake Powell, and these campaigns could greatly reduce the high water usage that comes with activities like incorrectly watering plants or taking long showers. Over 5 acre-feet of water can be saved in a year if .1% of the population of Colorado managed to save a gallon every day [Alternative Water Sources].

Capping general water use might be difficult because of the amount of water states must use to maintain a normal American lifestyle in both residences and public places. There is a possibility, however, that placing water usage caps at a smaller level can greatly increase the amount of water that can be saved. Capping the amount of water that a nonresidential hose is allowed to spray in a minute is another way to reduce water usage. Lowering water usage in car washes and botanical gardens can greatly increase inflow into Lake Powell. Regulating the amount of water that government buildings use can greatly reduce water consumption without stepping on the rights of private citizens.

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