**M3 Challenge Fourth Place (Meritorious Team Prize) - $ 7,500**
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## EXECUTIVE SUMMARY

Lake Powell, the reservoir formed by the Glen Canyon Dam, is a major element of the Colorado River Reclamation project. In the past few years a drought in the Colorado River Basin has caused the level of the reservoir to drop substantially.

We created a model for the volume of Lake Powell using pseudo-random normally distributed data (based on previous trends), and we predict that the volume of the lake will increase in the coming years. This was similar to the trends predicted by the model provided in the question (with outflow based on the Colorado River Compact); however, our model is more accurate because it uses historical data combined with normally distributed random numbers and a large number of trials to get a good estimate of future trends.

Though our model predicts an increase on the water level, we wanted to expand our investigation by taking into account the possibility that the water levels may decrease in Lake Powell and Lake Mead. If the drought were to continue, the power plants at the Glen Canyon and Hoover Dams would become less efficient, and their outputs would decrease, though this would not have a huge impact on the surrounding areas. However, falling water levels (most significantly in Lake Mead) would severely damage the economies and welfare of the nearby communities dependent on the water from these reservoirs. In addition, the tourist economy would be hurt because of the limited recreation opportunities available due to the low water levels. Lower water levels also increase salinity, causing issues with the water quality, as well as quantity.

We determined that, by changing the inflow and outflow by just 5%, we could get changes of about 6.40%, which is bigger than the original value, showing the large effects of small changes on the model.

By defining a recommended minimal capacity for Lake Powell based on recreational activities, we suggest the capacity be set at 10,458,739 acre-feet. The ideas and programs most likely to have the greatest increase on water capacity would be agricultural programs focused on maximizing irrigation efficiency and using reclaimed water. Other less effective methods include using water covers, increasing depth, and increased efforts toward public water conservation programs.

In conclusion, we believe that the volume of Lake Powell will increase over the next 5 years, with the condition that this estimate is sensitive to small changes in lake inflows. This increase will be beneficial for the community—but if it decreases, the results will be fairly dramatic. In order to avert these issues, there are several changes—including increasing irrigation efficiency and using reclaimed water—that can decrease water use in the Colorado River Basin.

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# “Calculations in the Canyon”

# INTRODUCTION

## A Model of the Volume of Lake Powell

The change in volume of Lake Powell depends on two factors: the total amount of water that is introduced into the lake, from the Colorado River and rainfall, and the total amount of water that is removed from the lake through water release and seepage at the Glen Canyon Dam, and evaporation. That is, the net change with respect to time is

$$\Delta V(t) = I(t) - O(t)$$

where I(t) is a function representing the total inflow to the lake and O(t) is a function representing the total outflows from the lake. Mathematically, the change in the dam's volume (represented by ΔV) is the derivative of the dam's volume. The previous equation can be re-written as

$$\frac{dV}{dt} = I(t) - O(t)$$

Using this model, the total change in the volume of the lake over a certain time period from a year 0 to *t* can be determined analytically by integrating the change of the lake's volume, as shown below:

$$\int_{0}^{t} \frac{dV}{dt} = \int_{0}^{t} I(t) - O(t)\, dt$$

The total volume of the lake at any specific year, then, can be found by integrating the change over time of the lake's volume for the time period between a known year (T) and the year for which the volume should be predicted (P), and adding the volume of the lake at the known year:

$$V(P) = \int_{T}^{P} \frac{dV}{dt} = \int_{T}^{P} I(t) - O(t)\, dt + V(T)$$

For example, using a known value for the lake in 2011, the volume of the lake in 2016 could be modeled as follows:

$$V(2016) = \int_{2011}^{2016} I(t)\, dt - \int_{2011}^{2016} O(t)\, dt + V(2011)$$

The factors that affect total inflow and outflow include the following:

Inflows:

- Water entry from the Colorado River ($I_C$)

- Rainfall ($I_R$)

Outflows

- Water released from the Glen Canyon Dam ($O_R$)
- Dam seepage ($O_S$)
- Evaporation ($O_E$)

Since the total inflow and total outflow are each the sum of their respective components, the general equation for V(P) (where P is the year for which the volume of the lake is being predicted) can be re-stated as follows:

$$V(P) = \int_T^P I_C\,dt + \int_T^P I_R\,dt - \int_T^P O_R\,dt - \int_T^P O_S\,dt - \int_T^P O_E\,dt + V(T)$$

## Model Data Sources

*Assumptions*: For this model, we made several simple assumptions. We assumed five primary sources of change in the lake (river inflow, precipitation, river outflow, evaporation, and dam seepage), and that the lake is a closed system otherwise. We also assumed that there will be no large scale changes in the climate and geography of the lake, and that the drought of the last decade will continue for the next five years. We assumed that historic trends are accurate and linear, and that they can be applied to the future of the lake. We further assumed that the flows are normally distributed. In our model, we calculated outflow by historic trends, not by political agreements (as in the Colorado River Compact of 1922); such agreements do not reflect actual climate (such as the drought of the past decade) and hence have had to be revised (as it was in 2007).

Although the previously discussed equation is eloquent, it cannot be implemented: the data sources available are discrete, not continuous, and hence cannot be integrated analytically. Instead, a numerical method of estimation was used, in which the 5-year period for which lake volume is estimated was divided into 60 month-long periods. Mathematically, this can be expressed as a recursive equation:

$$V(P+1) = I_c + I_r - O_R - O_S - O_E + V(P)$$

in which V(0) is the current value of the lake's volume, and each of the terms $I_c$ through $O_E$ is the change for the month P.

However, the model is not fully deterministic. The inflows in particular are variable; after all, the dam itself was installed in order to allow the fluctuations of the river's flow to be evened out. The functions $I_C$, $I_R$ … $O_E$ are probabilistic, but working with probabilistic functions is very difficult. Instead, the implementation of our model uses Monte Carlo Methods. Monte Carlo

Methods essentially involve the averaging of very many (pseudo-)random[1] simulations, which for large numbers of simulations closely approximate the analytically derived value. In order to complete this, a computer program was written in the Java programming language. The number of trials used for estimating values herein was at least 100,000, though sometimes as high as 5 million—the number of trials used to estimate any given value will be provided. The computer program is detailed and source code is provided in Appendix A.

There are two independent sources of data for the Colorado River inflows. The problem stated "Estimates of Colorado River inflows to Lake Powell vary between a low of 39% of average to 137% of average, with 83% being most likely."[2] Based on this information and the estimation of elements discussed below, the following applies:

| **LOWER ESTIMATE** | Average Volume (taf) | Standard Deviation (taf) |
|---|---|---|
| 2012 | 10,275.8 | 187.7 |
| 2013 | 7,468.8 | 261.03 |
| 2014 | 4,730.1 | 293.4 |
| 2015 | 2,059.6 | 292.7 |
| 2016 | 0/0 | 284.6 |

| **MIDDLE ESTIMATE** | Average Volume (taf) | Standard Deviation (taf) |
|---|---|---|
| 2012 | 16,739.2 | 2,342.2 |
| 2013 | 20,390.1 | 3,354.3 |
| 2014 | 24,115.4 | 3,505.9 |
| 2015 | 27,886.6 | 3,309.9 |
| 2016 | 31,686.2 | 3,488.4 |

| **HIGH ESTIMATE** | Average Volume (taf) | Standard Deviation (taf) |
|---|---|---|
| 2012 | 26,171.1 | 329.3 |

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[1] Computer programs cannot generate true random numbers. However, the pseudo-random numbers that are generated are considered random enough for cryptography and hence are considered random enough for our simulations.

[2] Moody's Math Challenge 2011 Problem Definition

| | | |
|---|---|---|
| 2013 | 38,864.5 | 698.0 |
| 2014 | 51,246.0 | 1,143.7 |
| 2015 | 63,320.2 | 1,597.5 |
| 2016 | 75,096.2 | 2,028.2 |

*Inflow from the Colorado River*: One inflow prediction states that "Estimates of Colorado River inflows to Lake Powell vary between a low of 39% of average to 137% of average, with 83% being most likely." This specification provides an average inflow of 83% per year. This prediction poses some problems—what is meant by low, and what is meant by high? What is the probability of a 39% average? What is the probability of a 137% average? There is no basis for comparison with this simple specification. With this in mind and in order to more accurately analyze the likely impact of the drought, historical data can be analyzed. Using information for the Lake Powell reservoir from the US Department of the Interior website,[3] a linear regression predicts a yearly change in inflow as follows:

The linear regression used data from 2005 to 2010 in order to avoid being thrown off by a major spike in inflow in 2004. The coefficient of regression (overall, about -1,6400 acre-feet per year) is not particularly high.

In the model, the $I_R$ term was defined by a normally distributed continuous random variable with means and standard deviations defined on a monthly basis below:

| | μ | σ | | μ | σ |
|---|---|---|---|---|---|
| Jan | 1082.4 | 703.3 | Jul | 571.3 | 856.1 |
| Feb | 646.4 | 382.9 | Aug | 372.680 | 432.15 |
| Mar | 565.2 | 386.6 | Sep | 739.3 | 326.9 |
| Apr | 330.2 | 77.0 | Oct | 1026.5 | 923.3 |
| May | 516.0 | 413.3 | Nov | 858.1 | 740.4 |
| Jun | 475.0 | 216.8 | Dec | 723.4 | 554.5 |

*Rainfall:* The only other way that water enters Lake Powell is through rainfall. Because the lake has a surface area of some 162,700 acres,[4] by definition each foot of rainfall induces 162,700

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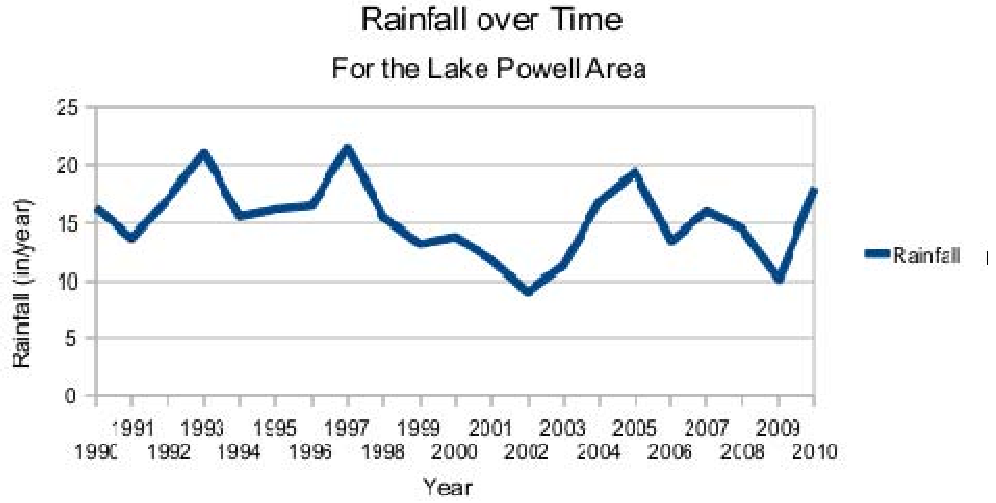
[3] USBR Database, http://www.usbr.gov/uc/crsp/GetSiteInfo

[4] "Lake Powell," http://www.waterquality.utah.gov/watersheds/lakes/LAKEPOWL.pdf

acre-feet of water into the lake. Although the rainfall in the Lake Powell area is usually little more than one foot per year, it is nonetheless included in our model for completeness. As shown in the graph below, there is very little change in the overall rainfall over time. About 203,375 acre-feet of water are introduced to the system over time.



*Water Outflows:* Water is removed from Lake Powell chiefly by outflows through the Glen Canyon Dam. Assuming that evaporation and seepage rates remain essentially constant, we can again use linear regression techniques to estimate the change in outflows through the dam. The regression factor 0.09451149, which was obtained from historic values of outflow rates[], shows a slight downward trend of outflow over time.

______[]Chart for predicted outflow change.

*Evaporation:* Evaporation is similarly important. Because evaporation is measured to be "between 2 and 3 percent per year,"[5] the volume of the lake itself has a significant impact on evaporation. In the model, the OE term is then defined to be (1-k)V(P), where k is a constant of evaporation (in the model, a uniformly distributed random variable between 0.02 and 0.03) and V(P) is the volume of the lake at the last time period.

*Seepage:* Seepage is an important factor to consider. The rate of seepage is equal to "about 2600 gallons per minute."[6] This works out to approximately 0.47 acre-feet per hour, or 350 acre-feet per month and 4197 acre-feet per year. Though not overwhelming, including this aspect in the model increases accuracy somewhat.

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[5] "CRSP Glen Canyon Unit Frequently Asked Questions." US Department of the Interior. http://www.usbr.gov/uc/rm/crsp/gc/faq.html

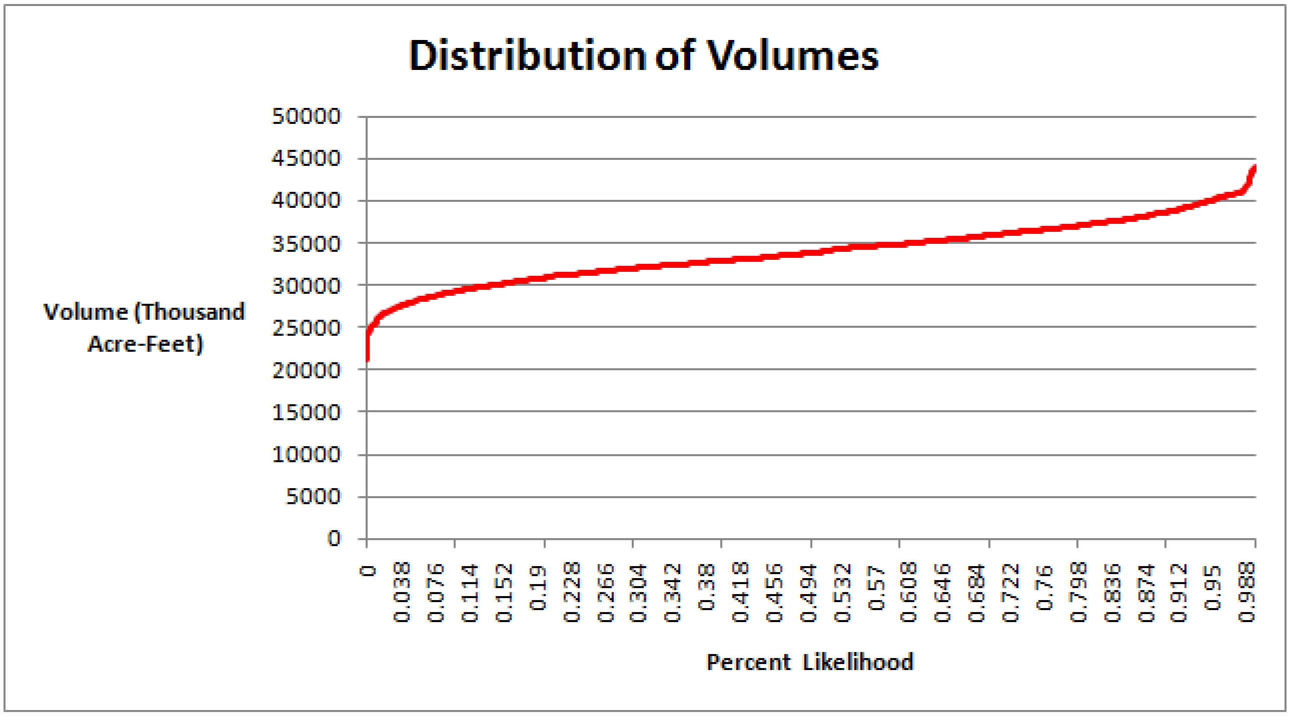
[6] Glen Canyon Unit Frequently Asked Questions

With 5,000,000 data points, our model predicted the following lake volumes for the next 5 years:

| Year | Volume (thousand acre-feet) | Standard Deviation (thousand acre-feet) |
|---|---|---|
| 2011 | 17173.28834 | 2468.13788 |
| 2012 | 21248.81234 | 3544.73468 |
| 2013 | 25384.17845 | 3709.80758 |
| 2014 | 29571.64148 | 3484.04585 |
| 2015 | 33812.58104 | 3654.89756 |

Our model predicts a decline in volume from the current 13154.627 thousand acre-feet to approximately 36548.97560 in 2015, a difference of 20657.95404 thousand acre-feet. Using the standard deviation calculated for the year 2015, the volume of the lake has a 68.27% chance of being between 30157.68348 and 37467.4786, and only a 31.74% chance of being above or below this range. Similarly, using the second standard deviation, the volume after 5 years has a 95.45% chance of being between 26502.78592 and 41122.37616 thousand acre-feet, and only a 4.55% chance of being above or below this range. These values, though based only on historical data and limited linear regression, have the advantage of precisely defining “low” and “high” probability.

This probabilities of certain values can be more easily seen in a chart, as below:



The cumulative frequency graph follows the curve of a normal distribution and shows the probability of various volumes in 2015 according to our model.

Our model can also demonstrate that small changes have large effects on the volume of the lake within 5 years. The table shows values for 2015:

| Percent Change in Inflows from Model | Volume (thousand acre-feet) | Standard Deviation (thousand acre-feet) |
|---|---|---|
| -.05% | 31660.71953 | 3487.32656 |
| 0.0% | 33812.58104 | 3654.89756 |
| +.05% | 35942.17461 | 3889.72963 |

Decreasing our model's inflow and outflow by 5% resulted in a net decrease in volume of 6.34%, and an increase of our model's inflow and outflow by 5% resulted in a net increase in volume of 6.30%. Clearly, a moderate change in the model results in a larger change of the final volume.

## Impact of Water Levels on Power Supply

The power produced by the Glen Canyon Dam can be modeled by the equation

$$Power(flow, elevation) = \frac{\Gamma * eff * flow * head(elevation)}{hptokw * 1000}$$

where

$\Gamma$ = 62.40, the specific weight of water at 50 degrees Fahrenheit ($\frac{lbs}{ft^3}$)
$eff$ = 0.88872889 efficiency factor (dimensionless)
$flow$ = Water Release (cfs)
$head\,(elevation)$ = effective head (feet)
*hptokw* = 737.5, Conversion Factor ($\frac{kW}{ft-lbs}$).[7]

The power produced from the hydroelectric power plant in the Glen Canyon Dam is dependent on flow and head, both of which are dependent on the water levels in Lake Powell. Although our model predicts rising water levels, there is a chance that water levels will decrease. In the case that the drought continues, the following analysis applies. The drought lowers the water level and thus decreases the capacity for power production. The recent drought has had a great effect on power production: from 1999 to 2009, the power production of the Glen Canyon Dam decreased 1.8 Billion kWh (kilo-Watt hours) from 5.5 Billion kWh to 3.7 kWh.[8] However, this dam produces less than one percent of the power for the Western Power Grid or about three percent of the power in the Four Corners area.[9]

The Hoover Dam could be similarly modeled (this is assumed because of the similarities in the two dams), though it would have a different efficiency factor. Again, lower water levels translate to less power production. It is especially important to note that particularly low water levels also decrease the efficiency of the turbines, further decreasing power production. However, neither of the communities surrounding these dams is particularly dependent on hydroelectric power . For example, the electric energy produced by the Hoover Dam[10] provides

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[7] "The Short-Run Economic Cost of Environmental Constraints on Hydropower Operations," United States Bureau of Reclamation. Updated June 1997, p. 34. http://www.usbr.gov/pmts/economics/reports/HOPT_REP003.pdf

[8] "Implications of Lower Lake Levels: Hoover Dam," United States Bureau of Reclamation. Accessed March 6, 2011. http://crc.nv.gov/docs/iolll_0410/Ken%20Rice.pdf

[9] "Frequently Asked Questions about Restoring Glen Canyon," Glen Canyon Institute. Accessed March 6, 2011. http://www.glencanyon.org/aboutgci/faq.php

[10] "Hydropower at Hoover Dam," United States Bureau of Reclamation. Updated February 2009. http://www.usbr.gov/lc/hooverdam/faqs/powerfaq.html

only 1.03% of Arizona's electrical energy consumption,[11] 2.76% of Nevada's,[12] and 6.48% of Burbank, Glendale, and Pasadena's.[13] It is assumed that the situation is similar around the Glen Canyon Dam (probably providing even less because of its smaller capacity). Most of the energy in these areas comes from the burning of fossil fuels.

Although specific efficiency data is unavailable for the Hoover Dam, total electricity production data is available. The dam produced an average of 4.2 billion kWh of electricity between 1999 and 2008.[14] Because the overall power production is directly proportional to the head, which is itself proportional to water depth, any percent change in the Hoover Dam's head depth will be reflected in the total power generation. For example, a 10% increase in head depth will cause a similar 10% increase in power generation.

However, there is a major confounding factor. Our model is based on the assumption that outflow remains more or less unchanged with respect to inflows—that is, when inflows drop, the reservoir is drawn down in order to maintain outflow rates. More precisely, the outflow rate is assumed to decrease by about 16 thousand acre-feet per year, based on a linear regression of historical data from 1999 to 2010. This change is negligible when compared to a Colorado River Compact–mandated 9 million acre-feet per year outflow.

If the total water volume at Lake Powell increases, as our model predicts, the total electricity output will also increase. The effect on the economy will likewise be positive.

### Impact of the Water Level on the Local Economy

The water level affects not only power production but also recreation and tourism. Below is a chart of safe water levels for recreation in Lake Powell. It is clear that the drought has brought water levels down to a point that hinders recreation, a large source of income for the surrounding area (bringing $2.5 million from tourists to Page, Arizona[15]).

| SITE/LAUNCH NAME | MINIMUM SAFE ELEVATION | ABSOLUTE MINIMUM USABLE ELEVATION | CURRENT LEVEL VS. ABSOLUTE MINIMUM | CURRENT ACCESSIBILITY |
|---|---|---|---|---|
| **Antelope Point** | 3587.00 | 3586.00 | 28.17 Above | **Open and Usable** |

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[11] "Arizona Fact Sheet: Energy Efficiency & Energy Consumption," Southwest Energy Efficiency Project. Updated July 2009. http://www.swenergy.org/publications/factsheets/AZ-Factsheet.pdf

[12] "Nevada Fact Sheet: Energy Efficiency & Energy Consumption," Southwest Energy Efficiency Project. Updated July 2009. http://www.swenergy.org/publications/factsheets/NV-Factsheet.pdf

[13] "Electricity Consumption by Planning Area," Energy Consumption Data Management System. Updated 2011. http://ecdms.energy.ca.gov/elecbyplan.aspx

[14] "Hydropower at Hoover Dam."

[15] "Economic Benefits of Lake Powell and the Glen Canyon Dam," Accessed March 6, 2011. http://www2.kenyon.edu/projects/Dams/gec02ros.html

| | | | | |
|---|---|---|---|---|
| **Castle Rock Cut-Off** | 3612.00 | 3608.00 | 6.17 Above | **Open and Usable** |
| **Farley Canyon** | 3653.00 | 3649.00 | 34.83 Below | **Unusable, go to main marinas** |
| **Copper Canyon** | 3663.00 | 3660.00 | 45.83 Below | **Unusable, go to main marinas** |
| **Bullfrog to Halls Creek Cut-Off** | 3668.00 | 3665.00 | 50.83 Below | **Unusable, use Main Channel** |
| **Piute Farms** | 3682.00 | 3680.00 | 65.83 Below | **Unusable, go to main marinas** |

Figure ###[16]

Falling water levels have made many of these recreational areas unavailable for use, limiting the income from tourism. Also, because lower water levels result in lower power production, efficiency of the power plant goes down while maintenance costs go up. These factors combine and result in higher electricity prices, damaging the local economy.

As to water supply, only the Navajo Generating Station and Page, Arizona get their water supplies from Lake Powell,[17] so the loss of this source would not be too damaging; however, there is much more reliance on Lake Mead. For example, Las Vegas relies on Lake Mead for ninety percent of its water.[18] If water levels were to drop too low in this lake, the results would be devastating to the surrounding areas. Another factor affected by water level is salinity. As the water level decreases, salinity increases.[19] Salt in this water causes lower crop yields, creates undesirable drinking water, and expedites the deterioration of pipes.[20] Not only is the volume of water important, but quality is also an important factor in considering the water supply and how it changes with water levels.

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[16] "Water Summary," Summit Technologies. Accessed March 6, 2011. http://lakepowell.water-data.com/

[17] "Frequently Asked Questions about Restoring Glen Canyon."

[18] Felicity Barringer, "Water Use in Southwest Heads for a Day of Reckoning," The New York Times. Updated September 27, 2010. http://www.nytimes.com/2010/09/28/us/28mead.html?_r=1

[19] "Environmental Program," Colorado River Commission of Nevada. Updated March 7, 2007. http://crc.nv.gov/index.asp?m=env

[20] Ibid.

# Recommendations for Reductions of Water Use

## Assumptions

- Generally, we assume a reasonable budget to accomplish these projects.
- We assume micro-irrigation is largely available and could change irrigation techniques on a large scale.
- It is safe and there is a practical method of mixing fresh water from the river basin with reclaimed water.
- The information correlated with meeting a minimal capacity in Lake Powell would be influenced by only the Upper Basin area.

Currently, about 65% of inflow from the Upper Colorado River Basin is being used for human purposes. This detracts from the inflow to Lake Powell and thus contributes to the gradual reduction of the reservoir. There are many causes that attribute to this loss of water, and most can be addressed and mitigated in order to provide for a larger inflow of water to the Lake Powell reservoir.

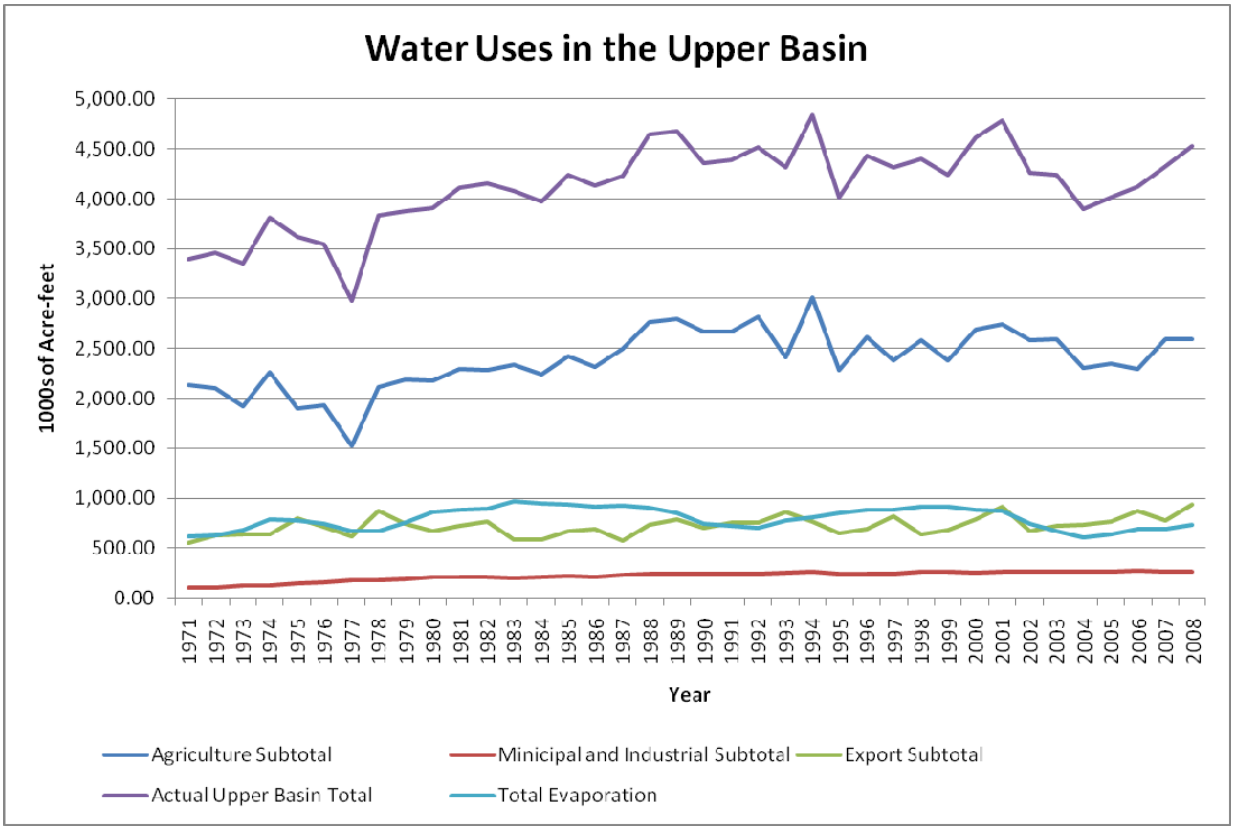

Figure ###[21] [22] [23] [24]

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[21] "Upper Colorado River Basin Consumptive Uses and Losses Report as Revised After Peer

By far the largest factor in this decrease in water supply, as shown by the graph above, is water diverted for agricultural use. These uses include: irrigation, anti-freeze, and animal consumption.

There are currently many methods for reducing the water used on farms for irrigation purposes. A large majority of current sprinkler systems are inefficient when compared to the most recent sprinkler technology. Micro-irrigation, a fairly new technology, averages about an 87% efficiency rating, which is extraordinary when compared to the average 79% efficiency created by regular surface irrigation.[25] If the states surrounding the basin were to pass legislation mandating a certain irrigation efficiency, to prevent waste of water, many farmers would have to switch to a more efficient system, reducing the gross amount of water used for irrigation. There is currently a system of incentives laid out in the Farm Bill, a document released by the Department of Agriculture every five years, that provides monetary incentives and funding for farmers who wish to improve the efficiency of their irrigation systems.[26] These programs, the Environmental Quality Incentives Program and the Agricultural Enhancement Program, can motivate farmers to change their irrigation systems. However, there is no specific efficiency rating required. The majority of water diverted to agricultural purposes is used for irrigation. According to the most recent available data, the 2008 Upper Basin water survey, 99% of this water is irrigation. If the law is simply set at 85% efficiency, assuming that all farmers have low-efficiency surface sprinklers and that they will increase efficiency as little as possible, then there is an average 6% increase in efficiency. This would have saved, in 2008, about 153.642 thousand acre-feet (taf) of water. As great an increase as this appears to promise, it doesn't have as great an impact considering that most computations of water use are in thousands of taf (or, simply, millions of acre-feet). This means only 6% of the 2,560.7 taf used in irrigation in 2008 alone would be accounted for.

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Review 1971-1995," United States Bureau of Reclamation. Updated September 20, pp. 5–55. http://www.usbr.gov/uc/library/envdocs/reports/crs/pdfs/cul1971-95.pdf

[22] "Colorado River System Consumptive Uses and Losses Report 1996-2000," United States Bureau of Reclamation. Updated December 2004, pp. 24–28. http://www.usbr.gov/uc/library/envdocs/reports/crs/pdfs/crs962000.pdf

[23] "Upper Colorado River Basin Consumptive Uses and Losses Report 2001-2005," United States Bureau of Reclamation. Updated June 2007, pp. 12–16. http://www.usbr.gov/uc/library/envdocs/reports/crs/pdfs/cul2001-05.pdf

[24] "Upper Colorado River Basin Consumptive Uses and Losses Report 2006-2010," United States Bureau of Reclamation. Updated 2008, pp. 12–14. http://www.usbr.gov/uc/library/envdocs/reports/crs/pdfs/cul2006-2010prov.pdf

[25] Terry A. Howell, "Irrigation Efficiency," United States Department of Agriculture. Updated 2003, p. 468. http://ddr.nal.usda.gov/bitstream/10113/4018/1/IND43939089.pdf

[26] "Farm Bill," Irrigation Association. Accessed March 6, 2011. http://www.irrigation.org/Policy/Farm_Bill.aspx

Another way to decrease the amount of water needed to irrigate nearby farmers' crops is to use reclaimed water. Reclaimed water is created when the solids are filtered out of waste water and it is treated to become sanitary. Recycled water is perfectly safe for irrigation, because it is sanitary.[27] The expense of reclaiming water may be foreboding to some state or national legislators. A possible solution to this is to mix fresh river water and reclaimed water and use both to irrigate fields. A federally established solution could work as follows: a minimum of so many parts of reclaimed water per thousand parts of irrigation water could be instated, further decreasing agricultural diversion of water and thus leading a higher volume of water into Lake Powell from the Upper Basin.

By the Law of Diminishing Returns, the other 1% of water used in agriculture is negligible when focusing on water conservation because the effort expended on fixing such minor expenditures would likely exceed the benefit of a very small decrease of water usage.

Due to the extremely vast surface area of the Colorado River and Lake Powell, a substantial amount of water is evaporated off of the surface. Lake Powell has an average approximate surface area of 162,700 acres.[28] The surface area of the Colorado River is undefined, due to the frequent change in water level and surface area. In 2008, 733.000 taf of water evaporated from the Upper Basin, more water than could be saved by improving irrigation efficiency. Putting a stop to evaporation altogether is simply impossible, but there are a variety of methods for reducing evaporation. Reducing the surface area of a body of water can help diminish the effects of evaporation. For example, there is an available product by the name of the "AquaCap," manufactured by a company called Nylex. This is a circular, floating, plastic cover that has an area of 0.256 milliacres.[29] This method would be inefficient in the Colorado River, due to the fact that the covers would simply float down the river. This would also be inefficient in Lake Powell, due to the extremely high surface area and the comparatively minuscule area that is covered by a single AquaCap. If the United States could allot the proper resources to this project, it would still be an improper usage of resources: Lake Powell is a popular boating area,[30] and the boats could not navigate around the devices. Other potential problems could include loss by theft or disappearance or malfunctions at the dam.

Another theoretical method of reducing evaporation is a reduction of surface area through increase of depth. This could be achieved with waterproof construction equipment or water-compatible explosives. The risk of such an operation, however, is far exaggerated when compared to the fruit of this labor. Also, the relatively small yield of this method advises any sensible engineer to avoid it. If this were attempted, however, it would be necessary for one to

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[27] "Water Recycling and Reuse: The Environmental Benefits," United Stated Environmental Protection Agency. Updated March 4, 2011. http://www.epa.gov/region9/water/recycling/

[28] "Lake Powell," Utah.gov. Accessed March 6, 2011. http://www.waterquality.utah.gov/watersheds/lakes/LAKEPOWL.pdf

[29] "AquaCap," Nylex. Accessed March 6, 2011. http://www.polarity.com.au/userfiles/file/AquaCap.pdf

[30] "Lake Powell."

account for the amount of water lost to absorption into the rock. When the reservoir was first filled, about 13.4 million acre-feet were absorbed into the rock.[31] A fraction of this staggeringly large loss would be repeated. Thus this method of reducing evaporation is counterproductive.

As shown by the graph above, very little of the water from the Upper Basin is used for municipal purposes. However, in efforts to minimize detraction from the Basin's flow, this must also be addressed. There is currently a shifting social paradigm towards the concept of "going green." This phrase describes the trend of increasing the electrical efficiency of devices, increasing concern for "environmental friendliness," and decreasing reliance on oil energy and fossil fuels. Some manifestations of this idea can be seen applied to the use of water, in the name of "water conservation." A multinational campaign, "Water. Use it Wisely," lists one hundred and eleven ways to conserve water on its website in order to help the socially minded public augment their resources and lower their water bills.[32] This list includes checking for leaks, reusing water, capturing overflow, and replacing old devices with newer, water-efficient models.[33] These steps can truly augment water conservation in any area if the people inhabiting that area commit to the cause. However, the amount of water used by municipal areas from the Upper Basin is insignificant in comparison to the total water used.

Exportation is defined by the Colorado River System made in the Colorado River Compact of 1922. The system is defined as the "portion of the Colorado River and its tributaries within the United States" with exports defined as "diversions from the system to areas outside its drainage area."[34] The water usage devoted to exportation usually hovers around the amount lost to evaporation, with the average export subtotal from 1971 to 2008 at approximately 722.3 taf and average evaporation total in the same time period at 792.3 taf. According to information also discussed by the United States Bureau of Reclamation, the Green River tributary and Upper Main Stem report considerable water exports, especially the Upper Main Stem (including Colorado and Utah), which exports 33% of its water "to serve agricultural and municipal needs on the Eastern slope of the Continental Divide in Colorado."[35] It may be possible to extend the ideas for conserving agricultural uses of water from the Upper Colorado River System as discussed above (irrigation efficiency, reclaimed water usage, etc.) to the Eastern slope of the Continental Divide that the Upper Main Stem focuses much of their Upper Basin resources on in order to reduce their export. Predicting a conserved value is difficult, in this case, because it is harder to gauge the dependency the Eastern slope region may have on this export, which could override any effects these conservation acts would attempt to influence.

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[31] "Glen Canyon Dam - Frequently Asked Questions," United States Bureau of Reclamation. Updated November 25, 2008. http://www.usbr.gov/uc/rm/crsp/gc/faq.html

[32] "100 Ways to Conserve," Water. Use it Wisely. Accessed March 6, 2011. http://www.wateruseitwisely.com/100-ways-to-conserve/index.php

[33] Ibid.

[34] "Upper Colorado River Basin Consumptive Uses and Losses Report 2006 - 2010," Accessed March 6, 2011, p. 4.

[35] Ibid.

The second major use of the Colorado River and Lake Powell, other than to supplement water resources, is entertainment. People from the surrounding areas come to Lake Powell to fish, SCUBA, and go boating. Thus, it stands to reason that an acceptable minimum for the volume of Lake Powell correlates with a lake water level equivalent to the minimum level allowable for boat launching. This level occurs at the altitude of 3586 ft above sea level.[36] On July 1, 2004, the altitude of the water level of Lake Powell was 3585.96 ft above sea level.[37] On this date, all docks would have been closed, disallowing recreational boating on the lake. To avoid repeating this event, the minimum level would be the same as it was on that day, allowing for a minimum lake storage capacity of about 10,458,739 acre-feet of water,[38] which should, hopefully, also eliminate any concern over accelerated decrease in the lake capacity. The absolute worst-case scenario, which must be avoided, would call for Lake Powell's minimal capacity to be approximately 2 million acre-feet, also referred to as "dead pool," a point at which the dam can no longer function.[39]

To avoid the water volume becoming even with or, at worst, dropping below this level, the above described methodologies will be extremely useful. All of these tools—irrigation efficiency, reclaiming of water, water covers, increased depth, and increased effort at domestic water conservation—will contribute to the decrease of usage of water volume that flows from the Colorado River in the Upper Basin to Lake Powell. Based on our model, however, these ideas could best be treated as a fallback plan or could be enacted in efforts to catalyze the predicted increase in the volume of the river in the nearby future.

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[36] "Lake Powell Water Database," United States Bureau of Reclamation. Accessed March 6, 2011. http://lakepowell.water-data.com/

[37] "Water Data for 20 days surrounding Jul 01, 2004," United States Bureau of Reclamation. Updated July 11, 2004. http://lakepowell.water-data.com/index2.php?as_of=2004-07-01

[38] Ibid.

[39] "Frequently Asked Questions about Restoring Glen Canyon."

# Appendix A

To calculate the values for our model, we used the programming language Java. For values that are subject to some randomness (rainfall, inflow, and outflow), we calculated the mean and standard deviations of historical data and combined it with pseudo-random normally distributed numbers generated by Java to obtain random estimates of these three elements. To ensure accuracy, we took data and separated it by month and year to get trends for each specific month and year, which could then be applied for smaller and more accurate changes. We took the three, along the more constant factors (evaporation and dam seeping) to calculate estimates for the total volume after a period of years. For each year, we ran the simulation thousands of times and averaged the value to get a more accurate estimate of the change in volume and combined this with the volume of the previous year to get the new volume. This process was then repeated for each subsequent year we wanted to predict.