Team Control Number:

11974

Problem Chosen:

B

2021 HiMCM

Summary Sheet

Currently, the reservoir Lake Mead is experiencing a dire problem. For the first time ever, the US Bureau of Reclamation has issued it a water shortage, and it has been plagued by droughts long before this. In order to solve this crisis, which affects not only Lake Mead but the millions who depend on it for their water, we must ask two important questions: how can we save Lake Mead? To answer this question, we decided to propose three solutions that can be used in conjunction to ameliorate the situation in Lake Mead.

Before we started to model anything, we decided to identify as much data on the situation as we could. The three main categories of data that we used was elevation, precipitation, and temperature data. Afterwards, we cleansed the data that we received and found in order to extract the most helpful parts.

Next, we needed to understand and verify the volume of Lake Mead using the provided data. We considered the factors that affected the volume of Lake Mead, such as inflows, outflows, and losses. Afterwards, we used our data to develop a formula that can find the volume of Lake Mead.

Then, we started on our drought model. In order to calculate the periods and effects of drought, we used a Mann-Kendall model. This model gave our predictions for droughts based on data from previous years.

The second model was needed to determine the water levels. Using the ideas that we had gained from our drought model, we decided to use a Markov model to predict water levels in the future from the data we received in the past.

Finally, informed by our research of Lake Mead's volume, droughts, and water levels, we decided to present solutions that would fit the situation of Lake Mead the most accurately.

Solution to the Lake Mead Crisis: The Arizona Dispatch

For the past 8 years, Lake Mead has been in crisis. Due to the abnormally high temperatures and low humidity, the water levels in Lake Mead have decreased rapidly. Currently, every year, Lake Mead loses about 1.2 Million Acre Feet (the amount of water needed to cover 1 acre of land with a foot of water). Due to this, the water depth of Lake Mead is decreasing at a rate of 5 feet per year. If the water of Lake Mead becomes depleted, 25 million people will be without water. It would also cut of water to industrial, commercial, and agricultural districts in Nevada, California, New Mexico, Arizona, and Mexico. According to models, by 2050, the depth of Lake Mead will drop to a meager 300 ft. as a conservative model.

However, there may be some solutions to this problem, One solution is to create more water pipelines from areas with water surpluses such as eastern Nevada and Colorado. To increase the amount of water that flows into the lake. This project would be expensive, however, with funding from the federal government, it is possible. However, the federal and state governments would need to do some campaigning and lobbying to ensure that the public supports the new initiative.

On the other hand, the State of Nevada is considering the roll out of a water surplus tax. This has little to no public support, but it would encourage the citizens of Nevada to reduce the amount of water that they use.

Contents

1 Introduction

1.1 Background

When a region receives abnormally low levels of rainfall or precipitation, it can enter a drought. There are many factors causing lack of rainfall and subsequent lack of water in the region, such as change in temperature, air circulation, and demand for water. Lake Mead is suffering from a drought that may have serious consequences on those who it supplies water to. There are many factors that go into play when figuring out how to beat this drought.

1.2 Problem Restatement

Our job is to establish the factors that need to be considered, consider them, and formulate a plan that would realistically end the lowering elevation of Lake Mead.

1.3 Our Work

In order to find a viable solution to the drought problem, certain constants need to be identified and assumptions need to be made, such as simplifying the sides of Lake Mead into linear slopes and eliminating factors such as ground absorption of water. These make finding a viable solution possible without being overwhelmed by negligible factors. The first step in solving the Lake Mead problem is finding the volume of the lake. By using data provided that details the relationship between elevation, area, and volume of the lake, an equation can be constructed that models that volume of water at any elevation.

Now that the dimensions of the lake have been identified, real-world constraints have to be applied, such as costs, demand, public support, and other factors. The hot, dry environment of Lake Mead leads to lots of water being lost to evaporation. The changing economy and population of the areas that the lake supplies water to creates a fluctuating demand that needs to be calculated. The costs of water treatment, recycling, and usage are also important, as well as what the public wants to see be done with their tax dollars.

2 Assumptions and Variables

2.1 Assumptions and Justifications

We make the following easily-justified assumptions to simplify the problem:

ASSUMPTION 1: The slope of Lake Mead's sides are linear between two elevations.
JUSTIFICATION: Our interval of elevations are much smaller than the area of the reservoir at each interval.

ASSUMPTION 2: The absorption of water by soil in Lake Mead is negligible.
JUSTIFICATION: The saturation capacity of soil below Lake Mead is not unlimited. The water table in Nevada is at 50-500 ft below ground level in the areas around Lake Mead meaning that the most parts of the lake reach the water table where no water is to be lost due to the fact that the soil is already saturated. [12]

ASSUMPTION 3: The consumption of water by the economy and the agricultural sectors of Nevada is constant.
JUSTIFICATION: The modeling for both economy and agriculture is heavily seated in the growth of the economy and population growth. The economy is very unpredictable so a model for both would result in a lot of errors. It would be better to assume that it was constant for the time being and have it be updated for every year that passes.

2.2 Variables and Definitions

Variable Symbol	Definition
S	The set of all contour subsections in Lake Mead, where a contour subsection is the information between two consecutive contour lines or elevations
S_i	The ith contour subsection in set S
$S_{i,A}$	The area that is enclosed by the contour line of lower elevation in S_i
$S_{i,B}$	The area that is enclosed by the contour line of higher elevation in S_i.
$S_{i,L}$	The difference between the two contour lines of S_i
S_{table}	The set of all contour subsections received from the information in Table 1
S_{map}	The set of all contour subsections received from the information in Figure 1
σ_{Mead}	The parametrized surface of Lake Mead
A	Surface area of the top of the lake
Θ	The evaporation coefficient
n	The current yearly period
Z_n	The elevation of the lake in the nth year
L	The loss of water in Lake Mead due to the environment
L_E	The loss of water by evaporation
L_G	The loss of water by absorption of the ground
L_T	The total amount of water lost
D_e	The demand of the economy
D_p	The water demand of the Population
D_a	The water demand of local agriculture
D_T	The total demand of water
S_T	Amount of water from all water supplies

3 Data Preprocessing

Before modeling the Hydrological state of Lake Mead, data was obtained and formatted in order to achieve more reliable and consistent results.

3.1 Data Identification

3.1.1 Elevation

Elevation is the height of an object relative to sea level. The **Elevation** of Lake Mead is the distance between the surface of Lake Mead and the sea level. This piece of information is significant because it is important in signifying Hydrological Drought occurrences, in which the water levels of surrounding aquatic bodies such as reservoirs and lakes are lowered. [10]

The Monthly Elevation Data provided was observed, and a sample usage is shown below (see Appendix A for more information on implementations of data tables):

Year	JAN	FEB	MAR	...	DEC
1998	1214.4	1214.05	1214.26	...	1212.53
1999	1212.89	1213.3	1211.75	...	1213.94
2000	1214.26	1213.79	1211.33	...	1196.12
2001	1197.27	1196.62	1194.68	...	1177.37
2002	1177.94	1176.5	1172.06	...	1152.13

Table 3.1: Water Elevation of Lake Mead in feet from 1998 to 2002.

3.1.2 Precipitation

Precipitation is an integral piece of information to determine a drought because, according to the National Integrated Drought Information System (NIDIS), a drought is defined as, "a deficiency of precipitation over an extended period of time (usually a season or more), resulting in a water shortage." The lack of precipitation will reduce the amount of groundwater inflow that Lake Mead receives, consequently lowering elevation levels and increasing drought impacts.

The precipitation data (both rainfall and snowfall) were obtained from local weather stations near Lake Mead through the National Climatic Data Center (NCDC) database. A sample of the data is provided below:

DATE	PRCP	SNOW
1998-02	2.99	0
1998-03	1.14	0
1998-04	0.34	0
1998-05	0.21	0
1998-06	0.05	0

Table 3.2: Cumulative Rainfall and Snowfall in inches from February to June of 1998.

3.1.3 Temperature

Temperature is a key part of determining weather conditions during these time periods, and is correlated with the seasonal changes in weather patterns. The **average temperature** was used in most instances, due to the fact that this data would be the most representative of the general temperatures during a selected time period, but **maximum temperature** and **minimum temperature**, which were recorded daily and averaged over a month, were also utilized to account for drastic changes air mass movement.

The temperature data was also obtained through weather stations near Lake Mead in the National Climatic Data Center(NCDC) database. A sample of the raw data is provided below:

DATE	TAVG	TMAX	TMIN
1998-02	54.8	64.9	44.8
1998-03	62.2	74.9	49.6
1998-04	66.8	79.9	53.6
1998-05	76.5	89.9	63.1
1998-06	86	101.2	70.9

Table 3.3: Average, Maximum, and Minimum Monthly Temperatures in degrees Fahrenheit from February to June of 1998.

3.2 Data Generation and Cleaning

The raw data obtained above needed to be cleaned and other data needed to be generated in a way that would allow accurate and consistent results when analyzing patterns or creating models.

The Monthly Elevation data, provided from February of 1935 to September of 2021, was very comprehensive, so the average annual elevation for each year was generated in addition to monthly data. Another piece of data generated was the annual change in elevation. These data points were useful due to the fact that they could be used to analyze general trends in elevation over the long-term.

An additional data table for elevation was created with the months being generated as a fraction out of 13 to better reflect the chronological time period in which elevations changed.

A linear regression model, analyzed specifically to a certain month, was created to fill in any empty data points for both precipitation data points, and all the temperature data points.

4 The Volume of Lake Mead

4.1 Understanding Lake Mead's Volume

Before analyzing the methods by which we might determine the volume of Lake Mead, we must understand the various means by which it can change.

4.1.1 Inflow

Inflow describes the flow of water that enters a body of water. In this case, the inflow for Lake Mead comes from numerous different places. Firstly, the largest suppliers of inflow are the Colorado River and its tributaries. These rivers supply the vast majority of water to Lake Mead, but this does not mean that all other factors are negligible. For example, rainwater and runoff are the other main sources that contribute to the inflow for Lake Mead. Using the commonly known statistic that 97% of inflow comes from the Colorado River, we can determine the total inflow for Lake Mead.

4.1.2 Outflow

Outflow denotes the flow of water that intentionally exits a body of water. The first main source of outflow is the day-to-day water consumption of humans. This category consists of human actions that require water, such as drinking and showering. It also consists of the water sold to households and businesses by utility companies. The second source is the water needed for agriculture and irrigation systems.

4.1.3 Loss

Loss is determined by the amount of water that unintentionally leaves a body of water. The main sources of loss are those by the environment, such as evaporation and absorption of soil. The magnitude and effects of these losses will be discussed later in the paper.

4.1.4 Net Inflow

Taking all these factors into account, we can find the rate of net inflow into Lake Mead by using a simplified model:

$$I - O - L = I_{\text{net}},$$

where I is the rate of inflows, O is the rate of outflows, L is the rate of loss, and I_{net} is the rate of net inflows.

All of the factors that contribute to inflow, outflow, and loss are interconnected, which is shown by Figure 4.1.

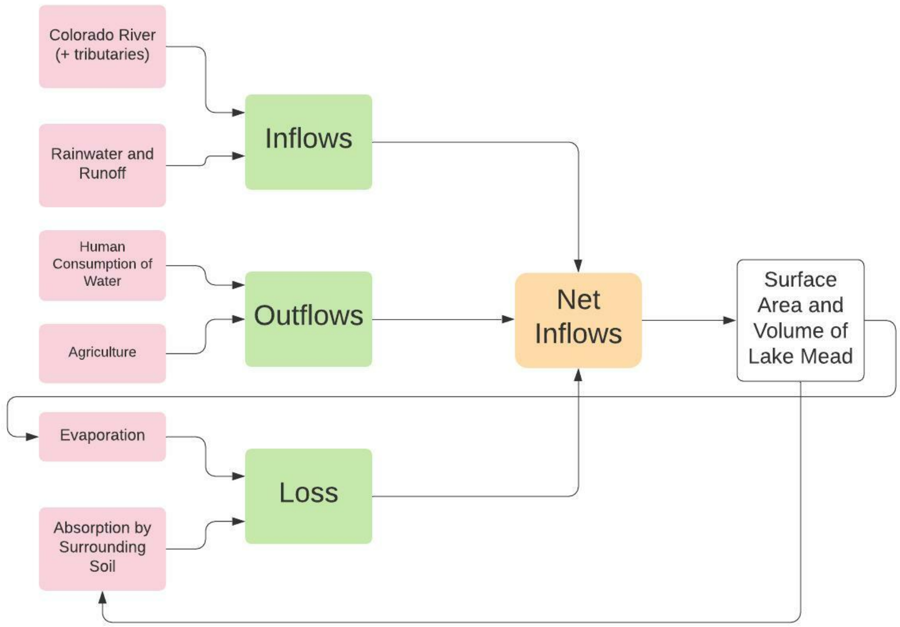

Figure 4.1: The Factors of Net Inflow

4.2 Verifying Volume Using The Provided Table

In Table 4.1, we are given 4 elevations and the areas of the cross-section of Lake Mead. From these data points, we can add three contour subsections to the set S_{table}. A visual representation of this set is shown in Table 4.2 in Appendix A.

Elevation (feet)	Area of Lake (acres)	Volume of Lake (acre-feet)
1229.0	159,866	29,686,054
1219.6	152,828	28,229,730
1050.0	73,615	10,217,399
895.0	30,084	2,576,395

Table 4.1: Area and Volume of Lake Mead by Elevation Level

Because concrete data is given in the table, we can perform calculations to determine whether or not the volumes given in the table can be accurate. However, from this analysis, we cannot determine with certainty whether or not the volume data in the table are accurate to reality because the predictions found using the table are dependent on the data of the table rather than the direct acquisition of data from Lake Mead itself.

In order to determine the volume of each contour subsection, we can use the prismoidal method. [8] Specifically, by the prismoidal method, the volume of a contour subsection $S_{\text{table},n}$, which shall be denoted by V_n, can be found by

$$V_n = S_{\text{table},n,L}\left(\frac{S_{\text{table},n,A} + \sqrt{S_{\text{table},n,A}S_{\text{table},n,B}} + S_{\text{table},n,B}}{3}\right).$$

Therefore, we can create a function $V(n)$ that models the volume of water in the reservoir, where $0 \le n \le 3$ is the number of subsections:

$$V(n) = \begin{cases} V_0 & n = 0 \\ V_0 + \sum_{i=1}^{n} S_{\text{table},i,L}\left(\frac{S_{\text{table},i,A} + \sqrt{S_{\text{table},i,A}S_{\text{table},i,B}} + S_{\text{table},i,B}}{3}\right) & 1 \le n \le 3 \end{cases}$$

where V_0 is the volume provided at 895.0 feet, which is 2,576,395 acre-feet. A demonstration of the calculation of this formula for $V(2)$ will shown in Appendix B.

Table 4.3 shows the subsection number i, the provided volume from Table 4.1, the predicted volume $V(i)$, and the percent error with the volume originally provided.

i, **Number of Subsections**	**Provided Volume of Lake (acre-feet)**	$V(i)$, **Predicted Volume of Lake (acre-feet)**	**Percent Error between** $V(i)$ **and Provided Volume (%)**
0	2,576,395	2,576,395	0.00
1	10,217,399	10,365,604.54	1.45
2	28,229,730	29,163,563.1	3.31
3	29,686,054	30,633,100.8	3.19

Table 4.3: Area and Volume of Lake Mead by Elevation Level

The largest percent error from the table is less than 5%, so we can say with relative certainty that the volume data in the provided table are accurate if the area and elevation data are correct.

4.3 Using Topographic Maps

From a topographic map of Lake Mead, we may use the prismoidal method detailed in Section 4.1 again, but on a larger scale. In order to find the area of each contour line, a computer program can be created to count the pixels that are enclosed by the lines. Afterwards, the number of pixels can be converted to form an estimate of the enclosed area. As elevation data increases, the magnitudes of the contour intervals will decrease, so the domain of $V(n)$ will also increase because of the increase in number of subsections. The contour subsections would be put in the set S_{map}, and the function $V(n)$ will be changed so that any reference to the set S_{table} will become a reference S_{map} instead.

Eventually, with more accurate data, we will be able to create a surface σ_{Mead} in $\mathbb{R}^3$. We can then determine the volume enclosed by σ_{Mead} and the plane at the desired elevation. To do this, we can convert our surface to a scalar-valued function $f(x, y)$, where the output is the absolute difference between the highest possible elevation at Lake Mead and the elevation at the point (x, y). Using a double integral, the volume V of Lake Mead at a given elevation would be

$$V = \iint_C f(x, y) - E \, \mathrm{d}x\mathrm{d}y,$$

where E is the absolute difference between the given elevation and the highest possible elevation at Lake Mead and C denotes the curve intersection between the given elevation's plane and σ_{Mead}. While this formula provides us with an exact volume, it is highly impractical as it requires large amounts of data. Therefore, the first method described in this subsection should be used to determine the volume of Lake Mead at any given point in time.

5 Lake Mead and Drought

Looking at the data for Lake Mead's water Elevation, we can see that the water elevations have historically fluctuated over 100 feet, with a historic annual high at 1214.95 feet, and the lowest annual rate at 1075.83 feet. Throughout the period, we also see many periods where the water level dropped dramatically, which may signify a lack of inflow or an excess of outflow. Overall, the water level of Lake Mead has declined greatly during the early 2000s, with the current water level sitting at around 1075 feet, the lowest it has been for nearly a century. Lake Mead is a major source of water for over 25 million people, so these low levels of water are a cause for concern. This section will provide insight into the efforts to model and predict future water levels in Lake Mead.

5.1 Defining Drought

As simple as the concept of a drought is, the actual metrics that determine a drought largely depend on the region. There are many definitions of drought, each defined for a different purpose. As such, a series of criteria were developed specifically for the purposes of determining a period of drought using the water elevation of Lake Mead:

- The elevation of Lake Mead must be on a consistent downward trend for at least 4 years, because a reduction in precipitation caused by drought results in less inflow into Lake Mead, which decreases the water level. Hydrological droughts typically are slower to react to changes in general weather conditions, so the trend must be long-term, and the observed historical data has shown droughts to have a period longer than 2-3 years [7]

- The elevation level of Lake Mead must be **decreasing** at an average rate greater than 10 feet per year for at least 4 years to mark the beginning of a drought period. This is to account for natural changes in Lake Levels due to multi-annual shifts in climate. If the decrease in elevation is not significant enough or long enough to be a drought, then the change will be considered normal.

- The drought period ends when the water level of Lake Mead **increases** by greater than 10 feet per year during a consistent upward trend. Droughts end when there is an increase in precipitation to a normal rate, so a significant upwards trend of water levels in Lake Mead after periods of drought would suggest a higher inflow, caused by the rainwater saturation of runoff and rivers flowing into Lake Mead. Although outflow is also a factor to consider in Lake Mead's water levels, previous studies have shown that outflows do not change a significant amount, even when the government places restrictions on water usage.

5.2 Drought Calculations

With a definition in mind, analytical methods need to be used to identify periods of droughts analytically.

5.2.1 Mann-Kendall Model

In order to determine consistent trends, our team used a Mann-Kendall Model. A Mann-Kendall Model calculates whether a data set has an increasing or decreasing trend. Each value in the data set is compared with all the preceding data points in order to determine an overall trend. In our case, a Running Mann-Kendall Model was utilized to calculate trends among each series of 4 consecutive years, per the assigned definition, which would provide points between -6 and 6, with 6 being a completely monotonic positive trend, and -6 being a completely monotonic negative trend. Any resultant value of less than -3 was considered to be a significant downward trend, and any resultant value greater than 3 was considered to be a significant upward trend. Any value greater than -3 and less than 3 would indicate an inconclusive trend, with similar amounts of upward and downward movement.

5.2.2 Elevation Rate of Change

The other criteria pertained to the average rate of change of elevation. We calculated the average rate of change of the elevation for 4 years in our model as:

$$ElevationChange_4 = \frac{Z_{n+3} - Z_n}{4} \frac{feet}{year}$$

Our criteria stated that the average rate of change over 4 years needed to be less than -10, which can be calculated with the above equation.

5.3 Drought Model

With the above criteria defined and mathematically determined, a data table was created with a 4 year Mann-Kendall Model and 4 year average rate of change of elevation using the year and the average annual elevation:

It is worth noting that the period of drought can be longer than 4 years, and thus, the drought period does not end until the water level trend is upwards and increasing at a rate of 10 feet per year.

Year	AVG	4Y Mann-Kendall	4Y Average
1996	1192.1	4	4.61
1997	1203.7	-2	-0.04
1998	1213.6	-6	-7.1325
1999	1210.5	-6	-12.09
2000	1203.5	-6	-14.55

Table 5.1: Average Water Level (feet), 4 Year Running Mann-Kendall, and 4 Year Average Rate of Change of the Water Level (feet/year).

5.4 Drought Periods

After analyzing the data, the drought periods were observed to be: 1952 - 1956, 1962 - 1965, 2000 - 2010, and 2012 - present. The most recent drought period is especially exceptional because it has occurred at a time when the water levels were already close to the lowest points. Even after the drought ceded in 2010, the water level only climbed up by 30 feet, which was still more than 80 feet below the peak in the early 2000s. This analysis shows that the series of droughts happening during the time period after the start of the 21st century have steadily decreased the amount of water to record lows, and the droughts seem to be lasting for longer, with the previous drought lasting for 10 years, while the ongoing drought has already lasted 9 years. Drought is an issue, and will continue to be an issue for Lake Mead.

6 Lake Mead Water Levels

With the droughts seemingly affecting water levels so drastically in the present, we sought to find out the long-term implications if the issues with water are not addressed.

6.1 Regression Predictions

Using a linear regression, we can predict the future levels of Lake Mead given that a current pattern persists. If we consider the pattern from the beginning of 2005 to the end of 2020, the linear regression model predicts that following elevations of the surface at the following years: 2025: 1060.665, 2030: 1043.882, 2035: 1027.099, 2040: 1010.316, 2045: 993.533, and 2050: 976.75.

6.2 Markov Projections

6.2.1 Limitations of Regression

Although a regression model is a quick and easy way to predict future outcomes given an year as input, there are significant limitations to what can be achieved. First, regression techniques are specifically built for data that follows a normal distribution, so while these models are a quick way to make sense of a linear or other formulaic set of data points, the change in Lake Mead's water levels do not correlate with any of the normal distributions observed due to the large amount of other factors that influence water level.

Instead, our team ran a Markov Chain Model to predict future outcomes given a set of data points that correlate with Lake Mead's water elevation. Using a Markov Model is a good way to determine future events, on the conditions that there are many correlative factors, and our current event is the only situation that affects future outcomes. Due to this fact, Markov Models are a strong candidate for predicting future water levels, as the current water level, temperature, and other data will directly affect how the subsequent water level will change, but in order to run a Markov Chain Model, additional factors that correlate with Lake Mead's water level will need to be used.

6.2.2 Additional Factors and Additional Preprocessing

The data in Section 3 that was used for the Markov Model included Precipitation, Snow, Average Temperature, Maximum Temperature, and Minimum Temperature, and the change in elevation. The justification for our usage is covered in Section 3.1, but most of the usage is due to the fact that they were found to be strong correlatives with drought and water level. Due to the fact that many factors such as temperature, change in elevation, and precipitation can have infinite unique amounts, these factors were rounded to a number in order to create more groupings of data that were similar.

6.2.3 Running the Markov Chain

The Markov Chain Model involved creating a list of current "states", which, in our model, were just the monthly recorded Precipitation, Temperature, and Change in Elevation data that was present. The current month's state could then be mapped onto the next month's state. In a large enough data set, there would be many of the same "current states" that correlated with many "next states", which would then create a probability map, where a certain outcome is XX% likely to happen. This would then allow us to continuously chain our data to predict a logical next step from our current state.

6.2.4 Markov Chain Results

In our modeling, we ran the Markov Chain 6 different times, 3 for a model trained on 2005-2020, and the other 3 trained on a model that used 2012-2021 data to predict future outcomes. Each training time frame was then used to predict the water level for 2025, 2030, and 2050. The results are as follows: For the 2005-2020 model, in the year 2025, the water level was 1050 feet; 2030 was 1030 feet, 2050 was 949 feet. For the 2012-2021 model, the year 2025 resulted in 1046 feet; 2030 resulted in 1021 feet, and 2050 resulted in 921 feet.

As seen, the data provided here is within a 5% margin of error compared with the linear regression, which, for this time period confirms our initial projections, given that the period-specific patterns of the data hold to the future.

6.2.5 Limitations of Markov Model

The Markov Model, although theoretically more precise than a Linear Regression in cases with many factors in which the current state is the only influencer of any future state, still has limitations. One of the most obvious issues with a Markov Model is the amount of data it requires. In order to create a very precise Model, the mappings from each state needs to be known, so that there are no cases in which the future state is unknown relative to the current one. Additionally, the Markov Model, like many other models, are only feasible if the **current patterns** hold, yet through our research and data observations, it is clear that many of the current drought patterns are a result of climate change, which is unpredictable in its current state.

7 Solution to the Problem

Finding all of this data and processing it would be useless if we did not apply it. In order to find a good solution we consider all variables. This includes environmental factors, water demand, public support, and cost factors.

7.1 Water loss factors

7.1.1 Environment

Lake Mead is located in Nevada, Nevada has a unique climate in that it is very hot and arid year round. This makes it really easy for water to evaporate and for water sources, such as Lake Mead. The environmental loss of water in Lake Mead can be expressed by two factors L_E for evaporation and L_G for ground absorbance.

L_E can be modeled this however, is very difficult as there are a lot of variables that go into this. Luckily, the USGS has already conducted a water loss survey of Lake Mead. This resulted in an average rate of water loss at 6.22 ft per year as a conservative estimate. In order to find total water lost that year, we then multiply this by A, which would change as water is lost, to get the total water loss that year at Lake Mead. This means that on average Lake Mead loses about 800,000 Acre Feet Per year conservatively. During droughts, this number becomes worse as environmental factors intensifies. According to the USGS during years of moderate drought, Lake Mead can lose up to 1.5 million Acre Feet per Year during a moderate drought. In years of severe drought, this could easily be doubled or tripled according to the USGS and the NWS. [2]

This means that the amount of water lost per year due to environmental factors is about 800,000 Acre Feet per year or 1.4 million Acre Feet per Year in moderate drought. During Severe drought this could easily be 4.5 million Acre Feet. By the Equation $L_T = L_E + L_G$

7.1.2 Water Demand

Water demand is the amount of water that a population needs in order to be sustained. This Includes demands of the economy D_e, the population D_p, and agriculture D_a. All three of these factors are changing factors which make them very hard to calculate. D_e and D_a are very hard to predict as the economic growth of a city which includes a summation of the water consumption of all businesses and buildings fluctuates with the economy. D_a is also tricky to calculate as it is tied to the population. According to the USGS, in 2015 D_a was 26.26 Mgal/day or 9585 Mgal/year. D_e was also surveyed by the USGS and in 2015 the sum of all industrial and commercial water consumption was 9.38 Mgal/day or 3420 Mgal/year. Finally we need to find population. The current consumption of the population is 353.06 Mgal/day or 128870 Mgal/year. All of these numbers are based on the USGS database for how much water is being drawn out of Lake Mead from the separate functions. All in all, Lake Mead loses 141870 Mgal/year from consumption. This converts to 500,000 Acre Feet per year. [11]

7.1.3 Net Water Losses

Lake Mead gains water from a variety of ways. A large factor in this is the Colorado River which supplies Lake Mead with 97% of its water. All together, all rivers supply 700,000 Acre Feet per Year on a good year. This includes the total net outflow from Lake Mead into Mexican rivers and other water tables. This allows us to subtract the Water gains from the total water demands in order to find the net total loss of water in Lake Mead. The formula for this would be D_T+L_T-S_T. Which is around 600,000 Acre Feet per Year conservatively and 1.3 million Acre Feet per Year as a non-conservative moderate drought estimate (which is Lake Mead's current state). In years of Severe drought this could be upwards of a net 4.3 million Acre Feet per Year loss. All of these numbers are also accounting for the consumption of humans. [7] [5]

7.2 Possible Solutions to the Problem

7.2.1 Water Recycling

Water recycling is a promising solution to this problem. Water recycling takes waste water produced by a population and recycles it into reusable water. This solution is fairly attractive, however, there are some problems with this solution. Lake Mead does not lose most of its water from usage by a population, but instead by environmental losses which are not reclaimable by water recycling. Even with a high efficiency water recycling, water recycling still would not be able to recycle enough water to fill the needs of the general public. On top of that, Lake Mead would still be hemorrhaging lots of water through environmental factors which would still drastically reduce the water levels of the lake. While it would keep the population that relies on Lake Mead supplied with water, it would still create a lot of problems with the water level. The water level of Lake Mead is also important as greater water levels means significantly greater water pressure which powers hydroelectric dams such as the Hoover Dam. The Hoover Dam at maximum capacity supplies around 2 Mega Watts of electricity to the city of Las Vegas and is a crucial power source for the state of Nevada. With the current decreases of Lake Meade, the Hoover Dam has already lost 25% of its power generation.[7] [1]

A good water recycling plant would be able to recycle around 60-65% of all water used by the population. This includes water that has been used industrially and commercially as well as in the households of the population. This would work to reduce the demand of water every year down to 240000 Acre Feet per year which is a significant improvement.[13] [1]

There is, however, a large problem with water recycling. As the water level goes down, the salinity of the lake also goes up. According to the many engineering papers on water recycling, removing salts from water recycling takes a lot of energy in order to do so. This extra salt must be removed as high salinity in water would have very adverse affects on the population of the area. One of these being the death of crops as many crops rely on low salinity water to survive and grow. Another problem with salinity is that as it increases so does the evaporation rates which as discussed is a major factor to how much water is lost at Lake Mead. [1]

Public approval is a large problem with water recycling. While it is relatively cheap to maintain, the cost of a water recycling plant can range from 200 million to 300 million USD. While this is fairly cheap compared to other solutions, a project that requires large amounts of funding would require support from the population first. As seen in many water starved states such as California, many people are reluctant to use recycled water due to the thought that the recycled water used to be part of their own waste/sewage. However, after a long period of drought in California, the population eventually cracked and the support level for recycled water went from 20% in the early stages of water recycling programs to 88% after the drought became more severe in 2015. [13] [6]

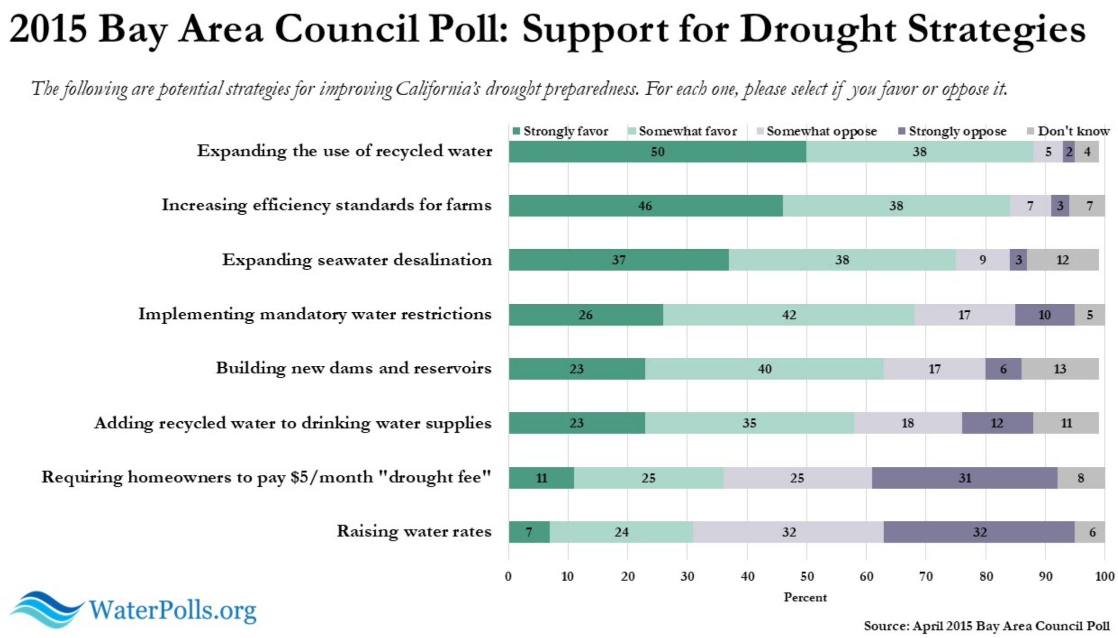

Figure 7.1: Public support of the use of recycled water and other initiatives in the state of California in 2015 [6]

This shows in that in drought zones are still reluctant to use recycled water until they are threatened with critical water shortages. In the case of Lake Mead and the rising salinity levels of the lake, waiting until there is a critical shortage may be too late for the population the relies on it for water. A solution to this problem would be to better educate the public on the safety and necessity of water recycling in order to increase public awareness and support for the project.

In conclusion, the water recycling, while able to feed the demands of the population, would not solve the problem as Lake Mead would still lose water at a very large rate. This would in turn reduce the amount of power available to hundreds of thousands of people. While water recycling is plausible, it is not sufficient to mitigate the economic damages that are caused from the loss of power generation from the Hoover Dam and additional measures should be taken.

7.2.2 Water Conservation

Another solution to help reduce the amount of water that is being hemorrhaged from Lake Mead is to reduce the water consumption of the population. Like Water recycling, this would not be able to solve the whole problem, but it would help reduce the strain on Lake Mead slowing down the loss of water which is the goal of these initiatives.

During times of drought, the state of Nevada could impose water consumption limits on households. If a household exceeds the monthly limit, the county could tax the extra amount of water drawn which would incentives the use of less water and bring in funding for the state to fund more water saving initiatives.

As seen in Figure 6.1, only 36% of the population supports the increase of this measure (in California support numbers in Nevada would be even less). Without the support of the majority of the public, this initiative would have trouble finding its way into reality. In order to force this initiative trough, the support of the public must be gained through education and outreach about the initiative or instead of going off of a punishment rewarding people with tax breaks if they use less then the allotted amount of water per household. [6]

Such measures if implemented could save a further 20-50% based on various different sources [14] [9]

7.2.3 Water Pipeline

Water pipelines could offer a potential solution to the water crisis that Lake Mead is experiencing. Unlike the other two solutions which would decrease the load of water needed by the human population that draws from Lake Mead, a water pipeline would work to increase the amount of water supply going into Lake Mead. A Water pipeline is a large pipe that connects a water source such as a river, lake, or reservoir to a different location such as another reservoir or a city.

There are three principle problems with a water pipeline, land, maintenance and break downs, and costs. However all of these problems are solvable or somewhat negligible.

Long pipelines would cut through a lot of land some of it may be owned by reservations or individual people. As a result, getting permission to build the pipeline may be difficult, however, Nevada is unique in the fact that about 85% of the land there is federal land making the connection of different water sources in Nevada to Lake Mead relatively easy as you could avoid reservations or privately owned lands. [3]

Much like other types of human infrastructure, Pipelines need to be maintained and sometimes break down. While a breakdown or failure of a water pipeline may not be as damaging as an oil pipeline failure, breakdown and maintenance fees could add up as seen in figure 6.2 below, the price of maintaining a water pipeline is similar to the yearly expenses of maintaining a road. This cost can be offset with a small increase in taxes and funding towards the infrastructure repair portion of the national budget. [4]

	Yuma Road		RID Canal	
Section	Cost to Construct	Operations/ Maintenance Costs[1]	Cost to Construct	Operations/ Maintenance Costs[1]
1st ½-mile	$114,000	$34,800	$114,000	$34,800
2nd ½ mile	199,000	35,800	199,000	35,800
3rd ½ mile	307,000	37,200	307,000	37,200
4th ½ mile	406,000	49,600	406,000	38,300
5th ½ mile	686,000	53,200	576,000	40,700
6th ½ mile	113,000	34,700	1,731,000	55,500
7th ½ mile	205,000	47,000	630,000	41,400
8th ½ mile	1,073,000	80,300	687,000	53,200
TOTAL	$3,103,000	$372,600	$4,650,000	$336,900

Table 7.2: Cost of maintenance between a road and a pipeline canal [4]

The relatively small pipeline project that is going from the Eastern Nevada Basins to Lake Mead currently has a capacity for 270,000 Acre Foot per year, however, a much larger pipeline or a network of smaller ones could have the capacity to deliver up to 650,000 Acre Foot per year to Lake Mead. This would make up for the water loss deficit during non drought years allowing for Lake Mead to recover water level during non drought years. [4]

7.3 Solution

The three solutions that were proposed in sections 6.2.1, 6.2.2, and 6.2.3 are not mutually exclusive, but seeing as the water pipeline has the potential to completely wipe the water deficit of non drought years, it should be the main focus of upcoming initiatives.

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[5] *Lake Mead's Water Budget*. National Park Service.

[6] *Measuring the yuck factor: recycled water and public opinion*. waterpolls.org.

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[8] ESurverying Softech. *Volume Calculation - Based on Contour Method*.

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[14] *Water Sense*. EPA.

A Tables and Images

i, Subsection Number	$S_{\text{table},i,L}$ (feet)	$S_{\text{table},i,A}$ (acre)	$S_{\text{table},i,B}$ (acre)
1	155	30,084	73,615
2	169.6	73,615	152,828
3	9.4	152,828	159,866

Table 4.2: Visual Representation of S_{table}

B Calculations

$$
\begin{aligned}
V(2) &= V_0 + \sum_{i=1}^{3} S_{\text{table},i,L}\left(\frac{S_{\text{table},i,A} + \sqrt{S_{\text{table},i,A}S_{\text{table},i,B}} + S_{\text{table},i,B}}{3}\right) \\
&= V_0 + S_{\text{table},1,L}\left(\frac{S_{\text{table},1,A} + \sqrt{S_{\text{table},1,A}S_{\text{table},1,B}} + S_{\text{table},1,B}}{3}\right) \\
&+ S_{\text{table},2,L}\left(\frac{S_{\text{table},2,A} + \sqrt{S_{\text{table},2,A}S_{\text{table},2,B}} + S_{\text{table},2,B}}{3}\right) \\
&= 2576395 + (155)\left(\frac{30084 + \sqrt{(30084)(73615)} + (73615)}{3}\right) \\
&+ (169.6)\left(\frac{73615 + \sqrt{(73615)(152828)} + (152828)}{3}\right) \\
&= 29163563.1
\end{aligned}
$$