M3 Challenge Runner Up (Magna Cum Laude Team Prize) - $15,000
Ridgefield High School, Team #538, Ridgefield, Connecticut
Coach: David Yolen
Students: Kimberly Cohen, Allison Collins, Andrew Klutey, Sean Scott, Will Yolen

NOT ENOUGH DAMMED WATER!

Summary

As the second largest reservoir in the United States, Lake Powell is vital in providing water to a rapidly growing population in the Lower Basin states of the Southwest (Arizona, Nevada, and Southern California). In response to the decade-long drought currently plaguing the Lower Basin, we have prepared a report for the Department of the Interior on the water shortage, projecting several possible outcomes over the next five years, as well as proposing steps to reduce water consumption among the Lower Basin states.

To model the changes in volume of water in Lake Powell over the next five years, while assuming that outflows of water remain at current levels, we wrote an equation that took into account the major factors in water level changes. These included inflows from the Colorado River (and the Escalante and San Juan Rivers), precipitation directly onto the lake, and losses to water released downstream, evaporation, and water absorbed by surrounding soil. It was apparent that current outflow through the Glen Canyon dam is not sustainable with the low inflow estimate into the lake, and too low with the high estimate. These problems led to a revision in the model.

Realistically, the volume of Lake Powell would never be allowed to run dry. Looking at past records, we realized that operators of the Glen Canyon Dam would maintain a flow of water out of Lake Powell and mainly increase it when the lake was in danger of flooding. Using this knowledge, we were able to test the low, high, and most likely percentages of inflow rate. With the low rate of 39% we came to the conclusion that the Lower Basin's water supply would face a shortage while trying to maintain the 60% capacity in the lake. On the other hand, with the high flow rate, Lake Powell would boast a 95% capacity with the excess water spilling over to increase the water supply of the Lower Basin. In the most likely outcome—an 83% inflow rate—the lake would gradually fill over the next five years while still managing the 8.23 million acre-feet outflow to the Lower Basin, as required by the 1922 Colorado River Compact.

With a model based so heavily on the inflow rates of the Colorado River into Lake Powell, slight alterations in these rates will be amplified by the model. We determined that even a 1 percent increase or decrease in the inflow rate can change the total volume of the lake by 3 percent. This demonstrates the possibility for minute adjustments to have large impacts.

In the final section of the paper, we addressed possible ways to reduce the removal of water from the Colorado River, in an effort to ensure that minimum capacity is maintained at Lake Powell. We focused on two major sources of water consumption: irrigation and municipal and industrial usage. We found two possible techniques for reducing water used in irrigation: drip irrigation and low-energy precision application (LEPA). Based on our calculations, a total of 1,697,807.85 acre-feet per year of water could be saved through these methods. We then turned to conservation techniques that could be employed to reduce municipal and industrial usage of water. We found that the most water could be saved through investing in more efficient appliances and fixtures in homes and buildings.

TABLE OF CONTENTS

Introduction

Lake Powell is United States' second largest reservoir, and in this role it is vital in providing water to the Lower Basin states (Nevada, Arizona, and Southern California) of the Southwest. Particularly with the growth of immigration from Mexico and the increase of Baby Boomers retiring to milder climates, the southwestern United States, often referred to as the "Sun Belt," has acquired a newfound importance. With this rapid population growth, however, has come a multitude of problems, especially with regards to the supply of water. A particular problem is the minimum amount of outflow from Lake Powell required by the Colorado River Compact of 1922. Criticized for its overestimation of the River's flow, the Compact now forces Lake Powell to release more water than is considered sustainable in the long term. The decade-long drought that has plagued the Lower Basin states brings with it a plethora of economic and health problems that must be solved by taking drastic measures soon. If not, the millions of people that rely on Lake Powell for so much may find themselves in trouble.

Global Assumptions

1. No other major natural disasters will occur over the course of the five year time period.
2. To determine the impact on Lake Powell over a five year time period, it was necessary to establish that March 5, 2011 is Day 1 of Year 0 and March 5, 2016 will be the end of the five year time period.

1 Water Level After Five Years

Problem

To provide an estimate of Lake Powell's volume as a percentage of capacity at the end of the five year period based on the low, high, and most likely inflow predictions.

Assumptions

1. The output amount of water from Lake Powell will remain constant at 8.23 million acre-feet (MAF) per year, which is the minimum annual flow that the Upper Basin States must provide to the Lower Basin States as mandated by the Colorado River Compact [Clayton].
2. The bank seepage rate will remain relatively constant at about 458 thousand acre-feet per year ["Water Supply and Lake Powell"].
3. The amount of precipitation is assumed to be negligible because the amount that falls directly onto the lake is insignificant compared to that which falls on the much larger drainage basin.
4. The average annual water temperature of Lake Powell will remain relatively constant over the next five years, so this will not impact evaporation rates.
5. The amount and impact of snow is negligible; we assume that it is included in the inflow rate.

Analysis of Problem

Establishing the first model of the volume of water in Lake Powell as a function of time was the critical groundwork of the entire problem, as it provided the basis for comprehension and comparison as we moved forward with the analysis of the economic effects and other impacts. We began developing the model by considering the factors that would influence the volume of water in the lake the most and stating that the volume in the lake at a given point in time is equal to the current volume, taking into account any changes.

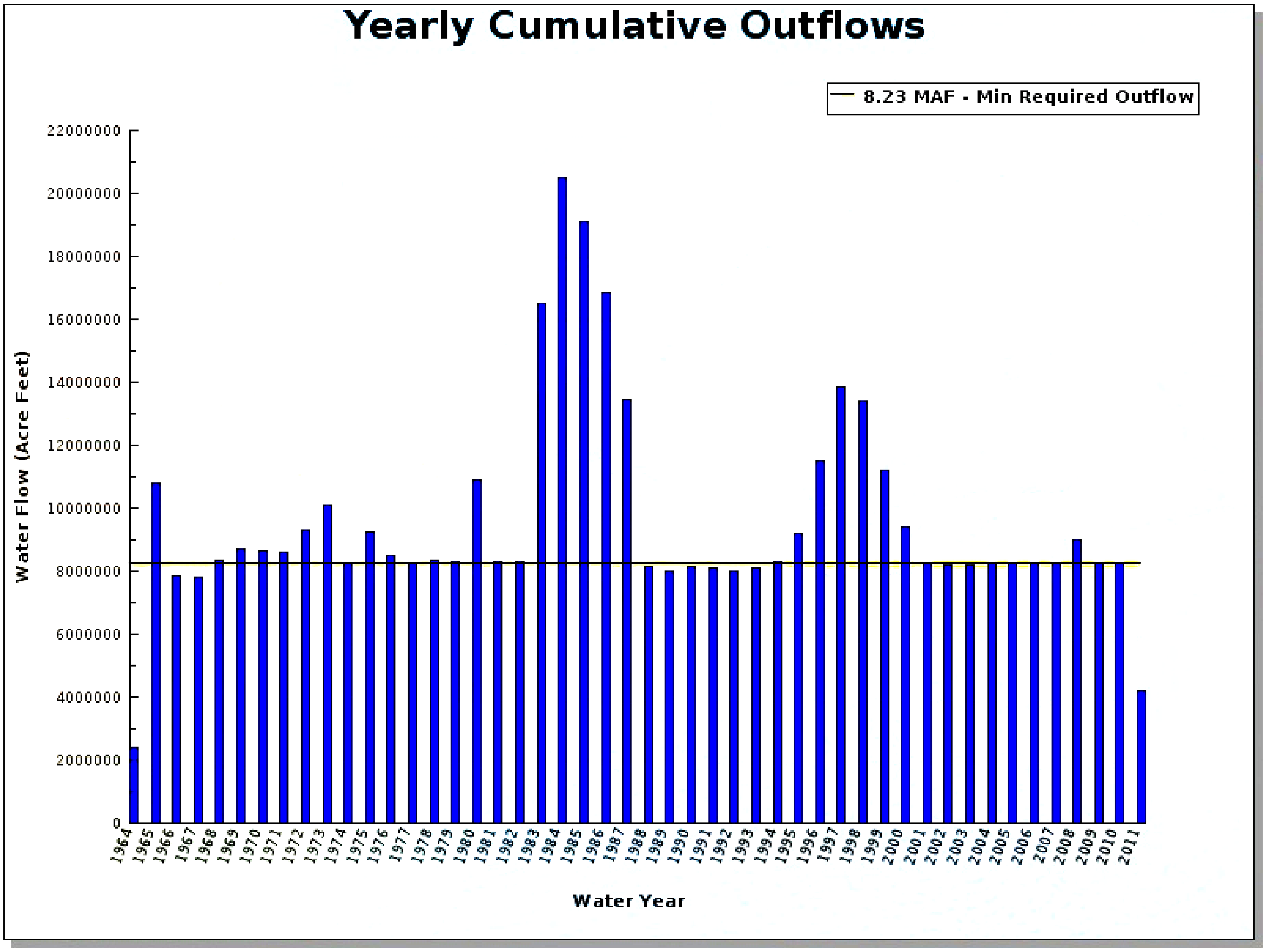
The factor that we found would most significantly increase water volume was **inflow**, or the volume of water that enters the lake from the Colorado River. It is assumed to include the contribution from the **drainage basin**, which is the area where precipitation converges to the lake. Since this drainage basin is significantly larger than the lake itself, as stated in the assumptions, we decided to assume that all precipitation occurring directly on the lake is negligible, instead focusing on inflow from the Colorado River.

The factors determined to most affect the decrease in the volume included bank seepage, evaporation, and outflow:

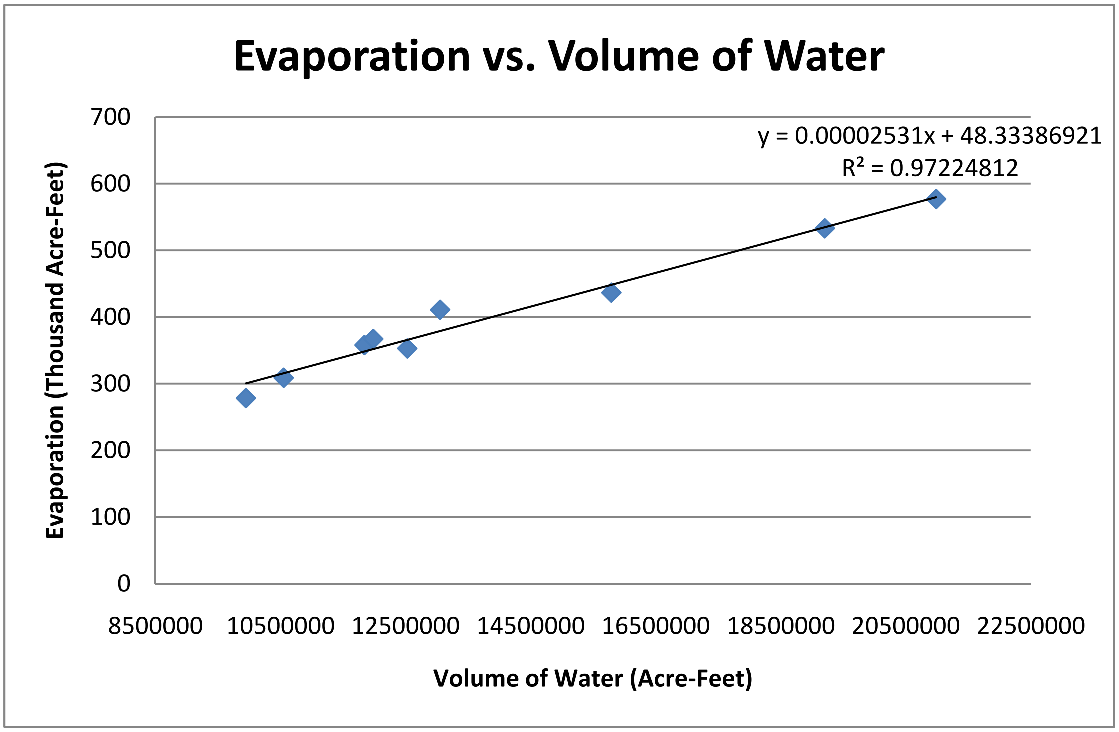
Bank seepage is the amount of water absorbed by the banks surrounding Lake Powell, soaking up a fair amount of the Lake's volume each year. Due to the lack of yearly data for this number, we have decided to use a total average, estimating that it drains approximately 458,000 acre-feet per year. This is based on the fact that the yearly average of water lost to both evaporation and bank seepage is about 860,000 acre-feet per year

["Water Supply and Lake Powell"]. The average evaporation rate for the past decade has been calculated to be 402,000 acre-feet per year [*Upper Colorado River Basin*], so the average amount of water lost per year to bank seepage is the difference between evaporation rate and the total average, or around 458,000 acre-feet.

The **outflow** is the amount of water going through the dam. We were able to assume that the outflow would be 8.23 MAF per year, which the states are required to provide by the 1922 Colorado River Compact, especially over the last ten years, since the drought began ["Lake Powell Water Database"].



The **evaporation** is the amount of water lost from the lake to the atmosphere. In creating an equation to compute the amount of water lost through evaporation, we first found historical data concerning the amount of water that evaporated from Lake Powell each year since the start of the drought. We compared this to factors that influence evaporation, including temperature and volume. As temperature did not vary greatly from year to year, we were unable to find a strong relationship. Plotting evaporation versus volume, however, yielded a strong positive, linear correlation. The high r^2 value indicates that 97.22% of the variability can be explained by the model of the volume of Lake Powell versus evaporation, so it is a viable means to predict the amount of water that will be lost through evaporation.



Model

After taking all of the aforementioned factors into consideration, we developed this model:

$$V(t) = V(0) + Inflows \cdot time - Outflows \cdot time,$$

$$V(t) = V(0) + (Inflow + Precip) \cdot t - (Evap(V) + BankSeep + Outflow) \cdot t,$$

where:
$V(t)$: the volume of water in Lake Powell at time t; $V(0) = 13.19$ MAF
$Inflow$: the inflow into the lake from upstream (with three different estimates)
$Precip$: the amount of water that falls directly on the lake as precipitation (assumed 0)
$Evap(V)$: the loss of water to evaporation (as a function of volume);
$Evap(V) = .02531x + 48{,}333$, all in units of acre-feet/year
$BankSeep$: the loss of water to bank seepage (457,400 acre-feet/year)
$Outflow$: the volume of water lost through the Glen Canyon dam, 8,230,000 acre-feet/year.

An Euler approximation with 5 intervals was used to find the evaporation rate for each of the three estimates of inflow.

Low estimate of inflow

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)
1	13,190,000	4,680,000	0	382,172	457,400	8,230,000	8,800,428
2	8,800,428	4,680,000	0	271,072	457,400	8,230,000	4,521,956
3	4,521,956	4,680,000	0	162,784	457,400	8,230,000	351,773
4	351,773	4,680,000	0	57,236	457,400	8,230,000	-3,712,864
5	-3,712,864	4,680,000	0	-45,640	457,400	8,230,000	-7,674,624

Likely estimate of inflow

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)
1	13,190,000	9,960,000	0	382,172	457,400	8,230,000	14,080,428
2	14,080,428	9,960,000	0	404,709	457,400	8,230,000	14,948,319
3	14,948,319	9,960,000	0	426,675	457,400	8,230,000	15,794,244
4	15,794,244	9,960,000	0	448,085	457,400	8,230,000	16,618,759
5	16,618,759	9,960,000	0	468,954	457,400	8,230,000	17,422,405

High estimate of inflow

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)
1	13,190,000	16,440,000	0	382,172	457,400	8,230,000	20,560,428
2	20,560,428	16,440,000	0	568,717	457,400	8,230,000	27,744,311
3	27,744,311	16,440,000	0	750,542	457,400	8,230,000	34,746,369
4	34,746,369	16,440,000	0	927,764	457,400	8,230,000	41,571,206
5	41,571,206	16,440,000	0	1,100,500	457,400	8,230,000	48,223,305

$PercentCapacity_{low}$, $PercentCapacity_{likely}$, and $PercentCapacity_{high}$ represent the low inflow rate, likely inflow rate, and high inflow rate estimates, respectively, of Lake Powell, all after five years. The full capacity of the lake is 21,505,000 acre-feet [Utah Division of Water Quality].

$$PercentCapacity = \frac{V(5)}{V_{full}} \times 100\%,$$

$$PercentCapacity_{low} = \frac{-7{,}674{,}624 \text{ acre} - \text{feet}}{21{,}505{,}000 \text{ acre} - \text{feet}} \times 100\% = -35.7\%,$$

$$PercentCapacity_{likely} = \frac{17{,}422{,}405 \text{ acre} - \text{feet}}{21{,}505{,}000 \text{ acre} - \text{feet}} \times 100\% = 81.0\%,$$

$$PercentCapacity_{high} = \frac{48{,}223{,}30 \text{ acre} - \text{feet}}{21{,}505{,}000 \text{ acre} - \text{feet}} \times 100\% = 224.2\%.$$

The model shows the predicted percentages of capacity at the end of the five year period for each of the three inflow conditions: low, average, and high. Based on the model, the low inflow estimate of 39% of average after five years would cause the lake to contain -35.7% of its capacity, meaning that the lake would have run dry, signifying that if the low estimate were to hold true, the current outflow rate would be unsustainable. The likely inflow estimate of 83% would allow for the lake to be at 81% of its capacity after five years, which would be the most ideal of these inflows. The high inflow estimate of 137% of average would cause the lake to have 224.2% of its capacity at the end of the five years, which is also implausible because the lake would have to contain more than twice its capacity. In both extreme cases, the outflow rate will need to be altered, as is explored further in the following sections.

2 Effects on Water Supply and Economy

Problem

To determine the impact of the projected lake outflows on the water supply and economy—including power generation—of the Lower Basin.

Introduction

We began by identifying the three possible values for the inflow: low, most likely, and high. The most likely water inflow parallels current levels, and thus we thought it would not exert significant change on water supply or economic activity. We then continued by comparing average outflow with average capacity per year, as outflow is the water supply received by the Lower Basin. We determined that the past trend has been to let the lake reach full capacity and then increase outflows. To determine the outflow at the highest level of inflow, we used the model we had previously generated to predict what the volume would be. At the lower level, since capacity had not yet been reached, the outflow would be equal to the inflow. Once we determined values for the water supply, we then moved to examining the impact on the economy, focusing on energy, irrigation, and recreation.

Assumptions

1. Current water outflow is sufficient for the economy.
2. For the low estimate of water supply, outflow will equal inflow (minus water lost to bank seepage and evaporation) since maximum capacity has not yet been attained.
3. Water allocated to Native American tribes is not a significant amount of the total.

Effects on Water Supply

Model

We realized that the preexisting conditions of the extreme inflow rates made it necessary to alter our original model. Our original model,

$$V(t) = V(0) + Inflows_{NET} \cdot time - Outflows_{NET} \cdot time,$$

$$V(t) = V(0) + (Inflow + Precip) \cdot t - (Evap(V) + BankSeep + Outflow) \cdot t,$$

does not prevent the lake from running dry, as it did with the low inflow rate, nor does it take into account the possibility of the lake overflowing and filling beyond maximum capacity, as was the case with the high inflow rate. In order to compensate for these scenarios, we established conditions that the outflow rate must meet in order to proceed. There will then be new, altered projections from the model that allow for the scenario to run through the five years without the lake water depleting or overflowing.

Altered Model

We chose not to allow the lake to reach 100% capacity, due to the possibility of measuring errors and to prevent against overflow, so we set the maximum volume to approximately 95%:

$$95\%\ Lake\ Powell = LP_{95} = \ 20{,}560{,}428\ acre\text{-}feet$$

$if\ V(t) > LP_{95}$

$$Outflow = Inflows_{NET} + [V(t) - LP_{95}]$$
$$V(t) = \ LP_{95}$$

$if\ V(t) < LP_{95}$

$$if\ (Inflows_{NET} > Outflows_{NET})$$
$$V(t) = V(0) + Inflows_{NET} \cdot time - Outflows_{NET} \cdot time \rightarrow \text{No change}$$
$$if(Inflows_{NET} < Outflows_{NET})$$
$$Outflow = Inflows_{NET} - [Evap(V) + BankSeep]$$
$$V(t) = V(0)$$

$if\ V(t) = LP_{95}$

$$Outflow = Inflow_{NET} - [Evap(V) + BankSeep]$$

Effects on water supply of low estimate inflow

The low inflow of 39% from the Colorado River alone was not enough to maintain the normal 8.23 MAF/year outflow without the lake running dry, as seen in the first use of our model. Therefore, following the guidelines of the altered version of our model, the volume of the lake was less than 95% and the net inflow was less than the net outflow, so the outflow was set equal to the inflow (minus the volume of water lost to bank seepage and evaporation). We then set the volume of the lake to remain constant at 61.3% (the original capacity) for the next five years. This all reflects the applicable portions of our altered model, as shown below:

$$V(t) < LP_{95};$$
$$if(Inflows_{NET} < Outflows_{NET}),$$
$$Outflow = Inflows_{NET} - [Evap(V) + BankSeep],$$
$$V(t) = V(0).$$

The table below displays our altered values:

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)	% capacity of Lake
1	13,190,000	4,680,000	0	382,172	457,400	3,840,428	13,190,000	61.3%
2	13,190,000	4,680,000	0	382,172	457,400	3,840,428	13,190,000	61.3%
3	13,190,000	4,680,000	0	382,172	457,400	3,840,428	13,190,000	61.3%
4	13,190,000	4,680,000	0	382,172	457,400	3,840,428	13,190,000	61.3%
5	13,190,000	4,680,000	0	382,172	457,400	3,840,428	13,190,000	61.3%

The total water supply to the Lower Basin would go below the required value of 8.23 MAF/year, to a value of 3.84 MAF/year, decreasing the supply by 4.39 MAF/year. This would violate the terms of the Colorado River Compact of 1922, a necessary compromise to make in light of the extreme water shortage.

Effects on water supply of "likely" inflow estimate

Utilizing the conditions in our altered model with the likely 83% inflow rate, we have that the volume of the lake will be less than 95%, yet the inflow rate will be greater than the mandated 8.23 MAF/year outflow of water to the Lower Basin if it is held constant. We held this outflow constant, so the inflow was in fact larger. This logic can be followed in our model:

$if\ V(t) < LP_{95}$

$\quad if\ (Inflows_{NET} > Outflows_{NET})$

$V(t) = V(0) + Inflows_{NET} \cdot time - Outflows_{NET} \cdot time$→ No change.

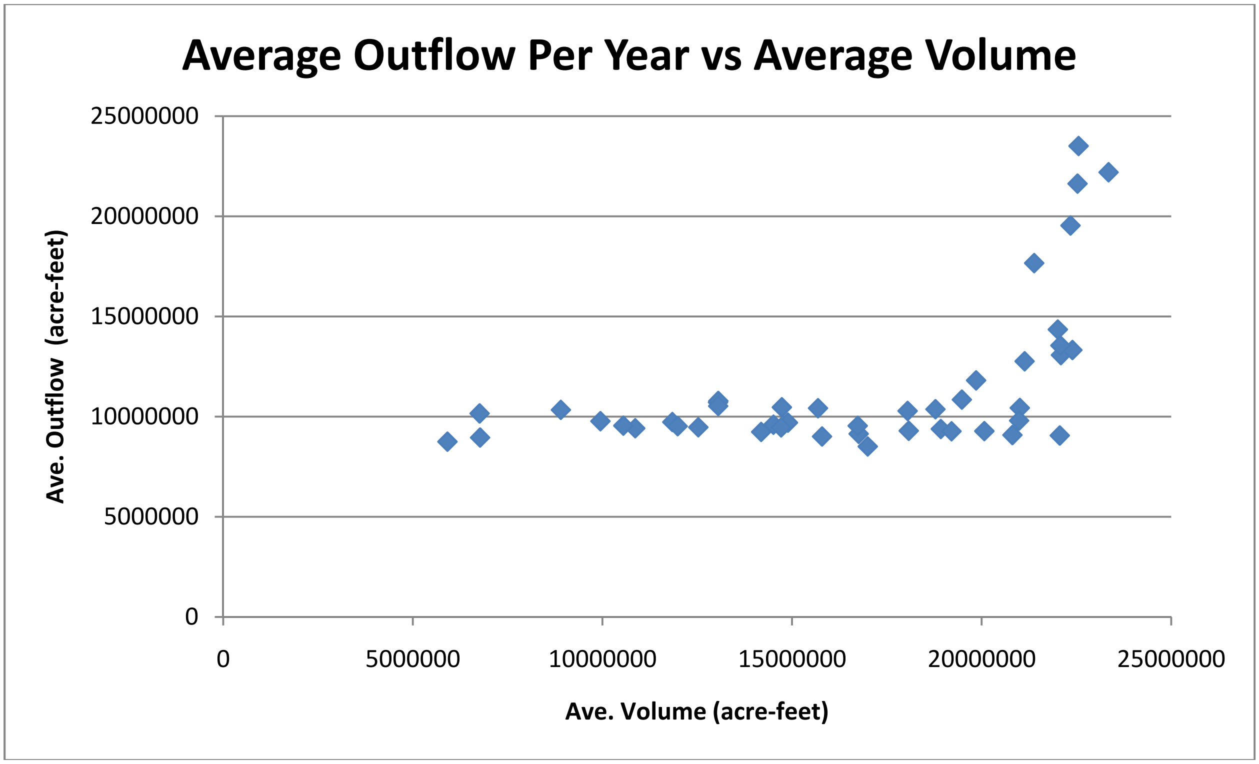
The table below shows our altered data:

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)	% capacity of Lake
1	13,190,000	9,960,000	0	382,172	457,400	8,230,000	14,080,428	65.48%
2	14,080,428	9,960,000	0	404,709	457,400	8,230,000	14,948,319	69.51%
3	14,948,319	9,960,000	0	426,675	457,400	8,230,000	15,794,244	73.44%
4	15,794,244	9,960,000	0	448,085	457,400	8,230,000	16,618,759	77.28%
5	16,618,759	9,960,000	0	468,954	457,400	8,230,000	17,422,405	81.02%

With the likely 83% inflow rate, there will be more water flowing into Lake Powell than flowing out. This will cause the volume of the lake to increase from around 60% of capacity to 81.02% of capacity over the next five years, reaching 17,422,405 acre-feet. This will supply the necessary amount to the Lower Basin while increasing the amount of water in the lake.

Effects on water supply of high estimate inflow

To determine the outflow of Lake Powell in the case where the inflow is at the high of 137% we graphed the average volume of the lake in each year against the average outflow of that year. This graph does not show a clear relationship between the average volume and the average outflow. Instead, it shows that once the average capacity reaches the approximate total capacity of the lake (≈21,500,000 AF), the average outflow spikes in order to maintain the lake at maximum capacity.



The past handling of high volumes led us to determine how to address the threat of Lake Powell overflowing. For the high estimate of 137% of the average inflow, we noticed that the lake would overflow after the first year, as the lake had a volume of 20,560,428 acre-feet, which is 95.61% of capacity. However, in each succeeding year, the lake would overflow unless the outflow was increased in compensation. In order to prevent overflow, the outflow was increased to hold the volume constant at 95.61%. This reasoning can also be followed in our altered model:

$$if\ V(t) > LP_{95}$$

$$Outflow = Inflows_{NET} + [V(t) - LP_{95}]$$

$$V(t) = LP_{95}$$

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)	% capacity of Lake
1	13,190,000	16,440,000	0	382,172	457,400	8,230,000	20,560,428	95.61%
2	20,560,428	16,440,000	0	568,717	457,400	15,413,883	20,560,428	95.61%
3	20,560,428	16,440,000	0	568,717	457,400	15,413,883	20,560,428	95.61%
4	20,560,428	16,440,000	0	568,717	457,400	15,413,883	20,560,428	95.61%
5	20,560,428	16,440,000	0	568,717	457,400	15,413,883	20,560,428	95.61%

Therefore, the outflow for years 2 through 5 increased to 15.4 MAF/year. This would increase the overall water supply for the Lower Basin by 7.18 MAF/year. The chart above shows the altered outflow and total volume values necessary to maintain the 95.61% capacity.

Economic Effects

Water has four major values to the Lower Basin states: hydropower, irrigation, municipal and industrial uses, and recreation. (Flood control is considered negligible since its approximate benefit is about .0007% of the total water from the Colorado River [*The Water Conservation Initiative*].)

Agriculture

One important usage of water from the Colorado River in the lower basin is to irrigate crop lands. In order to determine the economic effect of changing the water supply, we looked at the crop-value per acre-foot of water. This allowed us to determine a constant that we could multiply by the volume of water to obtain the total crop value which that volume equates to. A study in the Lower Basin in 1994 found that 3.5 MAF of water resulted in a crop value of $780,000,000 [Lellouch, Hyun, and Tognetti]. The crops studied were comprised of the major products of the region: cotton, wheat, alfalfa, lettuce, barley, cantaloupe, and citrus. Using an inflation calculator, we found that the $780,000,000 in 1994 would be worth $1,160,000,000 in 2011. We then divided this number by the number of acre-feet of water used in production, yielding an economic crop value of $331.43 per acre-foot of water. If the volume of water decreased from the "most likely" level of 8.23 million to the "low" of 3.84 million, a loss of $1,454,977,700 would be incurred (4,390,000*331.43). If the water volume is higher than the "most likely" level, the excess water will be allotted to the Hoover Dam.

Impact on Hydroelectric Generation

Assumptions

1. 100% efficiency in harnessing the hydroelectric power.
2. Height of water above turbine is constant for each dam (ignore changes in water level).
3. Outflows in excess of what is expected from Lake Powell will all reach Lake Mead, where they will all be used for hydroelectric generation to keep the water level constant.

Glen Canyon Dam

A simple equation for the electricity generated by a hydroelectric plant, derived from the gravitational potential energy of water, is $\Delta U = mgh = (dV)gh$ [Fowler], where ΔU is the change in energy, m is the mass of water falling (and equal to the density d times volume of water V), g is the universal gravitational constant ($9.8\frac{m}{s^2}$), and is h is the height the water falls down, 176m for the Glen Canyon Dam ["Glen Canyon Dam"]. Using the U.S. average electric rate, r = 9.27 cents per kWh [Soultanian], the value of the electricity per volume of water at each dam is given by

$$P_{GlenCanyon}(V) = dVgh \cdot r = \left(\frac{1{,}000\text{kg}}{\text{m}^3}\right) V \left(9.8\,\frac{\text{m}}{\text{s}^2}\right)(176.5\text{m})\left(\frac{\$0.0927}{3{,}600{,}000\text{J}}\right) = \$0.04454 \cdot V.$$

Therefore, a decrease of 4.39 MAF (low estimate) = $5.415 \times 10^9\text{m}^3$ of water coming through the dam annually corresponds to a revenue loss of $P_{GlenCanyon}(5.415 \times 10^9) =$ $241,184,100.

Conversely, an increase of 7.18 MAF (high estimate) = $8.856 \times 10^9\text{m}^3$ of water coming through the dam annually corresponds to an increase in revenue of $P_{GlenCanyon}(8.856 \times 10^9) = \$394{,}446{,}240$.

Hoover Dam

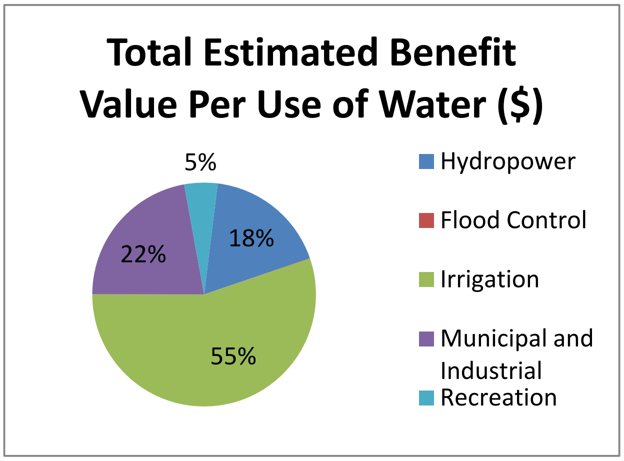
As stated in the assumptions, if the outflows from Lake Powell are less than expected, the change is absorbed by decreasing the amount of water used for irrigation. However, if there are excess outflows, it is assumed that Lake Mead will receive all of the excess, which generates additional revenue of

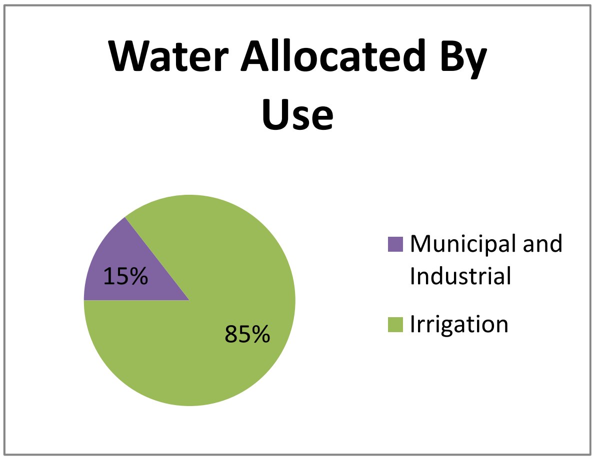
$$P_{HooverDam}(V) = \left(\frac{1{,}000\text{kg}}{\text{m}^3}\right) V \left(9.8\,\frac{\text{m}}{\text{s}^2}\right)(175.6\text{m})\left(\frac{\$0.0927}{3{,}600{,}000\text{J}}\right) = \$0.04431 \cdot V,$$

with the only change being the hydraulic height is slightly lower ["Hoover Dam"]. Considering only the high estimate of inflows into Lake Powell, the additional revenue gained at the Hoover Dam through generation is $P_{HooverDam}(8.856 \times 10^9) = \$392{,}432{,}917$.

Municipal and Industrial

As shown in the graph below [Lellouch], approximately 15% of the Colorado River's flow is diverted towards municipal and industrial uses. And while it is dwarfed in terms of water allocation by irrigational uses, it is proportionately more valuable in the monetary benefit estimate.





Due to its comparatively high value, and due to the fact that water is necessary for life, we can conclude that the demand for drinking water will remain unchanged over the next five years. The problem with the decreasing supply of water is particularly evident in the case of Las Vegas. Approximately 90% of Las Vegas' water supply is drawn from Lake Mead, whose water level is falling at a rapid rate. And if the water level falls below the city's intake at 1,000 feet, it will become cut off from a large portion of its water supply (the Lake's current level is 1059.92 feet [*Current Conditions*]). The very real danger of Las Vegas being left with only 10% of its water supply has led to large construction projects aimed at ensuring a secure source. One option that the Southern Nevada Water Authority is actively pursuing is building a $3.6 billion pipeline from Northern Nevada. Another strategy that has already been started is the building of a third intake at the bottom of Lake Mead. This project has been estimated to cost $700 billion to complete, and has already run into a number of problems. Thus, the battle to establish a secure source of water is already costly and economically inefficient, a penalty that will surely be passed on to the water's consumers and Nevada taxpayers. Beyond the dangers posed to drinking water, it is necessary to look at the much more problematic impact of the drought on construction and industry. Further shortages will divert water towards residential areas and away from economic development and growth, which would have far-reaching effects. In 2004, the Southern Nevada Water Authority decided to estimate the consequences of limiting construction in order to better manage the water supply. Their findings illustrated that just a 10% decrease in construction followed by a moderate recovery would affect economic output quite negatively, causing about $3.2 billion in losses within the first three years [*The Impact of a Growth Interruption in Southern Nevada*]. The decrease in industrial and construction sectors would be even worse in the long term, but the examination of such effects beyond five years is not required by the problem. Nonetheless, industrial and municipal users would be harmed significantly in the short term, as shortages would require drastic measures and decreased total output.

Recreational

The estimated value of recreational uses of water is about 1 billion dollars or 5% of the water's total value [*The Water Conservation Initiative*]. Due to the wide variety of recreational industries, it is immensely difficult to mathematically predict the effect of drought. It is possible, nonetheless, to examine the effects of the recent water shortages on certain industries and extrapolate the effect to similar industries. Take, for instance, the Lake Mead Recreational Area, a popular tourist location above the Hoover Dam. Estimates say that this particular area alone contributes $500 billion to local economies [*Lake Mead Facts and Figures*], and while it is unlikely that the drought will completely kill the Lake Mead recreational economy within the next five years, it is notable that there are many costs attached to a sinking water level. For example, the Lake is populated by five marinas [*Lake Mead Facts and Figures*], each of which has to move boat ramps and moorings further out with the water line. Add roads and utility lines which also must be moved, and the bill comes out to approximately $36 million over the last nine years [*Drought Stricken Lake Mead*]. Beyond Lake Mead, the impact on recreational uses of water is also directly affected by restrictions on municipal and industrial uses. Take, for instance, a study done by the National Conference of State Legislatures, which examines the impact of climate change on Las Vegas golf courses. Approximately three out of every ten Las Vegas tourists will play golf while on their vacations, but with decreased supply of water, golf courses may be forced to cut back on water used on the grass. Such a consequence may lead to browning of grass, less appealing courses, and a decreased incentive for tourists to visit. With even a 25% decrease in play on Las Vegas golf courses, economic losses could total almost $225 million [*Nevada: Assessing the Costs of Climate Change*]. Clearly, the tourism industry is adversely impacted in both of these cases by the lower water levels. And while it is certain that a severe drought would impact other important tourism industries in the Lower Basin, it is impossible to tell how far-reaching these impacts are [*Nevada: Assessing the Costs of Climate Change*]. Nonetheless, we will assume, based on the very negative effects on the aforementioned recreational activities, that other similar industries would be harmed in a comparable fashion.

3 Small Changes

Problem

To determine the sensitivity of the model and define how small changes in the assumed inflow rates affect the model and the estimates.

Assumptions

1. Flow rates are exact.

Analysis of Problem

The initial model that we created and then altered in the previous section according to the unique conditions has a high sensitivity to the inflow rate. Even before analyzing our model with different inflow rates, we thought that the overall volume of Lake Powell after the five years would not be resistant to alterations in the inflow rates because the inflow plays a very critical role in the volume of the lake. For example, the current volume of the lake is 13.19 MAF, while the necessary outflow rate is 8.23 MAF, which is approximately 62.4% of the current volume. This shows that if the inflow of water were to stop for even one year, the lake would run dry due to the necessary outflow rate. Therefore, changes in the inflow rate will cause changes in the volume of the lake or outflow rates.

To explore this, we decided to change each of the estimates of future Colorado River inflows into Lake Powell by 1%. We increased the low inflow rate of 39% to 40% and decreased the likely and high values of 83% and 137% to 82% and 136%, respectively. Although altering the rates by only 1%, we thought that the results of those changes would magnify the alterations. The changes are also compounded over five years, so this would further amplify the effect of the 1% modification.

Sensitivity of the Model with Low Inflow Rates

Following the same procedure that we used to determine the effects on water supply with the low estimated outflow, we recalculated the inflow from the Colorado River using an inflow rate of 40%. The implications of altering the 39% to 40% inflow rate can be seen in the table below.

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)	% capacity of Lake
1	13,190,000	4,800,000	0	382,172	457,400	3,960,428	13,190,000	61.3%
2	13,190,000	4,800,000	0	382,172	457,400	3,960,428	13,190,000	61.3%
3	13,190,000	4,800,000	0	382,172	457,400	3,960,428	13,190,000	61.3%
4	13,190,000	4,800,000	0	382,172	457,400	3,960,428	13,190,000	61.3%
5	13,190,000	4,800,000	0	382,172	457,400	3,960,428	13,190,000	61.3%

Although the five year compounding did not affect this particular case because the outflow rate was held constant, the outflow rate still increased as a result of the minor 1% inflow increase. The outflow increased from 3,840,428 acre-feet/year when the rate was 39% to

3,960,428 acre-feet/year, which was a 120,000 acre-feet/year increase, or a 3.12% increase.

Sensitivity of the Model with Likely Inflow Rates

To demonstrate the impact of changing the assumed inflow rate on the model for even the likely inflow rate, we used an inflow rate of 82% instead of the original 83%. Using the same procedure as outlined when observing the effects on water supply of likely inflow rate, we held the outflow rate constant and changed the inflow rate from the Colorado River to 82%. The impact of this change can be seen in the table below; especially note the change in volume of the lake.

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)	% capacity of Lake
1	13,190,000	9,840,000	0	382,172	457,400	8,230,000	13,960,428	64.92%
2	13,960,428	9,840,000	0	401,671	457,400	8,230,000	14,711,357	68.41%
3	14,711,357	9,840,000	0	420,677	457,400	8,230,000	15,443,279	71.81%
4	15,443,279	9,840,000	0	439,202	457,400	8,230,000	16,156,677	75.13%
5	16,156,677	9,840,000	0	457,258	457,400	8,230,000	16,852,018	78.36%

This case shows the impact of the 1% decrease in inflow rate because after five years, the volume of the lake only reached 16,852,018 acre-feet, decreasing 570,387 acre-feet or 3.27% from the 17,422,405 acre-feet at 83% inflow rate.

Sensitivity of the Model with High Inflow Rates

The effect of altering the inflow rate could once again be seen with the high inflow rate, as we decreased the assumed 137% inflow to 136% inflow. We again used the same corresponding procedure from the previous problem.

t	V(t-1)	Colorado	Precip	Evap	BankSeep	Outflow	V(t)	% capacity of Lake
1	13,190,000	16,320,000	0	382,172	457,400	8,230,000	20,440,428	95.05%
2	20,440,428	16,320,000	0	565,680	457,400	15,296,920	20,440,428	95.05%
3	20,440,428	16,320,000	0	565,680	457,400	15,296,920	20,440,428	95.05%
4	20,440,428	16,320,000	0	565,680	457,400	15,296,920	20,440,428	95.05%
5	20,440,428	16,320,000	0	565,680	457,400	15,296,920	20,440,428	95.05%

The impacts of the 1% alteration can be seen here in both the outflow rate and the volume of the lake. The outflow rate decreased 0.76%, or 116,963 acre-feet/year from 15,413,883 acre-feet/year to 15,296,920 acre-feet/year. The volume of the lake decreased from 20,560,428 acre-feet by 120,000 acre-feet to 20,440,428 acre-feet, or by 0.58%.

4 Reducing Water Removals

Problem

To recommend possible reductions to the amount of water removed from the Colorado River in an effort to maintain minimum capacity in Lake Powell.

Analysis of Problem

When approaching possible ways to reduce water removal from the Colorado River, we felt it was most important to first target the biggest consumer of water: irrigation. Since the Colorado River Basin produces diverse crops, we examined two possible techniques—drip irrigation and low-energy precision application (LEPA)—that encompass this variety. We then looked to another major source of removal from the water supply: municipal and industrial usage. We researched conservation methods that have achieved success in reducing water consumption. We looked at one area of the basin in particular, Las Vegas, where methods such as reducing usage and investing in more efficient appliances have the potential to make a serious impact. These water removal reductions would allow water consumers to adapt to a reduced outflow or water supply, so that a minimum capacity, which we assumed equal to the current capacity of 13.1 million acre-feet, could be maintained.

Assumptions

1. Crop production in the basin is evenly divided among crops that would pertain to the usage of drip irrigation (cotton, fruit, vegetables) and the usage of LEPA (wheat, alfalfa).
2. Economic costs of conservation are ignored.
3. 85% of the water supplied is used in agriculture [Lellouch, Hyun, and Tognetti].
4. Minimum capacity is equal to the current capacity of 13.1 MAF.

Improve Irrigation Techniques

A viable means to reducing the amount of water removed from the Colorado River is improving irrigation techniques, as irrigation is the biggest consumer of water outflows. As a variety of crops are grown in the river basin, there are two major techniques that can be applied: drip irrigation and low-energy precision application (LEPA). Drip irrigation is applicable to the cotton, vegetable, and citrus crops produced, while LEPA can be used to reduce losses with crops such as wheat and alfalfa. The percent efficiency of a normal water irrigation system is 70%, as water is lost due to other plants and evaporation, and efficiency with drip irrigation is 90% [Marlow]. Efficiency with LEPA is the highest, at 95% [Stalcup]. Thus, drip irrigation represents a $\frac{90-70}{90}$ or 22.22% increase in efficiency, and LEPA represents a $\frac{95-70}{95}$ or 26.32% increase in efficiency. Assuming the water supply of 8,230,000 acre-feet, and that agriculture uses $(.85) \times (8{,}230{,}000) = 6{,}995{,}500$ acre-feet, this would result in the following savings:

Drip Irrigation: $(.2222) \times (\frac{6{,}995{,}500}{2}) = 777{,}200.05$ acre-feet,

LEPA: $(.2632) \times (\frac{6{,}995{,}500}{2}) = 920{,}607.8$ acre-feet.

Total savings from a shift in irrigation technique would then amount to 1,697,807.85 acre-feet per year.

Improve Conservation Efforts

Current estimates project that water demand in Las Vegas and other Lower Basin areas will decrease approximately 7% over the next 30 years [Cooley et al.]. As municipal and industrial water usages currently account for about 15% of water used [Lellouch], this results in a miniscule 1% total reduction in water usage in the Lower Basin. As the Pacifist Institute recommends, the best step that could be taken among manufacturing and industrial users of water is to invest in more efficient fixtures and appliances inside homes and businesses. In Las Vegas alone, these steps would result in an 86,000 acre-feet per year reduction in water usage [Cooley et al.]. Furthermore, if these steps were taken beyond the boundaries of Las Vegas and applied to the larger Lower Basin area, it would surely have a significant impact on the total consumption of water for municipal and industrial purposes. And while this number is small relative to the large irrigation intake, it would nonetheless be significant in reducing the effects of drought on the Lower Basin states.

Works Cited

Bureau of Reclamation. *Upper Colorado River Basin Consumptive Uses and Losses Report 2006-2010*. Washington: U.S. Department of the Interior, 2010*. Bureau of Reclamation*. Web. 5 Mar. 2011. <http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html>.

Clayton, Rick. "Current Status: Lake Powell." Bureau of Reclamation. U.S. Department of the Interior, 25 Feb. 2011. Web. 5 Mar. 2011. <http://www.usbr.gov/uc/water/crsp/cs/gcd.html>.

Cooley, Heather, et al. *Hidden Oasis: Water Conservation and Efficiency in Las Vegas*. Ian Hart and Courtney Smith, eds. Pacific Institute, Nov. 2007. Web. 5 Mar. 2011. <http://www.pacinst.org/reports/las_vegas/hidden_oasis.pdf>.

"Current Conditions."Bureau of Reclamation. U.S. Department of the Interior, 4 Mar. 2011. Web. 5 Mar. 2011. <http://www.usbr.gov/lc/riverops.html>.

Fowler, Michael. "Gravitational Potential Energy near the Earth."University of Virginia Physics, 31 Jan. 2007. Web. 5 Mar. 2011. <http://galileo.phys.virginia.edu/classes/152.mf1i.spring02/GravPotEnergy.htm>.

"Glen Canyon Dam."Bureau of Reclamation. U.S. Department of the Interior, 29 May 2009. Web. 5 Mar. 2011. <http://www.usbr.gov/projects/Facility.jsp?fac_Name=Glen%20Canyon%20Dam>.

"Hoover Dam."Bureau of Reclamation. U.S. Department of the Interior, 29 June 2009. Web. 5 Mar. 2011. <http://www.usbr.gov/projects/Facility.jsp?fac_Name=Hoover+Dam&groupName=Dimensions>.

The Impact of a Growth Interruption in Southern Nevada. Southern Nevada Water Authority, 2004. Web. 5 Mar. 2011. <http://www.snwa.com/assets/pdf/econ_impact_summary.pdf>.

"Lake Mead."Bureau of Reclamation: Lower Colorado Region. U.S. Department of the Interior, Dec. 2008. Web. 5 Mar. 2011. <http://www.usbr.gov/lc/hooverdam/faqs/lakefaqs.html>.

"Lake Powell." Utah Division of Water Quality. Utah Dept. of Environmental Quality, 9 Aug. 2006. Web. 5 Mar. 2011. <http://www.waterquality.utah.gov/watersheds/lakes/LAKEPOWL.pdf>.

"Lake Powell Water Database."*Water-Data.com*. Summit Technologies, Inc., 5 Mar. 2011. Web. 5 Mar. 2011. <http://lakepowell.water-data.com/>.

Lellouch, Mark, Karen Hyun, and Sylvia Tognetti. *Ecosystem Changes and Water Policy Choices: Four Scenarios for the Colorado River Basin to 2050*. Washington: Island Press, 2007. Web. 5 Mar. 2011. <http://islandpress.org/assets/library/24_coloradofullreport.pdf>.

Marlow, Jeffrey. "Business Booming at Drip-Irrigation Company."New York Times, 17 Sept. 2009. *New York Times: Environment*. Web. 5 Mar. 2011. <http://green.blogs.nytimes.com/2009/09/17/business-booming-for-drip-irrigation-firm/>.

Nevada: Assessing the Costs of Climate Change. Center for Integrative Research, University of Maryland, n.d. Web. 5 Mar. 2011. <http://www.cier.umd.edu/climateadaption/Climate%20change--NEVADA.pdf>.

Soultanian, Richard. "Global Electricity Prices: On the up and Set to Rise." *Power-Gen Worldwide*, 1 Sept. 2010. Web. 5 Mar. 2011. <http://www.powergenworldwide.com/index/display/articledisplay/3575785812/articles/power-engineering-international/volume-18/issue-8/power-report/global-electricity-prices-on-the-up-and-set-to-rise.html>.

Stalcup, Larry. "Pressure Regulators Boost LEPA Efficiency." Corn and Soybean Digest, 15 Feb. 1999. Web. 5 Mar. 2011. <http://cornandsoybeandigest.com/pressure-regulators-boost-lepa-efficiency>.

The Water Conservation Initiative and the Implementation of the Secure Water Act. Bureau of Reclamation. U.S. Department of the Interior, Oct. 2009. Web. 5 Mar. 2011. <http://www.usbr.gov/lc/region/programs/crbstudy/SWA.pdf>.

"Water Supply and Lake Powell." Glen Canyon Institute, n.d. Web. 5 Mar. 2011. <http://www.glencanyon.org/library/water.php>.