Executive Summary

In order to surpass the constraints of an arid environment, the economic development of the Southwest involved significant damming of the Colorado River and water allocations to the Lower Basin in 1922. However, a sustained drought has raised valid concerns that future water consumption and allocations cannot continue at these levels. Upon further analysis of the impact of drought on Lake Powell, the team determined that an analysis necessitated a consideration of the Lake Powell-Lake Mead system, in terms of inflow/outflow and economic factors. The inflow and outflow of Lake Mead was therefore modeled as a function of the inflow of Lake Powell, and the consequent necessary outflow of Lake Powell was modeled.

The effects of the water supply, depending on the inflow of Lake Powell, had been determined by the previous model. The effects on the economy were calculated by approximating the change in land able to be irrigated by the Colorado River, per state, as determined by the water released by Glen Canyon Dam to Arizona, California, and Nevada. In the minimum scenario, irrigated land capacity decreased by 40%, 42%, and 74% for the three states, respectively. In the average and maximum inflow scenario, irrigated land capacity actually increased with the increased outflow from Lake Powell, indicating that water usage could be decreased in these scenarios. In the minimum scenario, the water level in Lake Mead decreased past 1,050 feet, a critical level at which hydroelectric power production ceases. The power production was determined by calculating the power produced by Hoover Dam, which depends on outflow rate and Lake Mead height.

The sensitivity analysis of small changes in inflow rates was determined by changing the percent inflow by incremental changes of 1% through 10%. The graph of the results shows that as the water entering Lake Powell changes, the water exiting Lake Powell/Glen Canyon Dam and the power generation at Hoover Dam diverges from the known data over time. The outflow of the lake eventually stabilizes to a certain value. A certain percent change in the water entering Lake Powell results in an almost equal change in the water volume change of Lake Powell, but a significantly smaller change in power generation at Hoover Dam.

The team was also asked to analyze methods of reducing water consumption from the Colorado River, to maintain minimal capacity at Lake Powell. The current interim guidelines for inflow/outflow between Lake Powell and Lake Mead increase the discrepancy between the water levels between the two levels. Therefore, the minimal capacity of Lake Powell was the inflow into the lake necessary to maintain a stable water level at Lake Mead that allowed for hydroelectric power generation. This reflects a necessitated change in policy that 1) Lake Mead's water level should be maintained at a stable level above Hoover Dam's critical requirement and 2) overall consumption should be decreased through conservation policies and efficient reallocation of water resources.

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Introduction

Background

Lake Powell, an artificial lake on the Colorado River, controls the water flow to the Lower Basin states of the river, most prominently California, Nevada, and Arizona, as guided by the Colorado River Compact of 1922. The lake is gathered behind the Glen Canyon Dam, which regulates the outflow of the lake. The main function of the lake is to store water for allocation to downstream states in dry periods of time(United States Department of the Interior).

Recently, the area has been suffering from a prolonged drought, causing a decrease in the inflow of water, and therefore the water storage volume, of Lake Powell. Current projections indicate that the drought will most likely continue, with both higher than average temperatures and lower than average precipitation in the area being predicted for the coming months. In the future, it is predicted that the inflow of water into Lake Powell may be as low as 39% of the historical average of 12 million acre-feet per year (MAF/yr) or as high as 137% of average, averaging out at approximately 83%. The effects of extreme fluctuations in the inflow would have drastic effects on the amount of water that inside the lake.

In addition to the immediate effects on Lake Powell, the current drought affects many areas in the Lower Basin that obtain water from the Colorado River. Hydroelectric power plants, such as the Hoover Dam, generate electricity as a function of the depth of water collected at the front of the dam. The power generators also need a certain depth of water in order to function at all; below a certain threshold, the generators must be shut down to prevent damage. Reduced water supply to Lower Basin states also adversely impacts the ability of those states to irrigate crops, leading to negative impacts on agriculture. These two major effects, along with other effects associated with decreased water supply, lead to deleterious effects on the economy.

In light of the above effects of the drought, accommodations must therefore be made to ameliorate the decrease in water supply.

Restatement

The goals of this paper are:

1. To model the water volume of Lake Powell over a five-year period based on given inflow rates.
2. To model the effect that changes of the inflow rate have on areas of interest downstream from the lake.
3. To examine the sensitivity of the model.
4. To recommend courses of action to counteract the effects of the current drought.

Global Assumptions

1. The data gathered from external sources on which the models are based are correct.
2. The government laws describing the allocation of water from Lakes Powell and Mead will not change during the period of study.

Fundamental Model: Inflow/Outflow of Lake Powell and Lake Mead

Assumptions

I. Over a five-year interval, the inflow rate into Lake Powell will remain fixed at the given value.
II. Over a five-year interval, changes in the weather will not significantly affect the evaporation rates of Lakes Mead and Powell and will not affect other sources of inflow into Lake Mead.

The effects of the change in water supply in Lake Powell cannot be determined without also considering the significant economic effects that Lake Mead and Hoover Dam have on the economy. Most of the outflow of Lake Powell continues down the Colorado River to the next dam, Hoover Dam, which is a significant source of hydroelectric power for the region. Since the water levels of Lake Mead depend on the outflow of Lake Powell, these two lakes must be evaluated as a total system.

Lake Powell

The volume of Lake Powell is dependent on the inflow, the outflow, the initial volume, and evaporation:

$$P_{vol}(n+1) = in_P(n) + P(n) - evapr_P \cdot P(n) - out_P(n).$$

The inflow of Lake Powell, as given in the assumptions, will take on three different values, upon which sensitivity analysis will be performed:

$$in_P = \begin{cases} 0.39 \cdot average = 4.68\dfrac{MAF}{year} & low\ estimate, \\ average = 12.0\dfrac{MAF}{year} & average\ estimate, \\ 1.37 \cdot average = \dfrac{16.44MAF}{year} & high\ estimate. \end{cases}$$

The amount of water evaporated is assumed to be constant, at a fixed value of 2.5% of the volume of Lake Powell (United States Department of the Interior).

Outflow was calculated by performing analysis on previous years of data from Lake Powell. It is assumed that the outflow of Lake Powell is related to the amount of water currently in the lake. Utilizing historical data, we plot water output rate to lake volume (Figure 1). We choose to ignore data from the years 1963, 1964, 1965, and 2011, as these are years in which (a) the dam was not yet filled to completion, and (b) we do not have complete data. After removal of these data, we note that two distinct regions of the relationship appear, separated at some critical lake volume (Figure 2). The first region appears to indicate a constant outflow rate, regardless of lake volume, while the second region (above the critical lake volume of 23 MAF) indicates a linear increase in outflow rate with respect to lake volume.

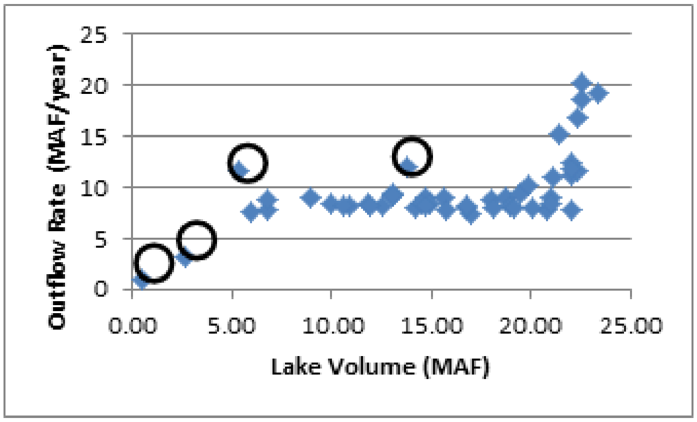

Figure 1- Outflow Rate versus Lake Volume of Lake Powell

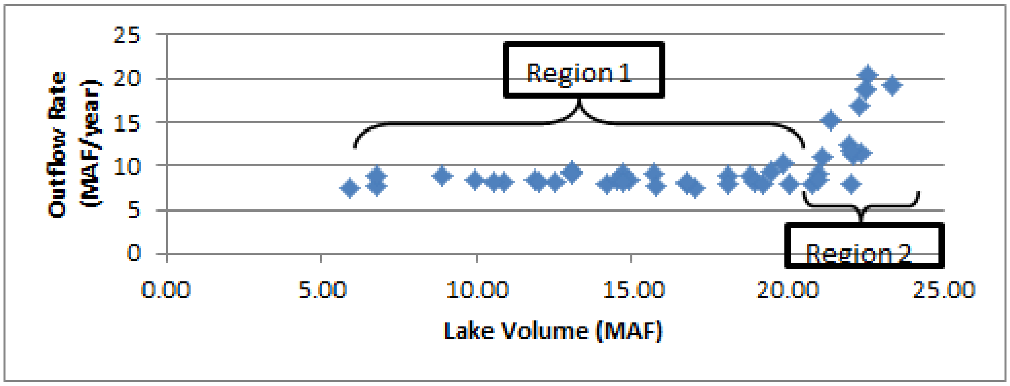

Figure 2- Lake Powell Outflow Rate versus Lake Volume

Because Region 1 is flat, the ratio of outflow rate to lake volume is found by taking a statistical average. This yields a value of $\frac{0.631821}{year}$. In Region 2, a linear regression is calculated. The line of best fit is $\widehat{outflow}\left(\frac{MAF}{year}\right) = \frac{3.903}{year} * \left(lake\ volume\ (MAF)\right) - \frac{77.337MAF}{year}$, with $r^2 = 0.3186$.

To test if there is dependence, a sampling distribution for regressions slopes is performed. For this test, H_0: $\beta_1 = 0$, H_1: $\beta_1 \neq 0$, $\alpha = 0.05$. The t-statistic can be found: $t = \frac{b_1 - 0}{\frac{s_e}{\sqrt{n-1} * s_x}} = \frac{3.903}{\frac{3.553}{\sqrt{10} * .591}} = 2.053$. The probability is then found by calculating the are under a t_9 distribution from 2.053 to infinity, and find that $P = 0.0352$. With P-value less than the $\alpha = 0.05$, the null hypothesis is rejected, indicating that outflow rate is dependent on volume of the lake in Region 2.

The model is now expanded to

$$P(n+1) = in_P(n) + P(n) - 0.025 \cdot P(n) - \begin{cases} 0.6318 \cdot P(n) & for\ P(n) < 2.3 * 10^7, \\ 3.903 \cdot P(n) - 77.337 & for\ P(n) > 2.3 * 10^7 \end{cases}$$

(where in(n) is the inflow rate based on 39%, 83%, and 137% of average inflow).

Lake Mead

The volume of Lake Mead can be analyzed in a similar manner:

$$M(n+1) = in_M(n) + M(n) - evapr_M \cdot M(n) - out_M(n).$$

The evaporation rate of Lake Mead is found from historical data to be $evapr_M = \frac{0.937500MAF}{year}$ (U.S. Geological Survey).

The inflow must be broken down. There are several sources of inflow into Lake Mead, including Lake Powell, which contributes 97.08% of the inflow, and other smaller sources, as seen in Figure 3 (Las Vegas Wash Coordinating Committee). The historic data of outflow of Lake Powell and inflow of Lake Mead were compared, to determine the ratio of outflow of Lake Powell that reaches Lake Mead (weather-data.com).

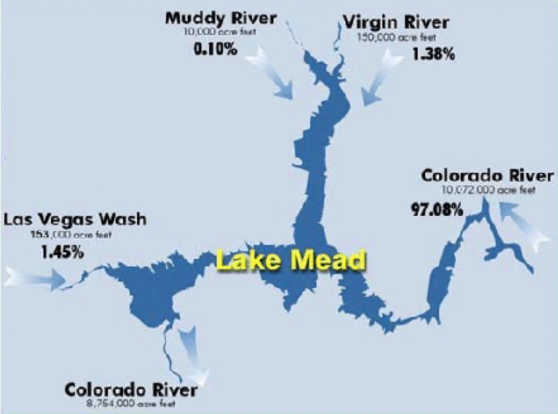

Figure 3- Sources of Lake Mead

The following equation was set up to find the proportionality constant:

$$.9708Mead_{inflow} = \gamma * Powell_{outflow}.$$

The γ factor was calculated for the years 1990 and onward, and a statistical average was taken. It was found that 94.72% of the outflow water of Lake Powell reached Lake Mead. The other 2.92% of Lake Mead's inflow was calculated taking a statistical average of the historic inflow rates multiplied by 0.0292, and was found to be 291983AF/year. This is assumed constant in the model.

Similar to the analysis performed on Lake Powell, the ratio of outflow rate to lake volume was calculated for data between 1970 and 2009 (Figure 4) (these years were chosen so as to avoid outliers).

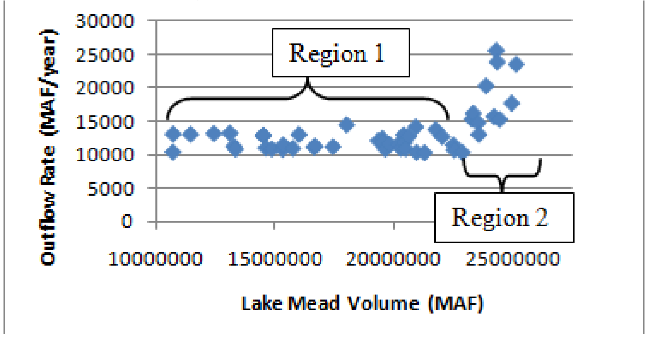

Figure 4- Lake Mead Outflow Rate versus Volume

Again, it is noted that the plot has two distinct regions, indicating that below some critical lake volume (equal to 23MAF), the output flow is independent of lake volume. Taking a statistical average, a value of $8.553412\frac{MAF}{year}$. Above this critical volume, the outflow increases approximately linearly. Performing a least squares regression, the line of best fit is $Mead\ \widehat{outflow}\ \frac{MAF}{year} = \frac{2.525}{year} \cdot lake\ volume\ (MAF) - 40.26\frac{MAF}{year}$ with an $r^2 = 0.30$. Performing a sampling distribution on the regression slope, we yield a t statistic of 1.9435, yielding a probability value of 0.0422, thus rejecting the null hypothesis. This suggests that there is dependence of outflow of Lake Mead on the volume of the lake, when the volume is above the critical value of 23MAF.

The Lake Mead volume model becomes

$$M(n+1) = .9472 * out_P(n) - M(n) - \frac{0.937500MAF}{year} + \frac{0.291983\text{MAF}}{\text{year}} - \begin{cases} \frac{8.55MAF}{year} & for\ M(n) < 23MAF \\ 2.525 * \frac{M(n)}{year} - \frac{40.26MAF}{year} & for\ M(n) > 23MAF. \end{cases}$$

The following tables show the predictions of the models.

Table 1- Lake Powell Inflow, Volume, and Outflow Data

	Inflow (MAF/year)			Water Volume (MAF)			Outflow (MAF/year)		
	Minimum	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**
2012	4.7	10.0	16.4	10.3	15.6	22.1	6.5	9.9	14.0
2013	4.7	10.0	16.4	8.5	15.7	24.6	5.4	9.9	15.5
2014	4.7	10.0	16.4	7.8	15.7	25.5	4.9	9.9	16.1
2015	4.7	10.0	16.4	7.6	15.8	25.8	4.8	10.0	16.3
2016	4.7	10.0	16.4	7.5	15.8	25.9	4.7	10.0	16.4

The data for Lake Powell can be seen in Table 1. For the low inflow estimates, the water volume significantly drops over the next five years, with a corresponding decrease in outflow. For the average inflow rate, the water volume remains nearly constant, corresponding to a nearly constant outflow rate of 10.0MAF/year. For the maximum estimated inflow rate, the water volume increases greatly, and the water outflow rate also increases, to nearly 16.5MAF/year.

Table 2- Lake Mead Volume and Height Data

	Water Volume (MAF)			Water Height (ft. above sea level)		
	Minimum	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**
2012	5.8	8.9	12.6	1063	1086	1114
2013	1.1	8.0	17.0	1028	1080	1147
2014	0	7.2	21.8	990	1074	1183
2015	0	6.8	26.9	990	1070	1222
2016	0	6.3	32.0	990	1067	1260

The data for Lake Mead can be seen in Table 2. The first interesting features of the data are the values of 0MAF for the minimum estimate of inflow into Lake Powell. This occurs because, by current law, 7.5MAF must be delivered to the Lower Basin. As the law does not account for a reservoir depletion, the model continued to outflow the maximum amount of water possible, even when this was less than the required 7.5MAF and 1.5MAF for Mexico. In the case of average expected inflow, the water volume and water level both drop steadily. For the maximum expected inflow, the value of water volume and water level both increase.

The second interesting feature of both data sets is that for the maximum expected inflows, both the Lake Powell and Lake Mead volumes go above the reservoir capacities. This occurs due to a delay effect in the model. The model uses inflow and outflow data from the previous year to calculate the next year's volume. If large changes occur in one year, the inflow and outflow (based on the previous year) may not be able to "catch up"; thus the model enters into an unstable trajectory. This could be corrected with smaller time increments, perhaps one month instead of one year.

The final percentage of capacity for Lake Powell and Lake Mead at the end of the five-year model is shown in Table 3.

Table 3- Percent of Capacity of Lakes Powell and Mead

Lake Powell	0.31%	0.66%	1.08%
Lake Mead	0.00%	0.22%	1.12%

Impact on Power Generation

Rationale

The Hoover Dam represents one of the largest electrical power plants in the Southwest. To illustrate, the list of contractors for the Hoover Dam's power output in the Lower Basin includes but is not limited to the states of Arizona and Nevada, the city of Los Angeles, the Southern California Edison Company, the Metropolitan Water District of Southern California, Glendale, Burbank, and Pasadena (Bureau of Reclamation). At these locations, the hydroelectric power is then allocated for residential and industrial use. While the Hoover Dam powers the light bulbs of a residential building, it also powers the slot machines of a casino in Las Vegas (Bureau of Reclamation).

However, the amount of hydroelectric power available for use depends heavily on the flow of water through the dam. If the flow of water through the Hoover Dam decreases, the hydroelectric power produced will in turn decrease. The loss of hydroelectric power output in turn will result in severe socioeconomic consequences. "It is an outcome that would destabilize energy markets in the Southwest, send retail customers that serve millions of residents to the spot market to buy power at up to five times the cost and dissolve the illusion that rivers are infinitely malleable to our own purposes" (Walton, Low Water May Halt Hoover Dam's Power).

As a result of the current drought situation, power generation has already declined at an alarming rate. Recently, the Hoover Dam's hydroelectric generating capacity has been noted to decrease by 23% (Walton, Low Water May Halt Hoover Dam's Power). For this reason, it is important to quantify the future effect of the current drought on the Hoover Dam's hydroelectric output. This may be achieved through a series of calculations.

Local Assumptions

I. As the following model predicts power production only for the next five years, dam power production can be approximated by the formula

$$P = hQgk,$$

where P is power in kilowatts (kW), h is the reservoir height in meters (m), Q is water flow rate in cubic meters per second (cms), g is acceleration due to gravity (9.8 m/s^2), and k is the efficiency constant (Strong). However, this formula yields significant error for predictions after this time period.

II. The average of the efficiency constants of historical data for the dam can approximate the efficiency constant for the next five years.
III. Plant efficiency will not change over the next five years.
IV. Methods of hydroelectric power production will not change over the next five years.

Procedure

The formula for a dam's power production in a year ($P = hQgk$) contains four input parameters: the reservoir height, the water flow rate (outflow rate), the acceleration due to gravity, and the efficiency constant. As the reservoir heights and water flow rates for the next five years have previously been predicted and g is assumed to be 9.8 m/s^2, only the efficiency constant remains unknown in this formula. In order to project hydroelectric power outputs for the next five years, the value of k was first found.

Data regarding the kilowatt-hours produced by the Hoover Dam in 2001-2009 were found and are shown in Table 4- Water Height and Inflow Data for Hoover Dam (Bureau of Reclamation). The average value of 4.2 billion kilowatt-hours per year was used for 2001-2009. In addition, the year 2010 was excluded in the efficiency constant calculations because the data were excluded in the Lake Mead Database (Summit Technologies, Inc.). This was then converted to kilowatts.

Solving the aforementioned formula for the efficiency constant results in the new formula $k = \frac{P}{hQg}$. Microsoft Excel was used to evaluate this formula for the data for each year to yield the average value of $k = 0.461$.

Assuming the efficiency of the power generation process remains constant for the next five years, the average efficiency constant, the projected values for outflow of Lake Mead, projected water elevation values, and the acceleration due to gravity in the Colorado River Basin will be used to calculate the projected values for the hydroelectric power output in the next five years.

The opportunity cost of not producing hydroelectric power is given by the cost that it takes to make up the production discrepancy using coal-produced power, the second most used source of power in the United States (EIA). Therefore, future production levels of hydroelectric power are compared with current production levels to determine the opportunity cost of decreased hydroelectric power production, costs that will be incurred through the production costs of coal, and the costs incurred by the consumer. The projected power output values were compared to the average power output of the Hoover Dam in recent years, 4.2 billion kilowatt-hours (Bureau of Reclamation). The deficiency in power output must be compensated by energy produced by burning of coal. The cost in dollars per kilowatt-hour of hydroelectric power produced is 0.016 dollars per kilowatt-hour (Walton, Low Water May Halt Hoover Dam's Power); the cost in dollars per kilowatt-hour of alternative energy produced in the form of coal is 0.036 dollars per kilowatt-hour (International Energy Agency).

The total cost of power generation each year is calculated using the following series of equations:

$$HEC = Qhk(9.8)(8760),$$

$$\begin{cases} TC = [(4.2 * 10^9) - HEC](0.037) + HEC(0.016), if\ HEC < 4.2 * 10^9\ and\ h > 1050, \\ TC = (4.2 * 10^9)(0.016), if\ HEC > 4.2 * 10^9, \\ TC = (4.2 * 10^9)(0.037), if\ h < 1050, \end{cases}$$

where HEC is the hydroelectric power generated by the dam, h is the water elevation in the dam, Q is the outflow rate of the dam, k is the efficiency constant, and TC is the total cost of the required power output. The values of 9.8 and 8760 in the first equation are constant and are used to represent the acceleration due to gravity and the number of hours in a year, respectively. The values of 0.037 and 0.016 represent, respectively, the cost in dollars per kilowatt-hour of coal power production and hydroelectric power production. $4.2*10^9$ is the required energy generated to supply the Colorado River Basin region, and 1,050 is the critical value of the water elevation at which the power plant shuts down.

Using the monetary conversion factors mentioned above, the cost per year of producing the required 4.2 billion kilowatt-hours of energy required by the residents of the Colorado River Basin region is calculated from the energy produced by the dam each year. If enough energy was produced by the Hoover Dam to provide the 4.2 billion kilowatt-hours of energy, the required cost of that year's power generation would be calculated based solely on hydroelectric power. However, when the hydroelectric power produced by the dam fell short of the 4.2 billion kilowatt-hours, energy produced by coal was then needed to compensate for the shortage.

Furthermore, the Hoover Dam power plant would be shut down if the water level at the dam were to drop below an elevation of 1,050 feet due to increased vulnerability of the turbines (Walton, Low Water May Halt Hoover Dam's Power). In the projected data for the height of water in the Hoover Dam, the water level falls below the 1,050 feet mark in 2013, 2014, 2015 and 2016 when Lake Powell is subject to the minimum inflow. In those years, the dam is shut down to low water levels and thus no hydroelectric power is produced by the dam. Ergo, all 4.2 billion kilowatts of power must be produced by burning coal to compensate for the deficiency of hydroelectric power produced by the dam.

Data/Results

Table 4- Water Height and Inflow Data for Hoover Dam

Year	Height (ft)	Inflow (cfs)
2001	1185	17368
2002	1162	17447
2003	1145	10162
2004	1131	14453
2005	1140	3629
2006	1131	12058
2007	1117	15732
2008	1109	21596
2009	1099	12280

Table 4- Water Height and Inflow Data for Hoover Dam shows the water height data in feet from 2001 to 2009, as provided by Lower Colorado River Operations Database (Bureau of

Reclamation); it also provides the inflow data in cubic feet per second from 2001 to 2009 provided by the Lake Mead Database (Summit Technologies, Inc.).

Table 5- Final Cost Projections for Minimum Inflow Scenario

Year	Energy Before Adjustments (kWh)	Energy After Adjustments (kWh)	Required Energy Compensation (kWh)	Additional Cost of Coal Power ($)	Hydroelectric Costs ($)	Total Cost ($)
2012	4263731154	4200000000	0	0	67200000	67200000
2013	4122512137	0	4200000000	155400000	0	155400000
2014	3971934244	0	4200000000	155400000	0	155400000
2015	3819482725	0	4200000000	155400000	0	155400000
2016	3665418784	0	4200000000	155400000	0	155400000

Table 5- Final Cost Projections for Minimum Inflow Scenario displays the projected energy outputs of the Hoover Dam for the next five years at 39% of average inflow and the total costs that would be required to supply the original 4.2 billion kilowatt-hours of energy to the residents of the Colorado River Basin region. The energies before adjustments shown in the table are the values projected by the power generation model. The data were adjusted to ensure that surplus energy produced was not included in cost calculations and to reflect the shutdown of the Hoover Dam power plant when the water level decreased to below 1,050 feet in 2013, 2014, 2015, and 2016.

Table 6- Final Cost Projections for Average Inflow Scenario

Year	Energy Before Adjustments (kWh)	Energy After Adjustments (kWh)	Required Energy Compensation	Hydroelectric Costs	Total Cost
2012	4356341647	4200000000	0	67200000	67200000
2013	4331776879	4200000000	0	67200000	67200000
2014	4307871108	4200000000	0	67200000	67200000
2015	4294261448	4200000000	0	67200000	67200000
2016	4280741120	4200000000	0	67200000	67200000

Table 6- Final Cost Projections for Average Inflow Scenario shows the projected power generated by the Hoover Dam in the next five years when the inflow into Lake Powell is at the most likely value of 83% of average. The projected values were all calculated to be higher than the required 4.2 billion kilowatt-hours of power and were adjusted to minimize required costs.

Table 7- Final Cost Projections for Maximum Inflow Scenario

Year	Energy Before Adjustments (kWh)	Energy After Adjustments (kWh)	Required Energy Compensation	Hydroelectric Costs	Total Cost
2012	4469999979	4200000000	0	67200000	67200000
2013	4600940154	4200000000	0	67200000	67200000
2014	4747946370	4200000000	0	67200000	67200000
2015	4900867764	4200000000	0	67200000	67200000
2016	5055967003	4200000000	0	67200000	67200000

Table 7- Final Cost Projections for Maximum Inflow Scenario shows the projected power generation data for the Hoover Dam for the next five years at the maximum inflow of 137% of average. Like the values projected for the average inflow scenario, the power generated for the five years are again above the required 4.2 billion kilowatt-hours and are adjusted to minimize total costs.

Impact of Outflow on Economy of Lower Basin

Local Assumptions

I. The allocations of Colorado River water supplies for states will not change in the next five years.
II. The current acreage of land will remain relatively constant.
III. The percent usage for agriculture and irrigation will remain relatively constant over a period of five years.

Procedure

The primary sector of industry that uses water from Lake Powell is agriculture. However, the arid climate of the Southwest necessitates the significant allocation of water for irrigation purposes. The Colorado River Compact of 1922 stipulates that Lake Powell must release at least 7.5 MAF for use in the Lower Basin. This water was allocated to Arizona, California, and Nevada on the premise that each state receives 37.3%, 58.7%, and 0.04% of the water output of Lake Powell/Glen Canyon Dam, respectively (U.S. Bureau of Reclamation).

The model estimates the approximate change in crop acreage by determining the crop acreage of each state for the year 2010 and assumes that overall crop acreage will not change. As a result, the water usage depending on outflow from Lake Powell can be modeled by the following formula:

$$irrigation\ water_{state} = (outflow_{LakePowell}) * \left(\frac{\%\ State\ allocation}{100}\right) * \left(\frac{\%\ agriculture}{100}\right).$$

To determine the projected amount of land that can be supported by the projected irrigation usage, the acreage of crops in each state that requires irrigation is divided by the acre-feet of water needed to irrigate each acre of cropland in

$$irrigated\ land_{state} = \left(\frac{acrefeet\ water}{acre\ crops}\right) * (acre\ crops) * (\%\ cropland_{irrigated\ by\ Powell}).$$

Therefore, the overall irrigated crop acreage can be predicted as a function of the projected outflow of Lake Powell:

$$A(outflow)_{state} = \frac{(outflow) * (\%_s) * (\%_a) * (\%_C)}{I}$$

$\%_s = state\ allocation\ of\ water\ from\ Powell\ Dam$ (U.S. Bureau of Reclamation)
$\%_a = allocation\ of\ water\ to\ agriculture\ (per\ state)$ (Owen)
$\%_c = percent\ of\ cropland\ irrigated\ from\ Colorado\ River$ (Office)
$I\ =\ acrefeet\ irrigation\ water\ needed\ per\ acre.$

Table 8 - Model Parameters, Water Usage

	Arizona	California	Nevada
Crop acreage	755333.3	4244000	506000
$\%_s$	0.8	0.75	0.75
$\%_a$	37.3	58.7	4
$\%_c$	0.5	0.25	0.3

The consequent decrease in available irrigated land is determined by the percent decrease in irrigated crop acreage, compared to the percent of current crop acreage that is irrigated by the Colorado River. The current crop acreage per state that is irrigated by the Colorado River is modeled by

$$current\ irrigated\ acreage = (crop\ acreage) * (\%cropland\ irrigated) * \left(\%\ cropland_{irrigated\ by\ Powell}\right)$$

The consequent percent decrease in available irrigated land is

$$\%\ decrease = \frac{current\ irrigated\ acreage - projected\ irrigated\ acreage}{current\ irrigated\ acreage}.$$

Table 9 - Percent Decreases in Crop Acreage Capacity Irrigated by Colorado River

		Minimum	Average	Maximum
2012	AZ	17.0	-25.4	-77.5
	CA	19.7	-21.4	-71.8
	NV	64.7	46.6	24.5
2013	AZ	31.8	-26.2	-97.5
	CA	34.0	-22.2	-91.1
	NV	71.0	46.3	15.9
2014	AZ	37.3	-26.5	-104.9
	CA	39.3	-22.5	-98.3
	NV	73.3	46.1	12.8
2015	AZ	39.3	-26.7	-107.6
	CA	41.2	-22.6	-100.9
	NV	74.2	46.1	11.7
2016	AZ	40.0	-26.7	-108.6
	CA	42.0	-22.6	-101.9
	NV	74.5	46.1	11.2

Discussion of Results

As shown in Table 9, the model produces results for each outflow of Lake Powell as provided by the inflow/outflow model projected five years into the future. The model's projections in the case of minimum inflow into Lake Powell indicate that all states will suffer a decrease in the acreage of cropland that can be irrigated from the Colorado River. The minimum scenario indicates that over the course of five years, Arizona's cropland available for irrigation from the Colorado River will decrease by 40.0%, California's will decrease by 42.0%, and Nevada's will decrease by 74.5%. However, in the most likely average and maximum inflow scenarios of 83% and 137%, the percent decreases in available cropland are actually negative as indicated by the green/grayed out cells. These negative percent decreases show that in these inflow scenarios, the output from Lake Powell is more than enough to supply irrigation needs in Arizona and California. Therefore, the percent of water allocated to agriculture, or the percent of water allocated to irrigation, can be decreased and optimized to reduce water consumption from the Colorado River.

It is assumed that each state irrigates the cropland according to a proportion from the Colorado River. This proportion was determined from statistics given by the U.S. Bureau of Reclamation. It should be noted that these proportionality constants, although determined from viable sources, contain some level of approximation and introduce some error into the model. The results indicate that Nevada does not follow this proportional irrigation usage, and therefore it determines its irrigation usage through another method. Nevada already is facing difficulty meeting its irrigation needs, logically because it is the driest state in the nation and faces more dire irrigation needs (Griffith). If there were more time allotted for solving this problem, the agricultural irrigation land usage model would have been updated to reflect this nuance.

Ultimately, this model represents a limited approximation of the effect on the economy of the Lower Basin, only quantifying the effects of power generation and agricultural water usage. Although agricultural water usage does represent the vast majority of resource apportionment of water from the Colorado River, other sectors do use water usage. Industrial usage accounts for approximately 6% of Arizona's water usage, while residential, commercial, and government account for roughly 16% of water usage (McKinnon). Furthermore, tourism in the Lower Basin has decreased with the water level of the Colorado River and its major lakes, Lake Powell and Lake Mead. Decreased water levels in these lakes and rivers decrease the utility of such recreational activities as fishing, boating, marina operations, white-water rafting, etc. The impacts on the tourism industry were not considered in this model due to the complex relationship between the Colorado River's water level, Lake Powell's water level, Lake Mead's water level, and the consequent prevalence of tourism/recreational activities.

Economics is the study of the scarcity of resources. As the water output from Lake Powell decreases, the supply of water must necessarily decrease. According to the basic supply-demand curve of economics, when the quantity supplied decreases, the price initially increases. Given more time, a model of the market economy of water could be developed to determine the incurred costs to both consumers and firms (Internet Center for Management and Administration, Inc.). Water is a significant factor of production in many industries, including industrial uses, and its scarcity in the Lower Basin might therefore increase marginal and fixed costs of production in industrial production. Therefore, firms would respond by increasing price levels (costs incurred by the consumer) in order to remain profitable while the costs have increased.

The decrease in water supply, especially in the minimum inflow scenario, has expansive and self-propagating effects on the economy.

Although the percent decrease in irrigated land capacity has been modeled, the effect on the economy in terms of employment should be evaluated. The decrease in irrigated land capacity would result in the decrease of overall available cropland for farm production, leading to a decrease in gross crop yields. This reduction in crop yields would translate into a "crowding-out effect" on small farmers: some farmers, since they cannot irrigate as much land and make the necessary profit on their land parcels to continue operating their small firms, will lose their jobs, representing a loss of employment. Furthermore, the effect of the scarcity of water on industrial content will result in the loss of profits of small firms, which would react by a combination of 1) terminating workers, 2) minimizing costs through other methods, and 3) decreasing quality of produced goods.

Effects of Changes in Inflow Rates

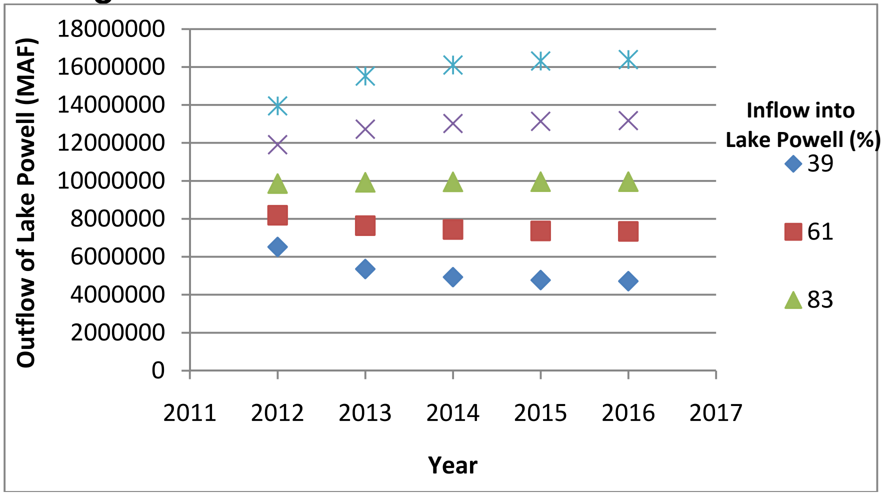

Figure 5- Effect of Inflow to Lake Powell on Outflow Rate

Based on the model, the effects of changes of outflow from Lake Powell can be predicted. As can be seen from the graph, a change in the current flow rate causes the outflow to gradually diverge from the past years for which data are known. Over time, the outflow of the lake, and therefore also the water level, stabilizes to a certain value, which is dependent upon the volume of inflow.

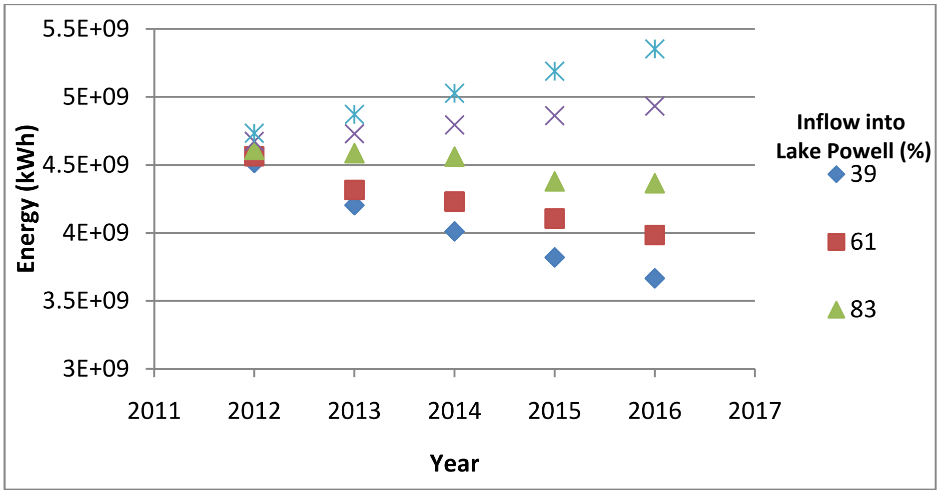

Figure 6- Effect of Inflow to Lake Powell on Power Generation at the Hoover Dam

Like the outflow of Lake Powell, the power generation at the Hoover Dam is also affected by changes to the volume of water flowing into Lake Powell. The effect is, again, initially small, but the values gradually diverge over time. It should also be noted that at 39% or 61% inflow rates, the graph is not entirely accurate, since the elevation of the water will drop below the minimum of 1,050 feet needed for dam operation within the five years that are being studied.

The sensitivity of the model, or the effects of small percent changes in input on the output of the model, can also be analyzed. Each of the three scenario inflow values (39%, 83%, and 137%) was changed by a certain percentage value, ranging from 1% to 10%, and the resulting percent change in the output if the model was computed. This procedure was used to examine both the sensitivity of the lake volume and that of the power generation of the Hoover Dam.

Table 10- Sensitivity of the Volume of Lake Powell in 2016 from Different Base Percentages

	39%	**83%**	**137%**
1%	0.9861%	0.9934%	0.9960%
2%	1.9722%	1.9868%	1.9920%
3%	2.9583%	2.9803%	2.9880%
4%	3.9444%	3.9737%	3.9840%
5%	4.9305%	4.9671%	4.9800%
6%	5.9166%	5.9605%	5.9760%
7%	6.9027%	6.9540%	6.9720%
8%	7.8888%	7.9474%	7.9680%
9%	8.8749%	8.9408%	8.9640%
10%	9.8610%	8.9408%	9.9600%

As can be seen from Table 10- Sensitivity of the Volume of Lake Powell in 2016 from Different Base Percentages, a certain percent change in the inflow to Lake Powell effects an almost identical percent change in the volume of the lake.

Table 11- Sensitivity of the Power Generation of the Hoover Dam in 2016 from Different Base Percentages

	39%	**83%**	**137%**
1%	0.1567%	0.0507%	0.3991%

2%	0.3134%	0.3363%	0.7982%
3%	0.4701%	0.6219%	1.1973%
4%	0.6268%	4.5406%	1.5964%
5%	0.7835%	4.8371%	1.9955%
6%	0.9403%	5.1337%	2.3945%
7%	1.0970%	5.4302%	2.7936%
8%	1.2537%	5.7268%	3.1927%
9%	1.4104%	6.0233%	3.5918%
10%	1.5671%	6.3198%	3.9909%

In contrast with the sensitivities of the lake volume, the amount of power generated changed much less than the changes in Lake Powell inflow.

III. Potential Reductions to Consumptive Use from Colorado River

Introduction

The model presented in this paper follows the legal constraints set out in the Compact of the Colorado River, dating back to 1922, and follows the legal interim guidelines set out in the Environmental Impact Statement. If the water level in Lake Mead drops significantly, the guidelines stipulate that the amount of water given by Lake Powell to the Lower Basin will be decreased. Conforming to these guidelines, in the event of a shortage, the shortage of water supply in Lower Basin will be exacerbated significantly due to the decrease of Lake Powell.

The current state allocations of water are based on 1922 consumption levels as set out in the compact, and do not reflect current actual water usage. The state allocation percentages did not account for unprecedented tourism growth in Nevada due to Las Vegas and other tourist attractions.

Policy Change

As of July 2009, significant consequences of the 2007 interim guidelines were imminent. The water level of Lake Mead was 1,094 feet, exceeding the “critical level” of 1,075 feet by only 19 feet. If the critical level is reached, a multi-billion dollar pipeline would have to be constructed to divert water from rural Nevada to supply Arizona (8NewsNow). Furthermore, as a result of the aforementioned shortage guidelines, the water level at Lake Mead had been decreasing while water levels at other Colorado River reservoirs were increasing (Bureau of Reclamation). The discrepancy in water supply between Lakes Mead and Powell had only been increasing month by month after the 2007 guidelines had been passed, whereas the two lakes’ water levels had been mirroring each other before 2007 (8NewsNow). This discrepancy between Lake Mead’s and Lake Powell’s water levels is especially alarming, considering that the Hoover Dam is one of the largest providers of hydroelectric power on the Colorado River (USBR). Furthermore, when the level of Lake Mead decreases to 1,050 feet, the hydroelectric power plants will most likely shut down due to the concern about possible damage to the turbines (Walton, Low Water May Halt Hoover Dam's Power). As calculated in the power generation model, the shutdown of the power production in Hoover Dam would result in an opportunity cost of production of the same energy in terms of price of a KWh of electricity generated from coal of $155.4 million.

A proposed policy change would equalize the water levels between Lake Powell and Lake Mead, as the majority of inflow of Lake Mead is determined by the outflow of Lake Powell. The policy change disposes of the stipulations in the negotiated 2007 interim guidelines in order to provide long-term stability to the water levels of Lake Mead. The previously produced inflow/outflow model provides the relationship between Lake Powell's inflow/outflow and Lake Mead's water level. The minimum capacity of Lake Powell is then defined as the inflow/outflow necessary to keep the water level of Hoover Dam sustained at the critical level of 1,075 feet.

To iterate through all possible levels of percentage of average inflow to Lake Powell to the precision of one percent, a Visual Basic program was written. The program used these inflow parameters as inputs to determine the minimum value for which the long-term change in lake height was approximately constant or not negative. It was determined that 88% of the average inflow to Lake Powell, or about 10.6 million acre-feet per year, was necessary to keep the water level of Lake Mead at about 1076.7 feet. This figure is close to the critical value and enough to keep Hoover Dam's hydroelectric power plants operating.

What consequences does this calculated average inflow value have on the policy changes necessary to keep Lake Powell operating at minimal capacity? This calculated inflow occurs at 88% of continued average inflow levels, or a relatively likely scenario, but not the most likely scenario. The current interim guidelines cannot proceed without drastically decreasing water levels of Lake Mead. Our calculation of minimal capacity will stabilize the water of Lake Mead at just the level it needs to remain functioning above shortage capacities.

Conservation

The following recommendations should be made to address the issue of water conservation:

1. The traditional apportionments dictated by the Colorado River Compact of 1922 should be readjusted so that lower levels of water are consumed for agricultural use and our impact on the capacity of Lake Powell is minimized (Western Water Assessment). As demonstrated by the results of our agricultural model, a major problem in water conservation is the large demand of irrigation water in various locations and the Colorado River Compact's inability to address this demand. With the implementation of current policy, while one region may receive a disproportionately large allocation of the Colorado River water, another region may simultaneously receive insufficient water supplies. Current usage by state of water allocated to the Lower Basin has California at 66.71% of the 7.5 million acres allocated by law, Arizona at 23.75%, and Nevada at 9.54%, deviating significantly from the obsolete legislation's allocations.

   However, in the event of average and high inflow scenarios, the model predicts that water available for irrigation actually exceeds current irrigation demands. Therefore, under these scenarios, the state allocations could be optimized such that states receive adequate, but not excess, water for irrigation of their cropland. In these same scenarios, Nevada's irrigation capacity is still decreasing. The excess irrigation water from the Colorado River should be reallocated such that Nevada receives some of the surplus, and the rest of the outflow should be conserved for future drought situations.
2. Partially switching to another source of alternative energy such as coal plants may help lower the Lower Basin's dependence on the hydroelectric power produced by the Hoover Dam and in turn decrease the amount of water humans remove from the Colorado River. Minimizing the demand of hydroelectric power places a lighter burden on the Colorado River and would ultimately help maintain a minimal capacity in Lake Powell. However, hydroelectric power remains one of the cheapest sources of electricity and retains an

absolute advantage over other methods of electricity balance. A tradeoff analysis should be determined to see whether the economic detriments of producing energy through more expensive methods are justified by the corresponding decrease in water consumption of the Colorado River, and the sustainable conservation of water for future usage.

3. Contractors of hydroelectric power should be required to uphold industrial practices that conserve the most water possible. For instance, legislature can be passed to institute periodic inspections of industrial facilities for water efficiency and to lower industry’s footprint on the Colorado River supply. However, this legislation would likely face major opposition from industrial lobbyists, and represents a very theoretical approach.
4. Funds should be invested in the production of desalination plants on the west coast of California to expand the water supply in the Southwest. This should provide a substantial increase in the supply of water for irrigable land in Southern California. Again, this represents a theoretical proposal that has significant production and operating costs. (Shankman)

By implementing these recommendations, human impact on the Colorado River will be reduced on legislative, political, and socioeconomic levels. If circumstances turn out favorably, the recommendations made should maintain the minimal capacity in Lake Powell.

In conclusion, change in interim guidelines and conservation policy should be implemented in conjunction with optimization of water allocations and overall reduction of consumption. Some of the approaches investigated represent very hypothetical scenarios with significant barriers to widespread implementation.

Conclusion

The issue of water conservation for Lake Powell in the face of unmitigated climate change and drought is an issue central to the economy and infrastructure of the Southwest. The impact of drought on Lake Powell cannot be modeled without considering the connections between inflow and outflow of Lake Powell and inflow and outflow of Lake Mead. The inflow to Lake Powell was determined by model assumptions, while the outflow of Lake Powell was based on the state allocations to the Lower Basin as set forth in the Compact of the Colorado River. These relationships were modeled, and the outflow of Lake Powell was then determined in order to investigate possible effects on the economy. The effects on the economy of the Lower Basin were modeled by determining the loss in agricultural productivity due to decreased capacity for irrigation usage. The effects on power generation were determined by analyzing the power production of a dam as it varies with water level, height, and flow rate. Sensitivity analysis identified how small changes in input rate to Lake Powell changed the consequent volume level and power generation at Hoover Dam. The analysis determined that inflow rate changed almost identically with volume level, while power generation was relatively insensitive to input changes. Finally, the team investigated methods of reducing water consumption from the Colorado River and determined that current interim guidelines will deplete water levels in Lake Mead. Therefore, our recommendation consists of two parts: 1) change policy to maintain water level in Lake Mead and output of Hoover Dam, and 2) decrease state consumption and optimize state water usage allocations.

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