The Effects of Drought and Decreased Water Volume on Water Quality in the Boulder Basin of Lake Mead

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Abstract

The 20-year historical megadrought in the southwestern United States has had lasting impacts on the major river systems in the region, including the Colorado River and its reservoirs. As drought intensity has increased due to climate change, the amount of water available to sustain ecological integrity and support economic activities has declined. This research analyzed the potential effects of decreased water volume from the historical megadrought on water quality in Boulder Basin of Lake Mead, one of the largest basins of the largest reservoir by volume in the United States. Over the past 20 years, Boulder Basin has shown rapid decline in elevation and water volume due to the drought. This analysis investigated the effects of this decline on overall water quality by examining water quality and meteorological data from the basin from primarily 2012 to 2016. The impacts of the drought on eight water quality variables were assessed. Specific conductance (a measure of ionic strength of the water) was the sole variable that showed a strong correlation to the decreased water volume of Lake Mead. For other water quality variables, it is possible that a threshold for water quality decline has not yet been met. In the future, water insecurity and drought could create uninhabitable conditions for communities that depend on Lake Mead for water supply. Therefore, it is important to assess the potential challenges the future will hold for the southwestern United States. This thesis seeks to address these water quality impacts as well as the effects on the social, economic, and environmental health of the southwestern United States.

Introduction

This study examines the potential effects of decreased water volume and elevation from the historical megadrought on water quality in Boulder Basin of Lake Mead. It questions how changes in water volume affect individual biotic and abiotic water quality parameters. The study was conducted using archival data analysis and sought to answer the research question, what effects does the drought in Lake Mead have on the local water quality in Boulder Basin? The goal of my research was to increase the amount of knowledge regarding the drought in Lake Mead and how it effects the local environment in Boulder Basin, referencing broader effects on society. I expect my data to show a correlation between water quality parameters and water volume, either positive or negative. Additionally, I provide a scientific analysis of the social, economic, and environmental implications of the historical drought in Lake Mead with the assistance of archival data.

Literature Review

Importance of the Colorado River System

The Colorado River system is one of the most economically and environmentally important river systems in the southwestern United States, spanning across seven states as well as a portion of northern Mexico. It begins at La Poudre Pass in the Southern Rocky Mountains of Colorado and historically flows into the Gulf of California; however, due to water withdrawals and recent drought, it often becomes dry miles before reaching the ocean (Heggie 2020). Alone, the Colorado River System provides water to nearly 40 million people in the southwestern U.S. for drinking water, irrigation, hydropower, and recreation. The Colorado River Basin, which consists of an Upper and Lower Basin, distributes water to over 5.5 million acres of agricultural

Figure 1: General Location Map of the Colorado River and its Upper and Lower Basins (USGS 2021)

land each year (Todoroff et al. 2021). Colorado River flow originates as precipitation and snowmelt in the Rocky and Wasatch Mountains of Wyoming, Utah, and Colorado (USDI 2021). As the snow melts in the mountains, it is collected by headwater streams across the basin, ultimately combining to form the Colorado River proper. There are 58 hydropower facilities along the Colorado River, such as the Hoover Dam and Glen Canyon Dam, that produce over 42 million megawatt hours of energy each year (USBR 2021).

Sitting behind these large dams are even larger reservoirs such as Lake Powell and Lake Mead, which are hotspots for tourism and recreation. In 2018 alone, recreation at Lake Mead brought in $366 million dollars of economic benefit from approximately 7.6 million tourists in the Lake Mead National Recreation Area from hiking, boating, fishing, and other activities (NPS 2018). Overall, the Colorado River supports a $26 billion dollar economy in water recreation each year (WRA 2022). This is a substantial amount of economic activity that funds jobs, conservation projects, remediation, and natural disaster mitigation. However, these sources of social and economic gain regarding the benefits of the Colorado River System are being threatened due to the historical and extended drought in the southwestern U.S. that affects regional water supply, hydropower, recreation, and the environment (USDI 2021).

The immense social and economic reliance the southwestern U.S. has on the Colorado River System brings forth the urgent and productive need for conservation and remediation. In Lake Powell, the second largest artificial reservoir by volume in the United States, water levels have dropped by 153 feet as of July 2021, sitting at an elevation of 3,547 feet (NASA 2021). If Lake Powell's levels drop below 3,525 feet by 2022, there will be many challenges in providing enough water for Upper Colorado River Basin states to meet allocation levels, and conservation measures will need to be taken (Sakas 2021). Conservation programs, such as asking ranchers and farmers to reduce water use, cost upwards of $120 million a year and still prove to be ineffective for long term sustainability (Smith 2020). Therefore, the Colorado River System is facing a future of concern for its long-term sustainability and serious actions will need to be taken by the people to help conserve the water. The importance of conserving water for drinking, irrigation, hydropower, and recreation from the Colorado River System continues to increase alongside the rising 20-year megadrought in the southwestern United States.

Additionally, the Colorado River is a delicate ecosystem with many native species, specifically fish. Many native fish species are endemic to this area, meaning they are restricted to this area most likely due to the geographic isolation of the Colorado River and the highly variable natural environment (USDI n.d.). This makes their risk of extinction high since they cannot survive in other systems. The Colorado River was once home to 8 native and endemic fish species, but only 5 are found in the system today. Altered river flows and competition with invasive rainbow and brown trout populations have reduced native fish diversity. The Native

Fish Ecology and Conservation Program (NFEC) is working to help conserve and restore native fish populations, especially the threatened humpback chub, in the Colorado River. This is important because native species increase the biodiversity of the river and serve many ecosystem functions for the community. They are also a source of food for native wildlife. Overall, the Colorado River is an essential ecosystem for fish and wildlife, which makes mitigating the effects of drought and climate change on the river an ecological imperative in addition to securing domestic water needs.

Effects of Drought on the Southwestern United States

The megadrought in the southwestern U.S. has been a very active topic in current times, as it has caused the water volume of the Colorado River and its subsequent reservoirs to decrease substantially during recent decades. This decline in water volume may lead to economic losses or unsafe living conditions in certain areas in the southwestern U.S. due to lack of a reliable water supply (USDI 2021). Climate change is the lead contributor to the megadrought in the southwestern U.S., where droughts are expected to become more intense, frequent, and of longer duration due to altered climate patterns (CSES 2022). Warming temperatures enhance evaporation rates, reducing surface water and soil saturation (CSES 2022). Additionally, climate change is leading to decreased snowpack in the mountains. Snowpack provides streams and rivers with water as the snow melts, and without snowpack stores, stream flow is reduced and can eventually dry out or become stagnant over time. With climate change, there is an increase in storm and precipitation variability, causing some areas to become more wet, and others to become drier. This is due to unbalanced water relocation from the water cycle and predicts destabilizing effects in the future for the Colorado River System (Kuzdas 2021). Also, the creation of dams to control and manage water for human use has serious ecological implications on fish and aquatic organisms who require specific temperature ranges to survive and reproduce.

Some of the main effects of the 20-year megadrought on southwestern states and northern Mexico are decreased water supply, decreased hydropower efficiency, decreased crop production, and increased wildfires which subsequently cause increased economic costs of basic goods and services, such as food, water, and electricity due to supply and demand principles (McLaughlin 2021). The main concern to the western states who rely on the Colorado River System as a significant source of water is simply not having enough to meet the demands of the people and agriculture. Major reservoirs such as Lake Mead and Lake Powell are facing high evaporation rates due to increased surface air temperatures and visibly show these changes in their bathtub rings which extend more than a hundred feet above current water levels (Martin 2021). Bathtub rings are recognized as the pale outline that lines a reservoir or canyon, indicating a past water presence. They are formed when calcium carbonate, $CaCO_3$, and other mineral

Figure 2: Image of Lake Mead's Bathtub Rings from May of 2021 (AZCentral 2022)

compounds such as sodium chemically combine with sandstone and leave behind a white residue (USGS n.d.). For lakes, ponds, and reservoirs in the southwestern U.S., bathtubs rings are a clear sign of water insecurity and drought, and for prolonged periods, they are a major concern for water budgets.

The federal government has already declared a water shortage for many areas of the southwestern U.S., and the first group to be affected by this shortage includes farmers and ranchers who draw water from the Colorado River (Hager 2021). Since 2004, the Colorado River Basin has lost nearly 53-million-acre feet[1] of freshwater due to increased evaporation rates and water withdrawal for agriculture and drinking water (Seametrics 2014). Irrigation accounts for 42% of all freshwater withdrawal in the United States, especially where water is scarce such as the southwestern U.S., and without this water, crop production is expected to decline substantially over the years (USDA 2021).

Hydroelectric power efficiency is also strained by climate change effects, specifically along the Colorado River System. The severe megadrought that has been occurring for the past 20 years has dried up many riverbeds and reduced the overall volume of the Colorado River System. With a reduction in volume, dams and hydroelectric power generators are not able to produce as much energy needed to sustain the people, causing many hydroelectric cities to have to rely on thermal power plants which burn fossil fuels (Bernstein et al. 2021). This fossil fuel reliance further feeds into climate change effects and intensity, making the underlying problem grow. At the border of Arizona and Nevada, the Hoover Dam alone produced an average of 4 billion kilowatt hours of energy per year from 1947 to 2000, with a maximum annual power

[1] One acre foot equals about 326,000 gallons of water and is defined as the volume of water that covers an acre of land to a depth of 1 foot.

generation of 10,348,020,500 kilowatt hours[2] in 1984 (USBR 2017). However, as of July 2017, the Hoover Dam is down by 25% of its maximum power efficiency due to decreased water volume (Bernstein et al. 2021) and is expected to further decrease as drought intensity increases. Since the Colorado River supplies water for hydropower plants which produce 10 billion kilowatt hours of electricity annually, this is a major economic, social, and environmental issue (Seametrics 2021).

With drought comes many health implications for civilians, some being long term such as impacts on air quality, sanitation, food, and disease (CDC 2020). However, in terms of water quality, reduced stream flow from dried up bodies of water can cause stagnation. Stagnant water, especially when in hot climates, can become a breeding ground for insects like mosquitos which can carry Malaria and West Nile Virus. Additionally, high air temperatures cause water temperatures to increase, especially in smaller volume rivers and lakes, which leads to a reduction in the dissolved oxygen levels in the water (CDC 2020). This directly affects fish and wildlife and can cause massive hypoxic zones in lakes. Hypoxic zones, also known as dead zones, contain less than 2 parts per million of oxygen, leading to potential organism death and uninhabitable conditions for many species (USDC 2019). A large portion of the southwestern U.S. relies on groundwater as their main source of water. Over time, drought conditions resulting in reduced precipitation and increased evaporation will reduce groundwater storage levels, decreasing water security in these areas. Overall, climate change and drought have a strong hold on the environmental and economic health of the southwestern United States. As these effects worsen with time, southwestern states will likely be unable to meet the demands of the current and growing population in the near future without change or conservation.

[2] For reference, 1,000 kilowatts equals 1 megawatt and can power up to 1,000 homes in the United States.

Description of Study Area: Boulder Basin of Lake Mead

The continuous drought in Lake Mead has caused a large drop in water volume over time and has been identified as an issue by the United States Geological Survey (USGS 2017) and the United States Bureau of Reclamation (USBR 2012). In Boulder Basin of Lake Mead, one can see these effects firsthand through the limnology of the lake system. Limnology is defined as the biological, chemical, and physical features of a body of water, and these components can change drastically due to climate change, drought, storm events, weather, and so forth (ASLO n.d.). Limnological health is important because it directly correlates to overall ecosystem health in communities since aquatic organisms are very sensitive to changes in pH, specific conductance, temperature, increased contaminants, and many other factors.

Boulder Basin is a very popular sub-basin of Lake Mead, and it stretches 9.23 miles (15 km) from Boulder Canyon to the Hoover Dam (LaBounty & Burns, 2009). It is the most downstream basin and receives water flow from two of the four other sub-basins as well as the drainage from the Las Vegas Valley. The Las Vegas region, which is full of tourism, has a total of four different wastewater treatment plants that process sewage each day. The water released from these treatment plants is known as the Las Vegas Wash, which drains into the Las Vegas Valley Watershed (NPS 2017). From here, it travels into the Las Vegas Bay region of Lake Mead, and then into Boulder Basin where it eventually flows out through the Hoover Dam.

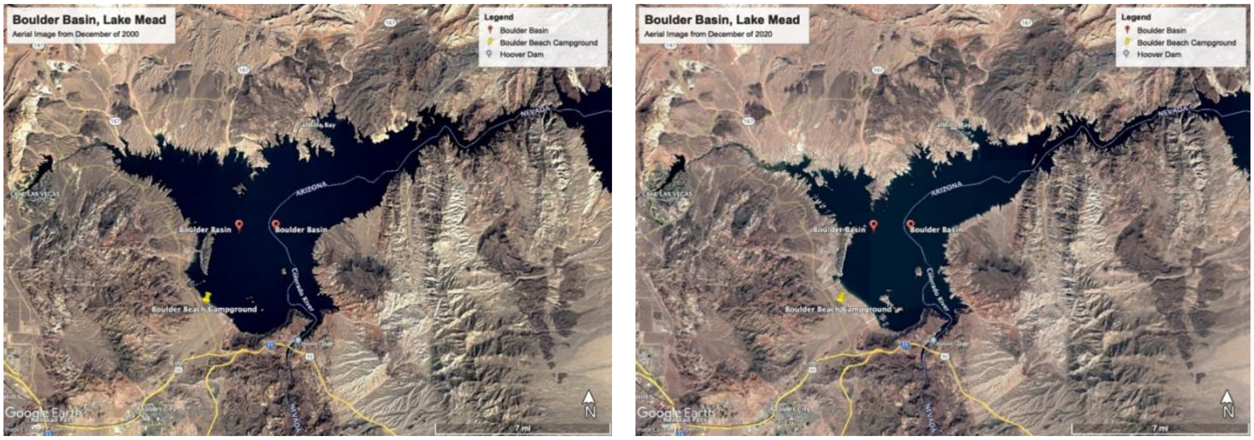

Figure 3: Google Earth Pro Landsat Copernicus Images of Boulder Basin, Lake Mead from December of 2000 (left) to December 2020 (right).

Since Boulder Basin's direct outlet into the Colorado River System is through the Hoover Dam, it is heavily monitored by the Southern Nevada Water Authority, United States Bureau of Reclamation, and the United States Geological Survey. Contaminants or water quality concerns in Boulder Basin have the potential to affect downstream communities or ecosystems such as Lake Mohave, which is about 43 miles downstream. In addition to Boulder Basin's connection to the Hoover Dam, it is a very popular and important tourism spot. There are many recreational activities and campsites around Boulder Basin in the Lake Mead National Recreation Area, which brings in $336 million in economic benefits as previously stated (NPS 2018). This revenue has been used to maintain floating sanitation stations for visitor convenience, install weather buoys for monitoring, and rehabilitate fish and native plant species. Overall, Boulder Basin is the most heavily trafficked area for water recreation in Arizona and Nevada, which is why it is the study area of my research.

Lake Mead is used primarily for recreation, agricultural irrigation, hydroelectric power, and domestic water use. It is the largest U.S. reservoir by volume and has three inflow sources and four basins, known as Boulder Basin, Temple Basin, Virgin Basin, and Gregg Basin

(LaBounty & Burns 2009). It extends 106 miles from Black Canyon to Pearce Ferry. Each year, it is responsible for supplying water to at least 3 million people in Nevada and Arizona (NASA 2021). Therefore, without the water in Lake Mead, many states would not be able to support current economic activities and recreation. Boulder Basin, which is the most western arm of the lake, is a part of the lake that has an outlet flowing into the Hoover Dam. The Hoover Dam provides electricity to more than 1.3 million homes in the southwest, and as water levels decrease, the dam is not able to produce sufficient electricity to meet demands from the communities that rely on it (Walton 2010). This is why the drought in Lake Mead is such an important topic for the sustainability of multiple sectors in the southwestern United States — it impacts water supplies, electricity generation, recreation, and environmental protection of fish and other wildlife.

Figure 4: Descriptive Map of Lake Mead and its surrounding Basins (LaBounty & Burns 2009)

A water budget analysis done in 2008 on Lake Mead by local hydrologists stated that 10% of Lake Mead's water volume would be gone by 2013 and that 50% would be gone by 2021 if no changes were made (Barnett et al. 2008). This report was based on the effect of the drought for communities that rely on Lake Mead and the Colorado River for water. The reasoning for the drop in water volume was due to increased climate change effects and increased water withdrawal in the southwestern U.S. These predictions underestimated the percent decrease of Lake Mead's water volume since it currently is only filled to 39% of its designed capacity (Pike 2021) instead of the predicted 50% by 2021. Additionally, Lake Mead is at a record low in elevation this year. Because of the drought, millions of individuals have had to follow water shortage precautions. These precautions include reducing household water use by taking shorter showers, doing less frequent loads of laundry, not watering lawns, and so forth (NDMC 2021). Additionally, during drought times, less water is allocated for crop irrigation, decreasing yearly food yields. Therefore, there are a lot of water security issues for Boulder Basin of Lake Mead regarding the historical drought in the southwestern United States.

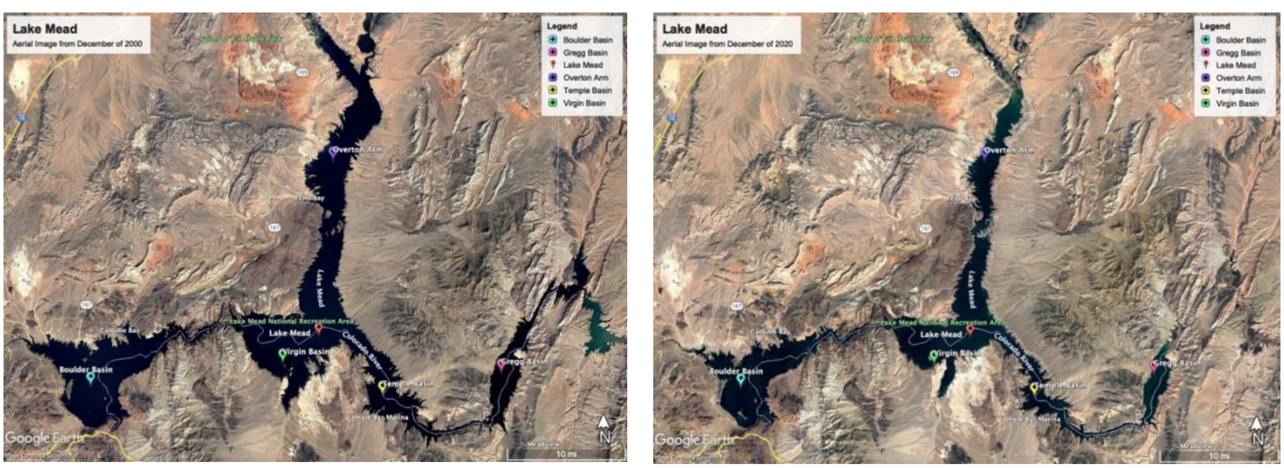

Figure 5: Comparative Change of Google Earth Pro Aerial Images of Lake Mead and its basins from 2000 (left) to 2020 (right)

Water Quality Variables and their Implications

Water quality is a critical factor in maintaining healthy aquatic ecosystems, and assessing water quality is a standard approach for monitoring the health and status of lakes, rivers, and reservoirs. In this study, I examined variables that describe water quality in Boulder Basin (**Table 1)**. These variables can show indications of low or high water quality. If water quality parameters change along with the increasing years of the drought in Lake Mead (decreased elevation/water volume), then these data can be used to explore relationships with changing water levels in Lake Mead.

Table 1: Water quality variables included in this study, their units, and a description of their importance to aquatic ecosystems

Parameter	Units	Description	Water Quality Importance
Water Temperature of Epilimnion	°C (Degrees Celsius)	The intensity of heat present in the topmost layer of a thermally stratified body of water	High temperatures increase growth rates. Too high of temperatures can kill aquatic organism or reduce spawning. Metabolic rates are also increased with high temperatures.
Air Temperature	°C (Degrees Celsius)	The intensity of heat present in the air	High air temperatures can increase the evaporation rate of water as well as increase the heat of water
Turbidity	FNU (Formazin Nephelometric Units)	The measurement of suspended particles in a body of water	Indicator of water clarity. High turbidity can come from contamination,

			particularly by soil erosion
Dissolved Oxygen	mg/L (Milligrams per Liter)	The concentration of dissolved molecular oxygen, O_2, in the water	All fish and invertebrates require dissolved oxygen for survival. Nutrient pollution can lead to low oxygen levels from eutrophication
Specific Conductance	µS/cm @ 25C (Microsiemens per centimeter at 25C)	The ability of the water to conduct electricity: an indirect measurement of the concentration of dissolved ions in the water	Most organisms are sensitive to high ion concentrations, especially when salt content increases in water due to evaporation
pH	no unit	A measurement of the acidity of the water	Most organisms can only survive in waters between a pH of 6 to 9
Escherichia coli	CFU/100mL (Colony-forming unit per 100 milliliters)	A measure of the concentration of *E. coli* bacteria in the water	Indicator of contamination from human, livestock, and wildlife waste: indicates possible presence of pathogens
Chlorophyll-a	mg/m^3 (Milligrams per cubic meter)	A measure of the concentration of primary photosynthetic pigment in the water	Chlorophyll-a indicates the abundance of algae which is the base of the food web. High concentrations indicate a nutrient loading problem

The quality of water is very important when it is used as a drinking source or for recreation. If there are contaminants or bacteria in the water that one drinks or swims in, there can be a negative effect on their health. Some examples of these negative effects include mercury poisoning from waters with high methylmercury concentrations (EPA 2021), cyanobacteria exposure from lakes or ponds with high blue-green algae levels, and lastly, water-borne diseases like cholera which can cause extreme sickness (EPA n.d.). The United States Environmental Protection Agency (EPA) summarizes the effects of these contaminants very precisely, and their research is applicable to many lentic and lotic systems across the United States. Overall, it is important to study these contaminants and how they affect the public in the case that an outbreak occurs.

These contaminants are diluted by increased water volume in a lab setting. However, in Boulder Basin, this may not be the case due to differences in hydrological patterns. In my research, I examined possible relationships or correlations between water quality variables and water volume in Boulder Basin. I was interested in the question of if/how overall water quality and contaminant concentration increased as water volume decreased. This is important to research because it allows for future predictions over time. If there is a positive correlation between water elevation and a specific water quality variable, one can expect to see further changes in the future if elevation continues to decrease, or if water levels recover.

Temperature in the epilimnion is one of the first water quality parameters that reflects signs of climate change impacts. First of all, temperature is defined as the intensity of heat present in a substance. In the case of Boulder Basin's water quality monitoring station, the temperature changes throughout different depths of the lake. In this research, all water quality variables will be analyzed in the epilimnion zone of the lake. The epilimnion is the upper most layer of water in a thermally stratified lake, and for Boulder Basin, the epilimnion zone goes from the surface to a depth of 11 meters (USGS 2017). Average temperatures in the epilimnion vary during different seasons of the year, but historically the average is about 20°C (LaBounty & Burns 2009). In the summer, the epilimnion is the hottest region of the lake due to solar energy and air temperature, and in the winter, the epilimnion is about the same temperature as the rest of the lake layers. Air temperature is the intensity of heat in the air and can increase the evaporation rate of the water, reducing water volume. Temperature is an important variable to look at because it affects growth and metabolic rates in plants and aquatic organisms such as phytoplankton, as well as reproduction rates. Certain species, such as trout and salmon, cannot survive in warm waters due to physiological stress and poor reproduction. When water temperatures rise, oxygen is released from the water, making less oxygen available to organisms, causing them stress, reduced mating, and potential death.

Turbidity is defined as the measurement of suspended particles, such as clay, soil, and silt, in a body of water. It is expressed in Formazin Nephelometric Units (FNU) and indicates water clarity. High turbidity can be the indication of a major storm event, soil erosion, contamination from runoff, as well as eutrophication from nutrient loading. Turbidity can vary from one waterway to another, and there is no specific normal range or reference number for what should occur. High turbidity can affect the type of vegetation that grows in water (YSI 2022). However, undisturbed water will naturally have lower turbidity allowing more light penetration from lack of suspended particles.

Dissolved oxygen is one of the most essential water quality variables for a body of water with a high ecological presence. All fish and invertebrates require dissolved oxygen for survival. Low levels of oxygen cannot support high biodiversity in an aquatic system (YSI 2022). Dissolved oxygen is measured by the concentration of dissolved molecular oxygen, O_2, in the water, and is expressed in milligrams per Liter (mg/L). Nutrient pollution from sources like agricultural runoff can create hypoxic zones in a body of water due to eutrophication. Too many nutrients cause an increase in productivity of phytoplankton and algae, meaning oxygen is consumed very quickly. These hypoxic zones do not support life and show poor water quality.

Specific conductance is defined by water's ability to conduct electricity and is an indirect measurement of the concentration of dissolved ions in a body of water. Specific conductance is measured in micro-Siemens per centimeter (µS/cm) at 25˚C. This is important to ecological systems and bodies of water because many organisms are extremely sensitive to changes in ion concentrations and too high of concentrations can make a water body uninhabitable by certain species of freshwater organisms such as trout and salmon (YSI 2022). pH is defined on a logarithmic scale and represents the acidity or basicity of a body of water. It represents the hydrogen ion concentration and ranges between 6 to 9 for most bodies of water. Pure water has a pH of 7. A water body that has a pH lower than 6 and higher than 9 cannot support much life, especially multicellular organisms.

Escherichia coli is the biological measurement of the concentration of *E. coli* bacteria in a body of water. The presence of *E. coli* is an indicator of potential contamination from human, livestock, or animal waste. However, the presence of *E. coli* does not mean there are pathogens in the water, but it does increase the likelihood of a potential infection if exposed. Therefore, it is an important parameter to examine, especially in regard to human health and recreation (Science Direct 2020). Chlorophyll-a is another biological component of a body of water and measures the concentration of primary photosynthetic pigment of water in units of milligrams per cubic meter (mg/m^3). It indicates the presence of phytoplankton/algae in a system, and since these organisms are at the base of the food web, Chlorophyll-a helps increase productivity of a system. Overall, all these variables are common measurements for analyzing the health of an aquatic ecosystem and monitoring changes over time. They are great indicators of underlying problems and have the potential to show great changes in the company of decreased water volume at Boulder Basin of Lake Mead.

Methodology

In this section, I address the methodology used to assess the water quality in the Boulder Basin of Lake Mead. To answer the given research question, quantitative methods by observational and archival analysis were most appropriate regarding the nature of this research. Limnology is a quantitative branch of science, meaning numbers, graphs, and correlational analyses are the basis for the environmental aspect of my study. Therefore, I sourced raw archival data from the United States Geological Survey (USGS) and the Southern Nevada Water Authority (SNWA) for analysis on abiotic and biotic water quality variables and volume in Boulder Basin. I also gathered current water volume data from the United States Bureau of Reclamation on Lake Mead water levels.

United States Geological Survey Dataset

The first set of data that I used in my research was gathered and compiled by the USGS from 2012 to 2016. The USGS is a scientific branch of the United States Department of the Interior that studies the landscape, natural resources, and hazards of the Earth in search of a broader understanding of the science and prevention of loss of life and property from disaster (USDI 2018). In Nevada, the USGS had responsibility for the Lake Mead water sampling until 2016, when the authority was then given to the Southern Nevada Water Authority. The USGS collected this data as a part of a multi-agency monitoring network that was utilized to gain knowledge on the hydrodynamics of the waters of the Lake Mead National Recreation Area (LAKE).

For Lake Mead, they have near continuous and depth dependent water quality monitoring stations at Temple Basin, Overton Arm Basin, Virgin Basin, Las Vegas Bay, Sentinel Island, and Boulder Basin. Near continuous monitoring means that water quality measurements are collected almost all hours of the day. Depth dependent monitoring means that the sonde used to measure the water quality variables is lowered into the water slowly until it reaches the bottom and is then brought back up. The sonde is lowered all the way to the bottom because Lake Mead has thermal stratification, meaning that different layers of the lake have different temperature profiles and oxygen levels. Therefore, it is important to measure all layers to see trends in the differing data. The following water quality variables were collected by the USGS using a multiparameter sonde: depth, water temperature, specific conductivity, pH, dissolved oxygen, and turbidity. They also collected meteorological data at these sites, including air temperature, relative humidity, barometric pressure, wind speed and direction, and solar radiation. This data is quality assured by USGS researchers through statistical analysis and notes outliers or suspicious results in the dataset.

Southern Nevada Water Authority Dataset

The second source of data that I used during my research process is from the Southern Nevada Water Authority from 2004 to 2019. The SNWA is a government agency formed by seven local water agencies that was founded in 1991 to manage Southern Nevada’s unique water needs regionally (SNWA 2021). The goal of SNWA is to properly manage the area’s water for current and future needs and to help conserve water across these areas as drought intensity rises. They are also responsible for managing wastewater treatment facilities in the Las Vegas region.

In 2001, the federal government transferred authority of the Southern Nevada Water System to the SNWA, but this excluded Lake Mead at the time.

For Lake Mead, the SNWA has field technicians gather water samples from Boulder Basin that are then brought back to their Clark County Lab where they are used to measure the following biological parameters: Chlorophyll-a and *E. coli*. I will be investigating the concentrations of these biological variables over time. These organisms grow on petri dishes in the lab and are then counted under a microscope. The units for Chlorophyll-a are milligrams per cubic meter (mg/m^3), and the units for *E. coli* are colony-forming units per 100 milliliters (CFU/100 mL). The SNWA measures biological parameters at this location for public safety since it is a recreational area. If a storm event was present at around the time of sampling, it is noted in the data since storm events can cause elevated bacterial levels. This dataset is also quality assured and regulated by the SNWA. Outliers are reported and there is a detection limit for the dataset, which highlights high and low values.

Overall, I used archival data from the United States Geological Survey and the Southern Nevada Water Authority to help assist in my research. Since the data are collected by government agencies, it is quality assured, and can be used to support my findings. It is important to look at the physical and biological water quality variables in the Boulder Basin of Lake Mead for public safety assurance, ecological health, and future implications. If the historical drought in the southwestern United States continues to increase, then my research can help provide future predictions for the changes in water quality in the Boulder Basin of Lake Mead.

Results

Change in Elevation over Time

The results of the comparative analysis between water volume and water quality of the Boulder Basin of Lake Mead are presented here. First in **Figure 6**, the yearly average of Lake Mead's water level is shown over time. The water elevation, which also can be seen as water level, has dropped in Lake Mead from 1200 feet to 1075 feet in the past 20 years. This is approximately a 125-foot drop and has continued to drop as drought intensity increases. Since there is a large drop in the water volume/elevation of the water of Lake Mead over the years, there is potential that this change could affect the water quality of Lake Mead. In this case, I studied the area of Boulder Basin of Lake Mead. I focused on the epilimnion (the first 0 to 5 meters) of the body of water and graphed it with the depth of the water for the end of the month values of January, July, and September to ensure that thermal stratification was occurring.

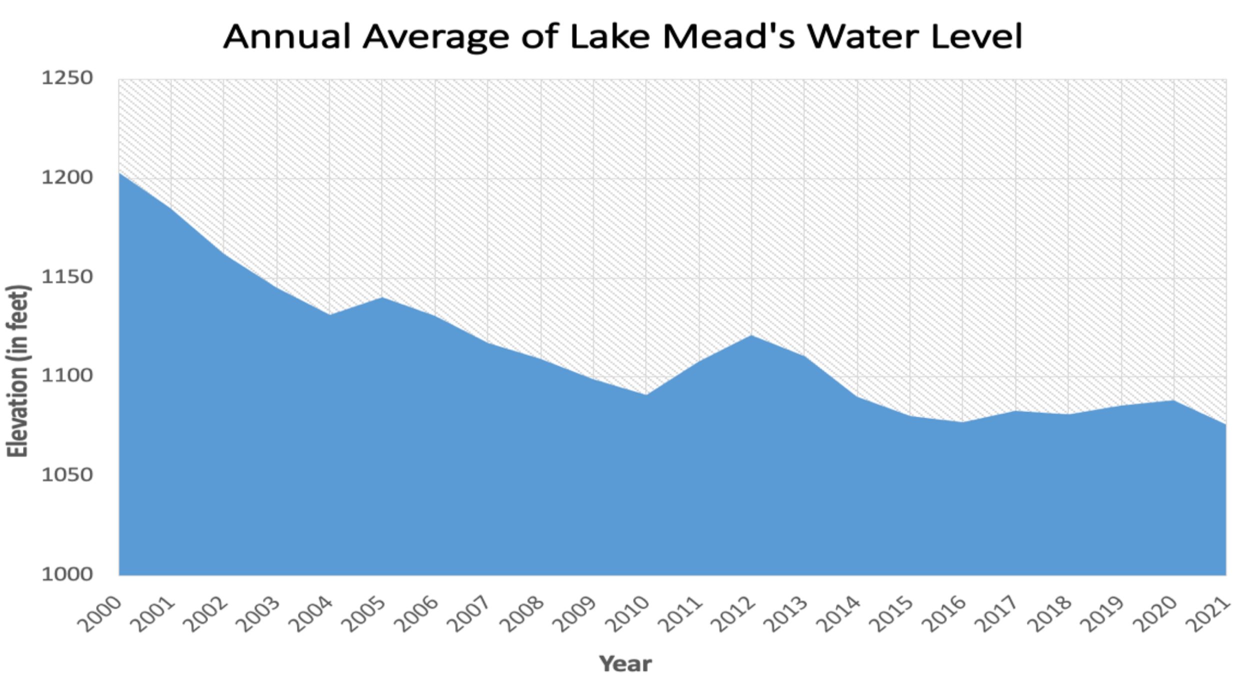

Figure 6: Elevation of Lake Mead from 2000 to 2021 as a Yearly Average

Thermal Stratification of Boulder Basin

In **Figure 7**, the different temperature profiles of Boulder Basin of Lake Mead are shown and demonstrate the importance of comparing water quality variables over time in terms of end of the month values for January, July, and September. During these months, the water temperatures are different, and they also show different layers of stratification. In the deeper sections of the water, the temperatures are colder than the shallower areas, especially in July and September. In January, the entire lake was about the same temperature, at all depths (a pattern referred to as isothermal). This is important to note because measuring water quality variables in deeper sections of the lake could give different values due to changes in temperature. In my research, I chose to only measure water quality in the first 5 meters of depth because this is the main area that will affect recreation for humans if there are any concerns.

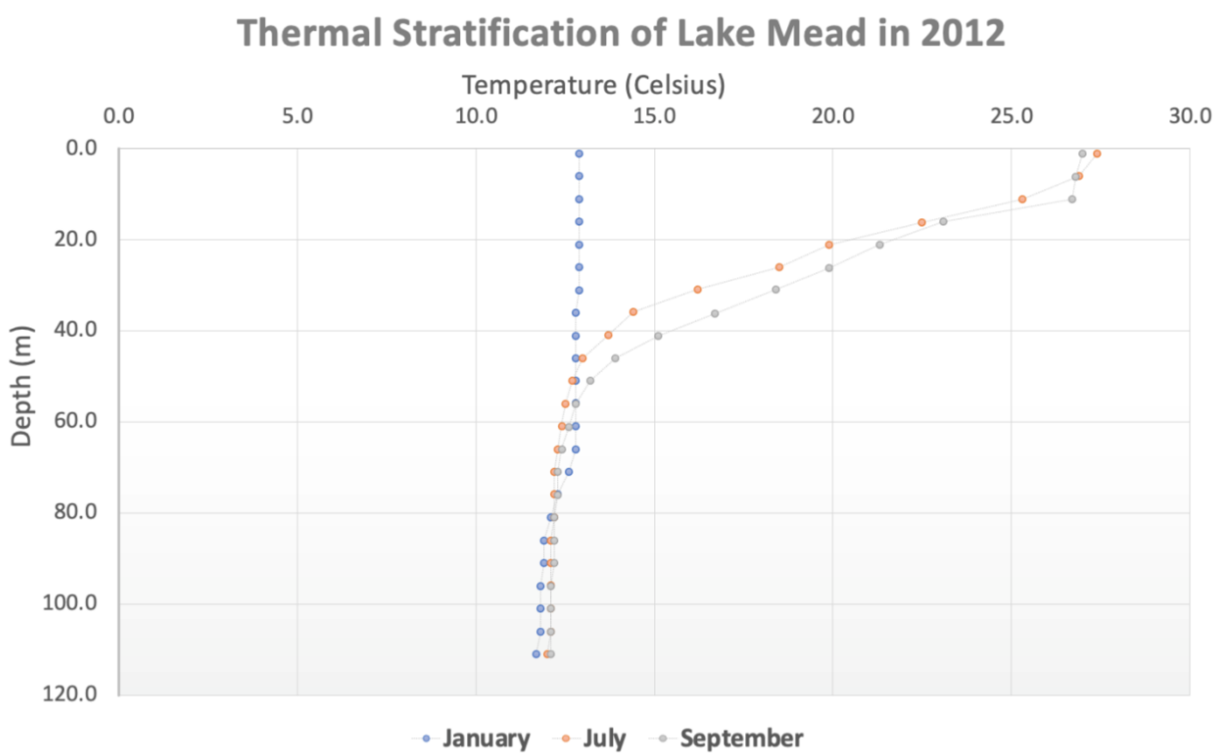

Figure 7: Graph of the thermal stratification of Lake Mead in 2012 for the months of January, July, and September with temperature on the x-axis versus depth on the y-axis

Relationship between Physical Water Quality Variables and Decreased Elevation

For each water quality variable tested, a graph was made to see if there is a change over time from the years of 2012 to 2016. A correlation was taken between elevation, which is a measure of water volume, to see if there is a relationship between water volume and the water variable in question in Boulder Basin. As water volume decreases, I was looking to see if these variables changed positively, negatively, or not at all.

In **Figure 8** below, there are 6 graphs showcasing the different water quality variables for the month of January and how they change over the timespan of 5 years from 2012 to 2016 in relation to change in elevation. The variables measured were taken from the first 5 meters of depth of the epilimnion, and only specific conductance and water temperature showed a relationship between elevation and the specific variable over time. Specific conductance shows a change from 906 $\mu S/cm$ to 110 $\mu S/cm$. Over the 5-year period in January, water temperature increased by 1.4 degrees Celsius as water volume decreased, which is dangerous to the aquatic community.

For **Figure 9**, the same variables are shown from 2012 to 2016 for the months of July and September. However, turbidity was not applicable for July from 2012 to 2016 due to the dataset from the USGS showing MAL (malfunction) measurements. This could be due to the depth-dependent and near-continuous sonde being either uncalibrated or producing unreliable measurements during this month over the years. In these graphs, you can see a trend over time in July for the following variables: air temperature, specific conductance, and pH. Specific conductance showed a strong increase in the specific conductance measurements as elevation decreased from 935 $\mu S/cm$ to 1075 $\mu S/cm$. Air temperature decreased with the decreasing elevation by 1 degree Celsius, and pH dropped by 1 unit from 2013 to 2014. This was a large drop and could affect the health of aquatic organisms. For **Figure 10**, the graph shows a strong change in specific conductance (from 965 $\mu S/cm$ to 1050 $\mu S/cm$) over time for the month of September in relationship to the drought and decreased water volume. Overall, specific conductance, the concentration of dissolved ions in the water, was the main variable that showed a consistent, negative relationship to decreased water volume of the Boulder Basin of Lake Mead.

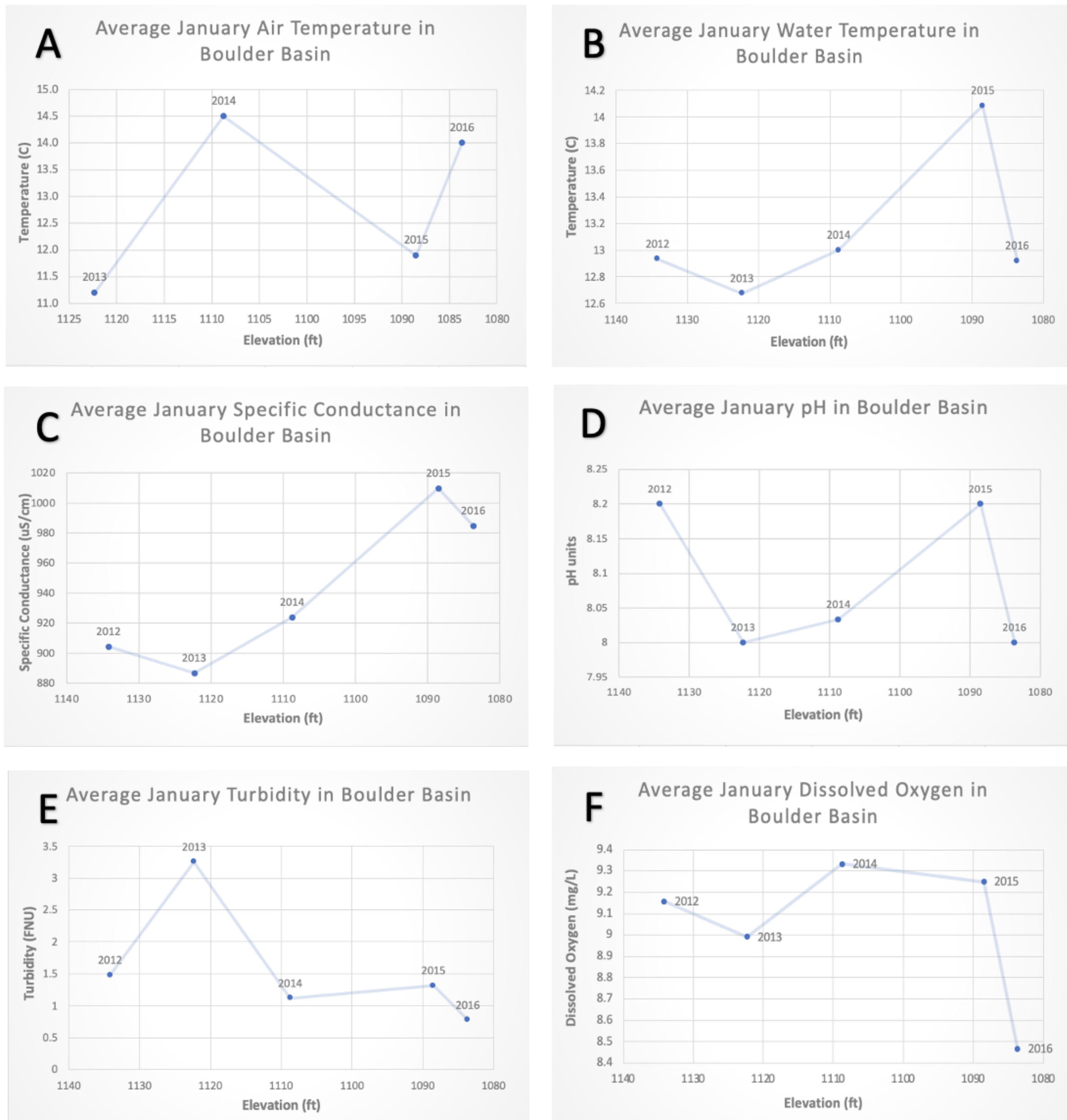

Figure 8: Change in A) Air Temperature, B) Water Temperature C) Specific Conductance, D) pH, E) Turbidity, and F) Dissolved Oxygen with respect to elevation in January for Lake Mead from 2012 to 2016

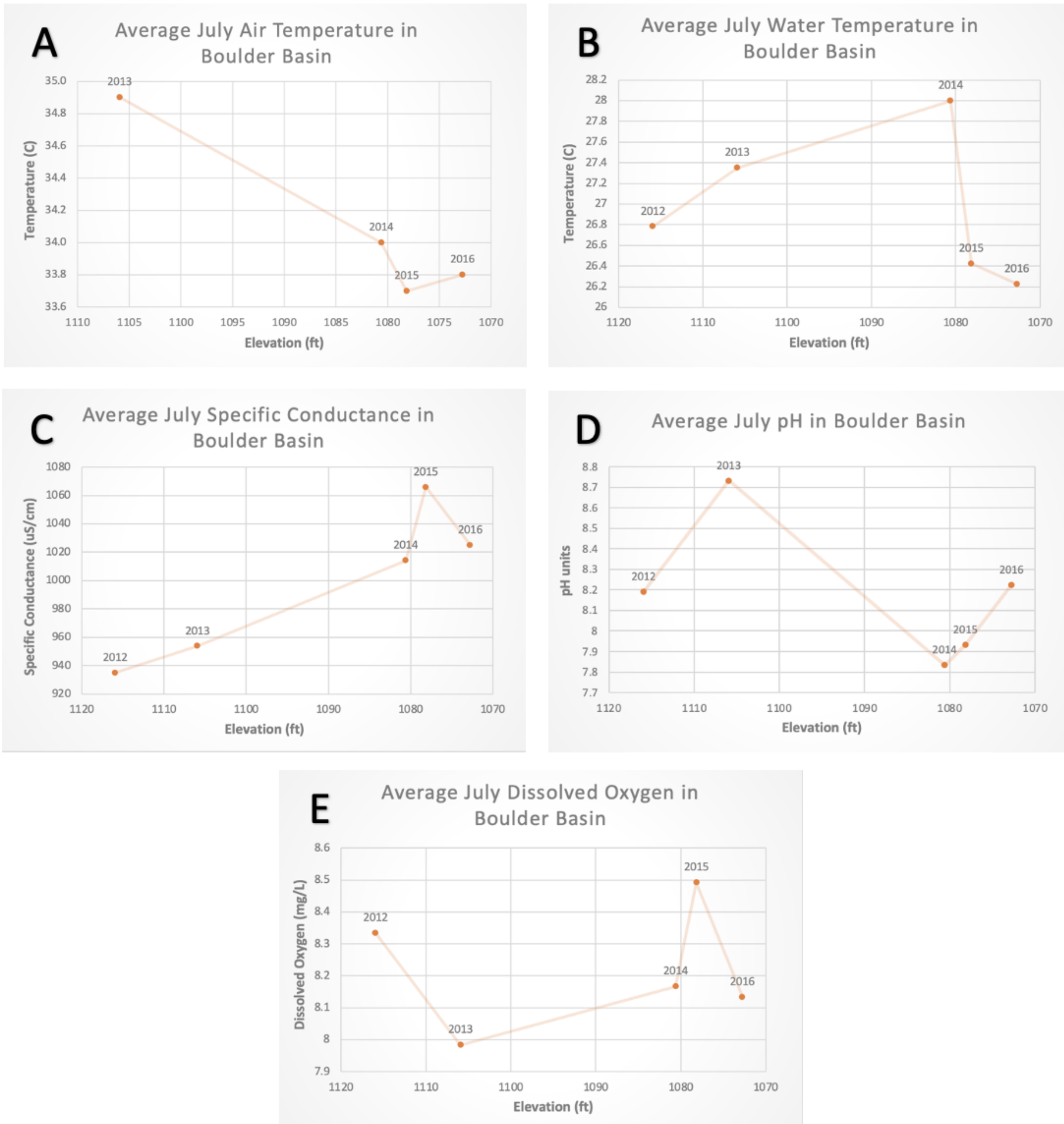

Figure 9: Change in A) Air Temperature, B) Water Temperature C) Specific Conductance, D) pH, and E) Dissolved Oxygen with respect to elevation in July for Lake Mead from 2012 to 2016. Turbidity was excluded from the data representation for the month of January.

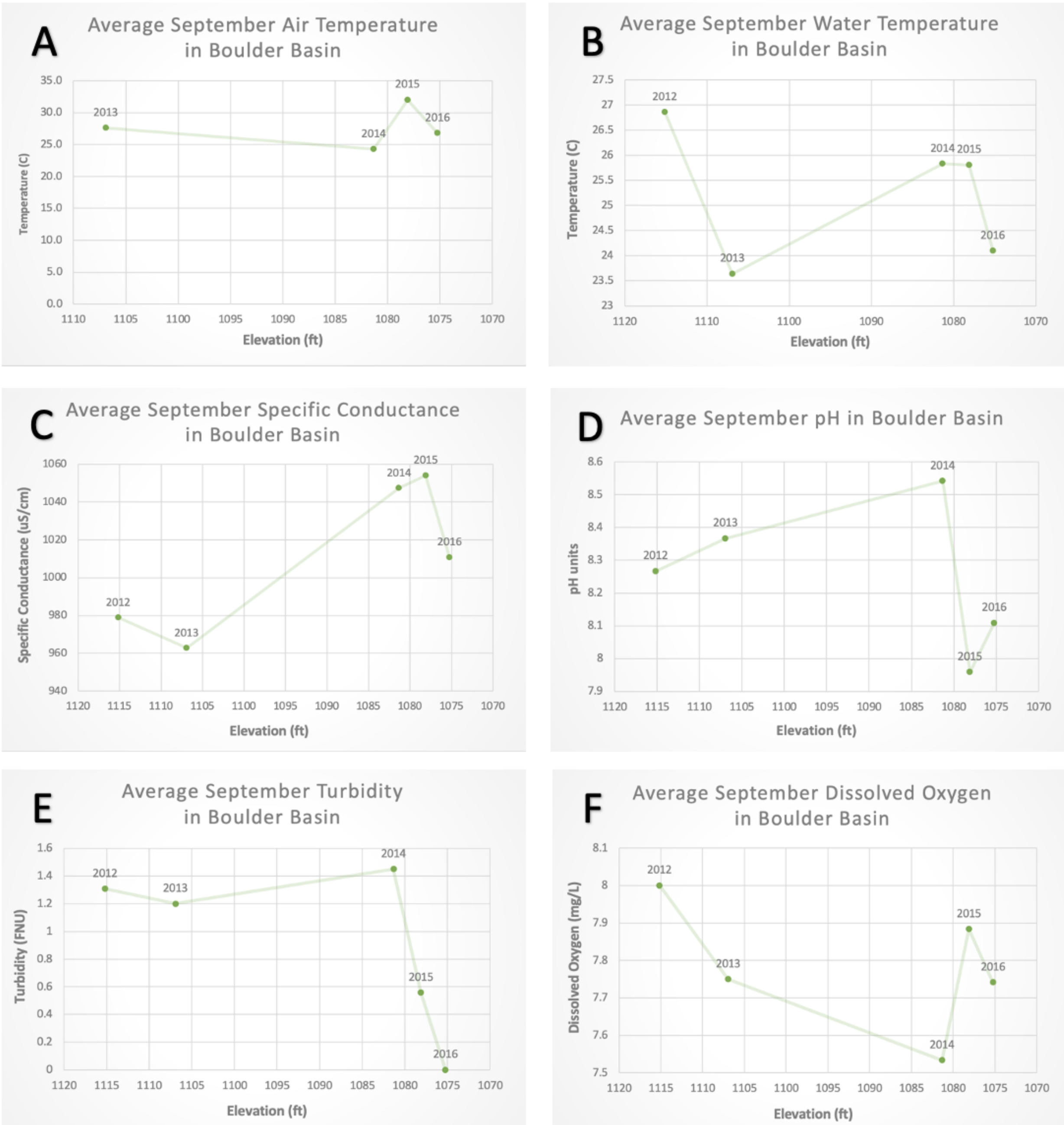

Figure 10: Change in A) Air Temperature, B) Water Temperature C) Specific Conductance, D) pH, E) Turbidity, and F) Dissolved Oxygen with respect to elevation in September for Lake Mead from 2012 to 2016

Table 2: Correlation Coefficients between Water Quality Variables and Lake Mead Elevation

	Water Temperature	Air Temperature	Specific Conductance	pH	Turbidity	Dissolved Oxygen	Chlorophyll-a
January	-0.529	-0.353	-0.908	0.176	0.548	0.420	0.010
July	0.198	0.974	-0.921	0.545	N/A	-0.138	-0.452
September	0.189	-0.075	-0.825	0.328	0.446	0.506	0.342

For **Table 2** above, the correlation coefficients, also known as a statistical measure of the strength of the relationship between two variables, are expressed for all variables except *E. coli*. The correlation coefficients were found by correlating the end of the month water elevation levels for January, July, and September to the end of the month average water variable values from 2012 to 2016. **Table 3** defines what is considered a strong, positive or negative correlation depending on the correlation coefficient produced. Values with a correlation coefficient of 1 are perfectly correlated and linear, and values with a correlation coefficient of 0 are completely unrelated.

Table 3: Range of Correlation Coefficient Values and the Corresponding Level of Correlation

Range of Correlation Coefficient Values	**Level of Correlation**	**Range of Correlation Coefficient Values**	**Level of Correlation**
0.90 to 1.00	Very Strong Positive	-0.90 to -1.00	Very Strong Negative
0.70 to 0.90	Strong Positive	-0.70 to -0.90	Strong Negative
0.50 to 0.70	Moderate Positive	-0.50 to -0.70	Moderate Negative
0.30 to 0.50	Weak Positive	-0.30 to -0.50	Weak Negative
0.00 to 0.30	Very Weak Positive	0.00 to -0.30	Very Weak Negative

Relationship between Biological Water Quality Variables and Decreased Elevation

The biological water quality parameters assessed were *E. coli* and Chlorophyll-a from the SNWA from 2004 to 2019. The *E. coli* variable was excluded from the data in **Table 2** because of the nature of the data. The *E. coli* data are expressed in Colony-Forming Units per 100 mL (CFU/100mL) of water, and the Boulder Basin levels were so low that most of the values were less than 2 CFU/100mL. Therefore, I could not investigate the correlation coefficients over time because there were very few specific values other than <2 CFU/100mL. Therefore, I used the 412 sample values from 2004 to 2019 and selected counts for values less than 2 CFU/100mL. Out of the 412 samples, 328 (80%) were classified as less than 2 CFU/100mL, and 84 (20%) were classified as greater than 2 CFU/100mL. The minimum value of *E. coli* measured was 0 CFU/100mL, and the maximum value was 45 CFU/100mL. The EPA recommends that recreational beach waters should not exceed 88 CFU/100mL, and Boulder Basin is way below that range, meaning there is no concern for decreased water volume on recreation.

As for Chlorphyll-a, shown in **Figure 11** below, there is a very weak correlation between the values from 2004 to 2019 and the elevation. Chlorophyll-a was plotted as a yearly average of the Chlorophyll-a concentration in milligrams per cubic meter alongside the decreasing elevation in feet. The correlation coefficients for Chlorophyll-a were weak during all 3 months, with the lowest correlation being 0.01 and the highest being -0.452.

Overall, specific conductance was the sole variable showing a very strong, negative correlation to elevation consistently from 2012 to 2016 for the months of January, July, and September. Specific conductance appeared to be affected by decreased water volume in Boulder Basin of Lake Mead, and water temperature, pH, turbidity, and dissolved oxygen showed moderate correlations between one month of the year and water volume changes. However, these correlations are not strong and consistent, therefore all variables other than specific conductance appear to have been unaffected by the water level and drought. It is possible that a threshold for water quality decline has not yet been met for the other variables, and that continued water level declines might cause a response in one or more of the variables.

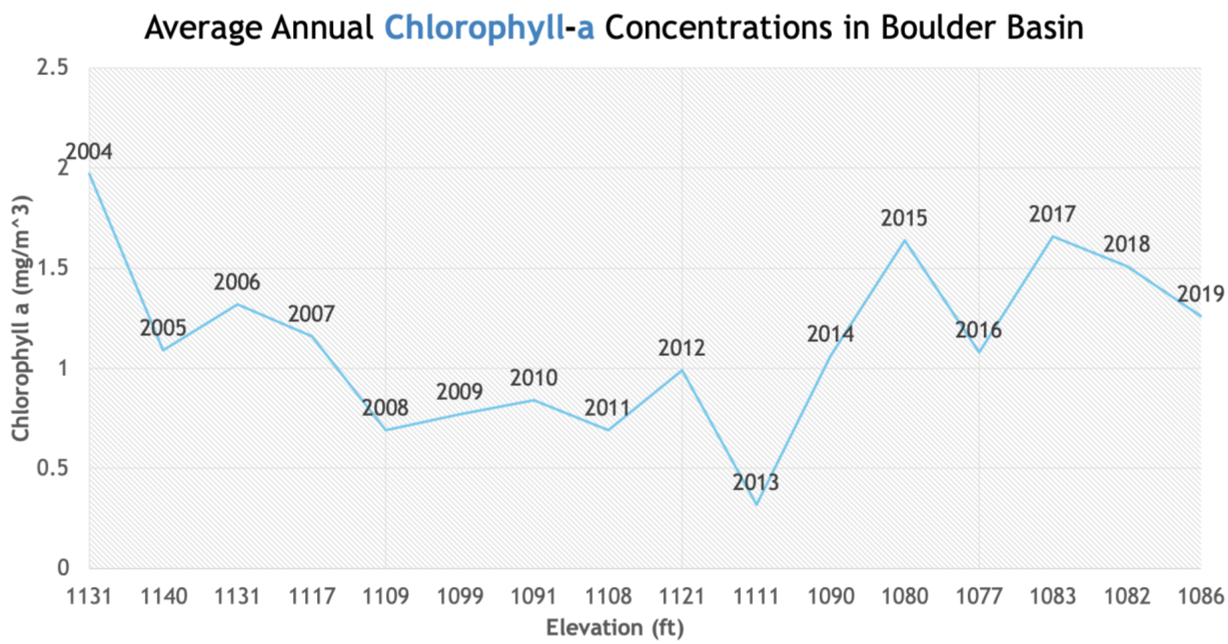

Figure 11: Average Annual Chlorophyll-a Concentrations in Boulder Basin

Discussion

Specific Conductance and its Implications for the Future of Boulder Basin

The data show that specific conductance was the main water quality variable that changed in response to the decreased water volume at Boulder Basin of Lake Mead. When the water volume or elevation decreases in a lake or body of water, it is common for the concentration of contaminants, pollutants, molecules, and so forth to become more concentrated since they are less diluted with water. Dilution is the addition of a solvent, like water, which decreases the concentration of the solute in the solution. Concentration is the opposite of dilution and removes the solvent (water), increasing the amount of solute in the solution (Key 2020). Since specific conductance is defined as an indirect measurement of the conductivity of a solution, as water volume decreases, the dissolved ions in the water increase, causing a gradual increase in the overall electrical conductance of the water at the Boulder Basin of Lake Mead. Specific conductance is also affected by temperature, and as temperatures rise in the southwestern United States due to climate change, the conductivity is expected to increase in the major lakes, reservoirs, and rivers (EPA 2021).

Increased specific conductance in the Boulder Basin of Lake Mead does not have a huge effect on the recreational aspect of Boulder Basin since the value of specific conductance only increased from 900 µS/cm to about 1,000 µS/cm. This value of specific conductance is in the range normally observed for freshwater ecosystems, though many water bodies have specific conductance of < 300 µS/cm. Good drinking water for humans and livestock is anything between 0 to 800 µS/cm, and low levels of salt are beneficial for plants and animals to grow. Anything between 800 to 2500 µS/cm is also safe to consume but can be detrimental to salt sensitive crops or organisms (MRCCC n.d.). Water with a specific conductance from 2,500 µS/cm to 10,000 µS/cm is not suitable for human consumption, crop irrigation, or livestock consumption. Seawater is about 50,000 µS/cm. Overall, specific conductance, especially in the form of salt concentration, does not affect the skin or human body unless it is consumed. Some individuals who have sensitive skin could be affected by high specific conductance, but this is rare.

However, an increase in dissolved solid concentrations in water can make it harder to purify the water for those that rely on Lake Mead as a source of water. Therefore, water treatment plants downstream the Hoover Dam and in Clark County of Las Vegas may struggle in the future with keeping up with the changing water quality. Overall, as the drought in the southwestern United States continues to increase from the advancing climate change effects, specific conductance concentration is expected to grow larger with time. Specific conductance showed a strong correlation to the decreased water volume in Boulder Basin, but it also could be caused by a source of disturbance, such as a human disturbance from runoff and decreased impervious surfaces (EPA 2021), though neither of these is occurring to any great extent around Boulder Basin.

There are also many biological implications that can result from increased specific conductance. Specific conductance is a high biological concern for aquatic organisms because there is not a natural process that breaks down the chloride salts in a body of water (NPS 2016). The only solution to combat high specific conductance is dilution, which is not an option in the southwestern United States where drought is persistent and water levels are low. In freshwater systems like the Colorado River and Boulder Basin, the National Park Services set a threshold of 171 µS/cm for fish health, and extended periods or spikes of high specific conductance can be particularly damaging for aquatic fish and organisms, wildlife, and habitat. The high temperatures that also usually cause a spike or increase in specific conductance can affect fish reproduction, habitat, function, and overall survival (USDI n.d.). Therefore, specific conductance has the potential to decrease the diversity of Boulder Basin of Lake Mead and the Colorado River System.

All Other Variables and their Implications for the Future of Boulder Basin

Air temperature, water temperature, dissolved oxygen, turbidity, pH, Chlorophyll-a, and *E. coli* did not appear to be affected by the decreased water volume in the Boulder Basin of Lake Mead. However, this is a good sign for the future of Lake Mead, as it shows that as drought intensity increases, the future health of the lake will not be threatened by changes in these water quality variables. Climate change and its effects, such as increased surface temperatures and increased severity of weather patterns can cause increased evaporation rates and higher water demands, further decreasing the water volume and elevation of Lake Mead. If Lake Mead's volume continues to decrease at high rates, there will be less water for the people in the southwestern United States as well as less energy due to the reduced hydropower efficiency in major dams such as the Hoover Dam and the Glen Canyon Dam. Additionally, if water continues to be depleted, water could stop flowing through the Hoover Dam overall. This would cut off all water to the Lower Colorado River Basin beyond the Hoover Dam.

However, the lack of a relationship between the seven other water quality variables and elevation does not mean that there will not be a relationship or correlation between decreased water volume and overall water quality in Lake Mead in the future. There could be a "point of no return" for the water quality of Boulder Basin of Lake Mead if volume drops below a threshold point. For example, if water volume drops below 800 feet in elevation, the lake could be threatened by alarming declines in water quality and major changes in the physical and biological components of the lake (Bolinger, 2021). However, as of 2016, the other seven water quality variables studied in Boulder Basin were not a concern for the public health of civilians or aquatic life, and recreation can continue as normal despite the ongoing drought. However, in the future, climate change could cause further water quality and demand concerns for the people who rely on Lake Mead's water supply for irrigation, recreation, drinking water, and hydropower efficiency.

Connections of the Drought to Climate Change

Climate change is one of the leading factors of the increased drought in the southwestern United States. As our average global air temperatures continues to increase, there will continue to be more dramatic storm events, drastic changes in climates, and decreased availability of resources (NDMC 2021). High levels of heat in an environment cause the atmosphere to be incredibly dry, forcing it to pull water/moisture from the ground, lakes, rivers, and even snowpack (Lindsey 2021). This atmospheric demand for water is known as the vapor pressure deficit (VPD), which has reached yearly record high levels in the southwestern United States due to the historical megadrought. When there is an increase in evaporation due to high air temperatures, the concentration of the ions in a body of water are expected to increase, like how when one boils salty water, they will eventually end up with just salt since the gaseous water is reabsorbed into the air. This is what is happening at Boulder Basin, and since climate change is expected to worsen in the coming years, Lake Mead could completely dry up or become uninhabitable for aquatic organisms and wildlife.

The National Oceanic and Atmospheric Administration (NOAA) estimates that the drought has cost the southwestern United States between $515 million and $1.3 billion in drought mitigation and water resource scarcity management, excluding the cost of wildfires that have occurred because of the drought (NOAA 2021). For the Colorado River and its major reservoirs, this is a huge concern for the future of cities that rely on the Colorado River Basin for their domestic water supply. Therefore, water conservation needs to be taken more seriously by cities in the Upper Colorado River Basin and factors that increase climate change rates, such as increased fossil fuel reliance, confined animal feeding operations, transportation, and so forth, need to be reduced to help protect future water supply.

Future Research Direction for Boulder Basin of Lake Mead

For the future research of Lake Mead’s water profile and budget, it is necessary to continue daily testing at all basins in Lake Mead, including Gregg Basin, Temple Basin, Virgin

Basin, and the Overton Arm. Additionally, expanded monitoring should be implemented to further evaluate any changes in water quality through time. Since most of this testing is done by an automated system, it is essential that this system is calibrated more frequently, and that the data produced is consistently monitored to stay ahead of any potential trends or declines in water quality. For Boulder Basin, there could be a moment where other water quality variables begin to respond, perhaps strongly, to reduced water levels, and it is essential to be prepared for this. Additionally, future research should investigate how these variables could affect the native wildlife and how water will be relocated to meet the needs of the people.

To combat the decreasing water volume in the Boulder Basin of Lake Mead, further solutions need to be explored in depth. In the 1900's, mistakes were made in the design of Lake Mead and Lake Powell as well as the overall water allocation plan that was created for the seven U.S. states that fall within the Colorado River Basin. Over 15 million acre-feet of water per year was allocated to these states, which is a large amount to withdraw for a location experiencing historical drought (Bolinger, 2021). However, in 2015, the Southern Nevada Water Authority built a $817 million dollar and 3-mile-long pipeline under Lake Mead as a "last straw" to be able to access every bit of water in the drought-stricken lake if water levels fall below the two main intake pipes (Ritter 2015). Near the end of April, Lake Mead's Intake Pipe No. 1 was exposed for the first time since 1971, which is when it began supplying water to Nevada customers. This means that Lake Mead's waters have reached a historical low as of 2022 (Fitzsimmons 2022). Las Vegas relies almost entirely on Lake Mead for water and has had to enforce strict water usage guidelines and recycling efforts to prevent overexploiting their water source. On top of the pipeline built by the SNWA, a drought contingency plan (DCP) was signed in 2019 by the seven southwestern U.S. states to cut down water usage in the Upper Colorado River Basin. In the future, this is expected to help protect and sustain the most important source of water for the southwestern U.S. – the Colorado River.

Besides the water scarcity concern, over 1.3 million people rely on the Hoover Dam, which created Lake Mead, for electricity. If Lake Mead's water level drops below 950 feet in elevation, the Hoover Dam electricity turbines will idle, and no water will flow downstream (Abdelsayed 2021). This will also cause no energy production, forcing many residents and cities to have to increase their natural gas or nonhydroelectric renewable energy production. If fossil fuel energy production is used to back up the lost energy production, climate change effects would worsen due to the increased greenhouse gas effect from burning more carbon dioxide.

Conclusion

Due to increasing climate change effects on drought, the Colorado River Basin is slowly decreasing in volume and causing reduced water allocation to major reservoirs and cities. These major reservoirs, such as Lake Mead, are feeling the effects more and more each day. The decreased water volume due to the drought in the southwestern United States is affecting the water quality of Boulder Basin. The only water quality variable with a strong correlation to decreased water volume was specific conductance. My research shows that as water volume decreased, the specific conductance of the water increased. An increase in the specific conductance of water at Boulder Basin means there are more dissolved ions in the water causing an increase in the water's ability to conduct an electrical current. For humans, this is of no current health concern, but it could cause increased costs in water treatment in the future if levels continue to rise. For fish and wildlife, high specific conductance can create uninhabitable conditions for survival, reducing biodiversity and essential habitat for organisms.

The other seven variables – water temperature, air temperature, dissolved oxygen, turbidity, pH, chlorophyll-a, and *E. coli* – were unaffected by the decreased elevation of Boulder Basin from 2012 to 2016 and 2004 to 2019. This is a good sign for the future health and water quality of Boulder Basin. However, there is a possibility that a threshold of water quality has not yet been met for Lake Mead. In 10 years, water quality could deteriorate quickly and increase water insecurity in the southwestern U.S. Therefore, it is important to continue testing and measuring changes in water quality over time to be more aware of future concerns in Lake Mead. Additionally, without cooperation between federal agencies and civilians, it would be near impossible to protect and maintain the economic and environmental health of the Colorado River Basin and its major reservoirs; therefore, civilian education on how to conserve water is crucial to the future of the Boulder Basin of Lake Mead.

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Appendix

Table 4: Lake Mead End of Month Elevation (in feet) provided by the USBR

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVERAGE
2000	1214.26	1213.79	1211.33	1208.78	1207.67	1204.09	1199.97	1196.66	1196.72	1196.66	1196.45	1196.12	1203.541667
2001	1197.27	1196.62	1194.68	1190.76	1187.32	1183.12	1180.78	1179.97	1177.96	1178.03	1177.22	1177.37	1185.091667
2002	1177.94	1176.5	1172.06	1167.49	1162.39	1160.19	1157.57	1156.42	1155.42	1154.89	1153.3	1152.13	1162.191667
2003	1153.33	1154.42	1153.09	1148.27	1144.68	1143.19	1141.93	1143.27	1142.12	1141.17	1139.48	1139.12	1145.339167
2004	1140.39	1140.11	1138.7	1134.98	1129.7	1126.93	1125.73	1126.67	1125.86	1127.43	1130.13	1130.01	1131.386667
2005	1137.4	1143.25	1147.66	1144.45	1141.89	1140.46	1139.01	1139.61	1138.36	1137.01	1135.27	1137.52	1140.1575
2006	1139.46	1141.2	1139.48	1135.94	1131.14	1128.26	1126.42	1126.54	1125.36	1126.13	1126.63	1128.12	1131.223333
2007	1129.55	1129.35	1125.79	1120.69	1115.89	1113.5	1111.58	1111.84	1111.06	1110.95	1111.22	1114.81	1117.185833
2008	1116.46	1116.93	1115.65	1110.61	1107.05	1104.98	1104.42	1105.13	1105.76	1107.94	1107.33	1110.97	1109.435833
2009	1111.78	1111.43	1107.4	1101.26	1096.92	1095.26	1094.2	1093.73	1093.68	1093.26	1093.52	1096.3	1099.061667
2010	1100.02	1103.21	1100.66	1098	1094.3	1089.3	1086.97	1086.91	1083.81	1082.36	1081.94	1086.3	1091.148333
2011	1091.73	1095.78	1096.39	1095.76	1097.9	1102.38	1107.07	1113.45	1116.04	1121	1125.82	1132.83	1108.0125
2012	1134.18	1133.06	1129.41	1123.93	1119.38	1115.84	1115.92	1116.56	1115.16	1116.5	1117.24	1120.36	1121.461667
2013	1122.32	1122.14	1118.59	1112.91	1108.36	1105.98	1105.92	1106.13	1106.92	1104.04	1106.36	1106.73	1110.533333
2014	1108.75	1107.94	1101.71	1094.55	1087.46	1082.66	1080.6	1081.55	1081.33	1082.79	1083.57	1087.79	1090.058333
2015	1088.51	1088.98	1084.87	1079.03	1076.57	1075.08	1078.15	1078.31	1078.1	1078.99	1078.23	1080.91	1080.4775
2016	1083.68	1084.17	1080.45	1076.13	1073.8	1071.64	1072.75	1075.17	1075.23	1076.34	1076.55	1080.82	1077.2275
2017	1086.08	1089.78	1088.26	1084.89	1081.56	1079.52	1079.03	1081.44	1082.05	1082.3	1080.95	1082.52	1083.198333
2018	1087.5	1088.21	1088.11	1084.49	1080	1076.81	1077.43	1078.88	1078.29	1078.52	1078.32	1081.46	1081.501667
2019	1085.75	1087.97	1090.24	1088.95	1086.48	1084.71	1082.82	1083.45	1083	1082.61	1083.85	1090.49	1085.86
2020	1094.68	1096.27	1098.59	1096.39	1091.32	1087.07	1084.63	1084.04	1083.21	1081.88	1081.07	1083.72	1088.5725
2021	1085.95	1087.26	1084.39	1079.3	1073.5	1068.77	1067.65	1067.96	1067.68	1066.77	1064.97	1066.39	1073.3825