

## LAKE POWELL MEGADROUGHT: IMAGE SIMULATION

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**ABSTRACT:** *Southwestern United States is experiencing a megadrought that started in 1999 and is now entering its third decade. This megadrought is centered on the Colorado River Basin, an area that has dealt with drought conditions for at least 2000 years. Throughout this basin numerous reservoirs have been developed to control and manage water distribution throughout the Southwest. A key reservoir in this distribution system is Lake Powell through which water from mountain snowpacks in the Upper Basin flow into the arid and heavily populated Lower Basin. This paper shows how the current megadrought has reduced the water level in the lower portion of Lake Powell. Between 1999 and 2004 the water level in the reservoir decreased at a significant rate mainly due to low snowfalls in the surrounding mountains. By 2009 the water level had reached a low stage. The reservoir's water level has remained at this stage and it has shown no sign of recovering to the height where the reservoir would again be near full capacity. This paper also provides a simulation of what the water level might be if another major decrease occurs similar to one that existed between 1999 and 2004. The simulation illustrates the fragility of this water system to meet the needs of the Southwest. Landsat 5 Thematic Mapper (TM) data for 1999, 2004, and 2009 were used in this study in conjunction with an image processing package.*

**Keywords:** *Lake Powell, drought, megadrought, remote sensing, Colorado River*

### INTRODUCTION

This paper shows how the current megadrought in the American Southwest has shrunk the water level in Lake Powell and provides a simulation of what the water level might become if the megadrought becomes more severe. Lake Powell is located on the Colorado River and is the second largest reservoir in the United States following Lake Mead, which is situated farther down the river. In 1922, the Colorado River Compact was established to control the river, and in the process, divided the river into the Lower Basin (Arizona, Nevada, and California) and the Upper Basin (Utah, Colorado, Wyoming, and New Mexico), basically defining the states that needed water and the states that had surplus water (Figure 1: Insert – Basin Map). Thirty four dams have been constructed on the Colorado River and its tributaries, making it the most dammed river system in the United States. Controlling and distributing water through this system is a complex process and Lake Powell behind the Glen Canyon Dam is the gateway for moving water from the Upper Basin to the Lower Basin and Mexico. If the lake does not have water, the entire system collapses. This paper focuses on the lower portion of the lake during the first decade (1999-2009) of the current megadrought. The lower portion of the reservoir is identified on Figure 1.

Figure 1 is a 2002 MODIS (Moderate Resolution Imaging Spectroradiometer) image that shows the Colorado Plateau and Colorado River. The inset is a 2010 Landsat 5 image that highlights Lake Powell. The Colorado Plateau consists of two main sections. The northern section, the Upper Colorado River Basin, is surrounded by mountain ranges on three sides and is situated in eastern Utah and western Colorado. This area is basically the Upper Colorado River Basin. The southern part of the Colorado Plateau is mainly outlined by plateau rims on three sides and is located in northeast Arizona and northwest New Mexico. The Colorado River is fed primarily by the mountain snowpacks in the Upper Basin. The river does not continue into the southern part of the Colorado Plateau but instead turns westward, moving off of the plateau down into the lower elevations of the desert regions of southeastern California and western Arizona before entering Mexico. Due to the high human water consumption along the river, water no longer reaches its historic outlet, the Gulf of California in Mexico.

A drought as defined by the American Meteorological Society is "a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area." The *Dictionary of the Climate Debate* defines a megadrought as an extended drought lasting two decades or more (<http://www.odlt.org/dcd/ballast/megadrought.html>). The term relates more to the length of the drought rather than its severity. A drought with a high level of intensity such as the Dust Bowl drought of the 1930s is generally viewed as a multi-year drought, not a megadrought. The current Southwest drought is entering its third decade making it a megadrought.

Lake Powell Megadrought: Image Simulation

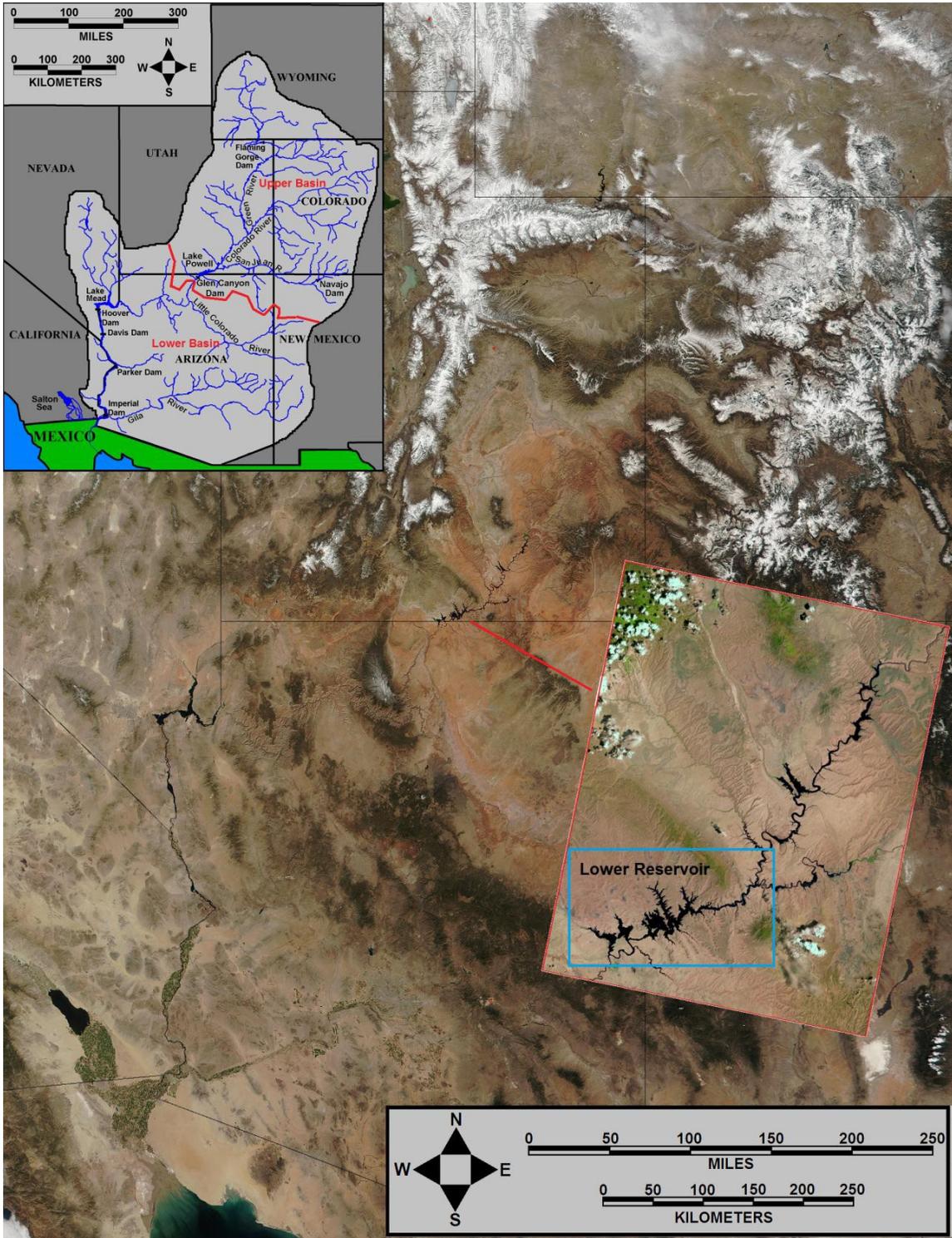


Figure 1. MODIS Image of the Colorado Plateau. Inserts: Landsat image of Lake Powell and Basin map.

## BACKGROUND

### Water Level Record

The U.S. Bureau of Reclamation provides daily and annual water data for Lake Powell dating back to 1963 when Glen Canyon Dam was constructed. These data are available through the Lake Powell Water Database web site maintained by Summit Technologies, Inc. Although this database contains a great amount of information, it does not directly include data about the total water surface. It does provide data with respect to the elevation of the water level at the dam and the water content (volume) of the reservoir. Using the annual water elevation level and the annual water content information the two graphs presented in Figure 2 were constructed. These graphs illustrate the filling period of Lake Powell (green) followed by its capacity years (blue) and then the present megadrought period (yellow). The water data presented in Figure 2 are based on a water cycle year that starts on October 1 of a given year and ends on September 30 of the following year. The winter with its mountain snowfalls starts a water cycle year and the late summer/early fall of the next calendar year when little snow is left in the mountains ends the year.

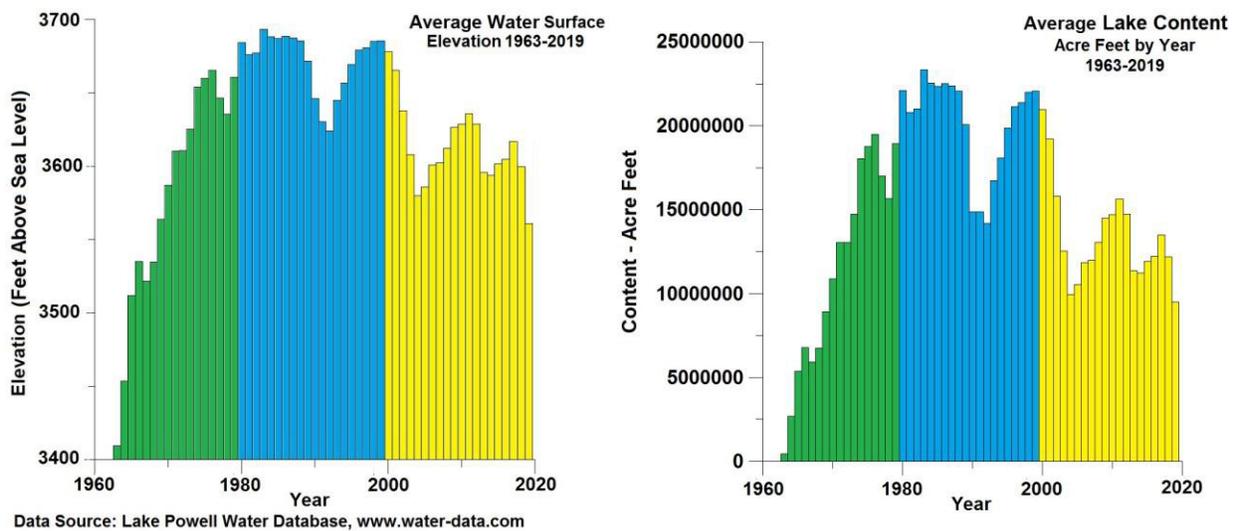


Figure 2. Annual Average Water Level for Lake Powell, 1963-2019

On September 13, 1963 water from the Colorado River started to back up behind Glen Canyon Dam. The elevation at the base of the dam in 1963 was 3,409 feet (1,039 m). Seventeen years later in 1980 the reservoir was at near capacity at 3,700 feet (1,100 m) and 22,089,896 acre feet of water (Figure 2). Over the next twenty years from 1980 to 1999 the reservoir remained at near capacity with the average annual elevation of 3,672.02 feet (1,119.23 m) and an average content of 20,222,962 acre feet per year. The highest water level occurred on July 14, 1983 when the lake was at 3,708.34 feet (1,130.30 m) and had 23,348,654 acre feet of water. This mark related to one of the largest Colorado River floods in recorded history. This average included a seven year drought period as shown in Figure 2. From 2000 to 2019, the present megadrought years, the average annual elevation of the water level has dropped to 3,614.11 feet (1,101.58 m) and the average content per year is 13,370,027 acre feet, a decrease of 6,852,935 acre feet or a 31 percent decrease from the previous twenty years, 1980-1999.

Another way to view the change is to examine the average daily inflow-outflow of water. These data are also available by the Lake Powell Water Database. During the 1980 to 1999 period the average daily inflow of water into Lake Powell was 17,392.5 acre feet and the outflow was 16,039.4 acre feet. More water was flowing in than going out of the reservoir. The Bureau of Reclamation was regularly releasing water down river during this period. Between 2000 and 2019 a reverse inflow-outflow of water has been occurring with the average daily inflow being 11,563.8 acre feet and the average daily outflow being 12,033.8 acre feet. The inflow and outflow dropped 33.5% and 25.0%, respectively, during the 2000-2019 period when compared to the 1980-1999 period. The daily outflow includes the minimum water needed to be sent to Lake Mead so that Hoover Dam can maintain its required hydroelectric production. Lake Mead's water level has also decreased significantly due to the megadrought and its obligation to provide water for agricultural, recreational, and urban needs in the Lower Basin. With more water going out than coming in Lake Powell faces a difficult situation of regulating itself as a functional reservoir.

### **Precipitation Patterns**

The arid and semiarid American Southwest constantly deals with precipitation variability. This variability relates to both geographic coverage and annual amounts. Annual mean precipitation across the Colorado River Basin generally fluctuates between 3.93 inches (10 cm) and 23.5 inches (60 cm).

What moisture the region receives to feed the Colorado River and its major tributaries, the Green River and San Juan River, is the result of different meteorological conditions. A change in any one of these conditions can bring on a flood or drought. The Upper Basin experiences both a winter and summer precipitation regime. In the basin's higher elevations that form its headwaters precipitation falls rather evenly throughout the year, building large snowpacks during the cold months. Much of the basin's summer water supply comes from the melting of alpine snowpacks (Hunter, Tootle, and Piechota, 2006). Cold frontal systems developing over the North Pacific Ocean bring large amounts of precipitation during the winter and spring months. These systems acting like large rivers flowing eastward across western United States carry moisture at high levels in the atmosphere. As these atmospheric rivers encounter the high elevations of the Colorado Plateau, orographic conditions occur, resulting in increasing amounts of precipitation with the rise in elevation. In the San Juan, Uinta, and Wind River mountains these frontal systems create large snowpacks that normally meltdown at a gradual rate during the late spring and early summer to provide most of the water for the Colorado River throughout the summer and into the fall. If these winter systems originate over warmer waters in the Pacific Ocean, precipitation in the form of rain might fall on the mountain snowpacks producing fast, high runoff and floods on the rivers.

During the summer regime rain over the Colorado River Basin comes from convectional systems. Low-level moisture arriving from the Gulf of Mexico, the Gulf of California, and the eastern Pacific Ocean generate thunderstorms in July and August. This atmospheric condition is referred to as the 'North American monsoon,' and normally generates 30 to 40 percent of the annual rainfall in the Lower Basin where the rainfall ranges between 3 and 10 inches (76.2 and 254 mm) per year. These storms generally produce high-intensity rainfall in the Lower Basin where high summer temperatures and low elevations exist. Lower-intensity rainfall occurs more in the cooler and higher Upper Basin. These thunderstorms tend to be local in geographic coverage. They can create flash flooding but contribute little to the large rivers within the basin.

The factors producing the drought conditions throughout major areas of western United States including the Colorado River Basin are not fully understood (Magill, 2017). The expansion of the warm El Niño ocean current within the equatorial portion of the Pacific Ocean has been associated with floods and droughts in western United States (Baum, 2015). Warm winter storms originating from warm ocean surfaces result in rapid meltdown of mountain snowpacks. Such meltdowns produce early above-average runoff followed by later below-average inflow into the basin. However, an El Niño event normally lasts 6 to 18 months, not long enough to create a long term drought. Another factor might be an ocean temperature pattern occurring in the North Pacific Ocean outside the equatorial region. Called the Pacific Decadal Oscillation (PDO) it varies between a warm and cold cycle over a 30 to 50 year period. The causes behind the variations in the PDO are not known but recent research points out an association between the PDO phases with the above- and below-average precipitation and stream flow in the Colorado River Basin (Mantua and Hare, 2002).

### **Megadroughts**

Droughts of 4 to 6 years are common throughout Southwestern United States (Cook, Seager, Cane, and Stahle, 2007). The region has also experienced several megadroughts in the past and is susceptible to extraordinary megadroughts that can last for decades or even centuries. The earliest known megadrought took place from around 124 A.D. to 210 A.D., almost 100 years in length. Tree-ring research shows that during this time span below-average tree ring growth occurred for 50 consecutive years. This study was conducted in the southern San Juan Mountains, the primary drainage basin for the San Juan River that feeds the Colorado River and Lake Powell (Cody, 2011).

A second megadrought took place between 1125 A.D. and 1180 A.D. and corresponded to the time period when the Chaco Canyon civilization located in northwest New Mexico started to decline (Fagan, 2005). Famine brought on by the overuse of the land followed by drought forced the Chaco Canyon people to abandon their large pueblos and migrate eastward to the Rio Grande Valley in what is today northern New Mexico and to the Black Mesa area in Northeast Arizona.

A third megadrought affected the Mesa Verde culture located in the Four Corners Region near Lake Powell. At the beginning of the 13<sup>th</sup> century an estimated 22,000 people occupied the Mesa Verde region (Cordell, 2007). This population remained rather stable during the 12<sup>th</sup> century but a 69 year below average rainfall occurred during the 13<sup>th</sup> century. A severe dry period from 1276 to 1299 ended seven hundred years of continuous human occupation at Mesa Verde (Varien, 2006). Like the Chaco Canyon people the Mesa Verdeans emigrated to New

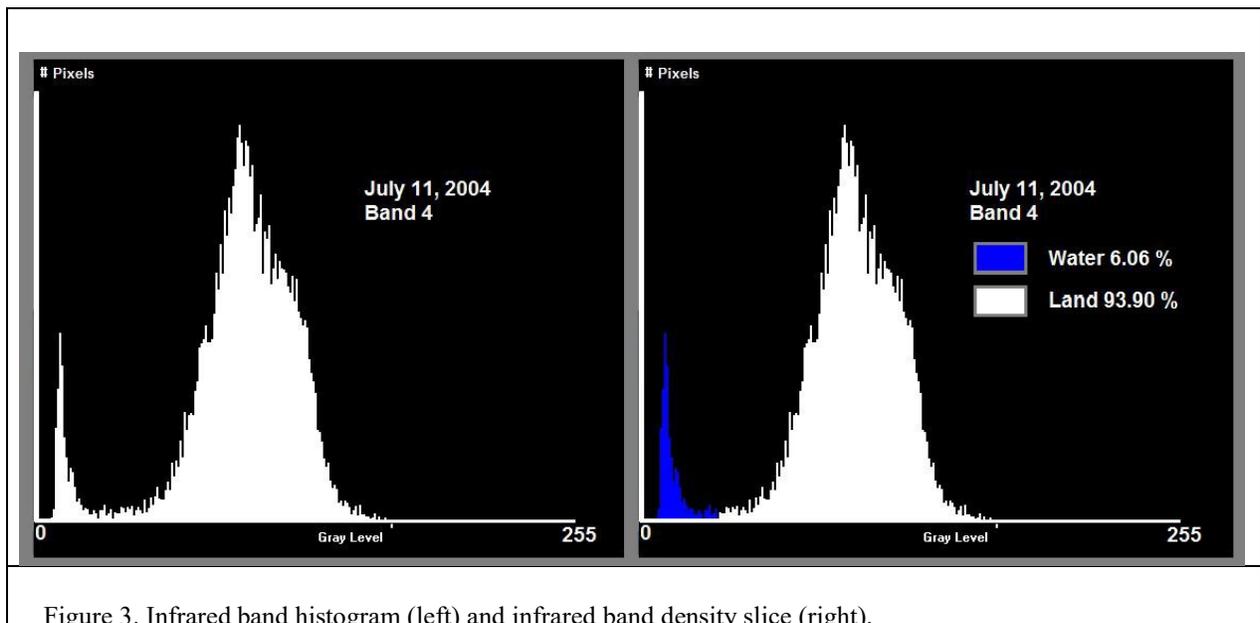
Mexico and Arizona. Each of these known megadroughts lasted longer than the current megadrought has, at least thus far. Archeological records show that the last two megadroughts experienced depopulation and outmigration issues.

## METHODOLOGY

Three Landsat 5 Thematic Mapper (TM) data sets were used in this study. The first data set was recorded on October 18, 1999. The drought started in the fall of 1999. After five years of above average mountain snow Lake Powell in the summer of 1999 was near 100 percent capacity but the below average snowfall in the autumn of 1999 indicated that the reservoir was likely to experience a drought in 2000. The second and third data sets were acquired on July 11, 2004 and July 9, 2009, respectively. These July data sets relate to the middle of the summer period when the reservoir has received the bulk of the snow melt down from the surrounding mountains. Also, the five year interval of 1999-2004 was a period of exceptional decline in water inflow into the reservoir. The reservoir had dropped 100 feet during this time span and in 2004 it was at its lowest level since the filling process started after the construction of the Glen Canyon dam. The 2009 data set was selected to determine the reservoir's water level at the end of the second five year span of the drought. These three data sets were cropped into subsets that covered the same geographic area and the lower portion of the reservoir. Figure 1 identifies the lower portion or study area.

A Landsat TM data set has seven bands (images), three reflective bands in the visible area of the electromagnetic spectrum, three reflective bands in the infrared area, and one thermal infrared band. A data classification method known as density slicing was used in conjunction with the near infrared bands of the three data sets. Density slicing divides the grayscale values associated with a black-and-white image into intervals, or slices, and assigns colors to the intervals. The intervals relate to different land and water surface classes. The image processing software package employed in this study was EarthScenes. This package not only slices an image into intervals or classes it also counts the number of pixels (picture elements) in each interval making it possible to determine the amount of area covered by a surface class.

Using the three TM visible spectral bands, true color composites were made for the subsets. Next, the density slice classification technique on the near infrared spectral band was used to separate water surfaces from land surfaces. Infrared shows water as being very dark and provides a very distinct pattern on a histogram showing the band's water concentration. Figure 3 is the histogram for the 2004 near infrared band. The horizontal scale relates to the pixel data range, which corresponds to a computer 8-bit byte. A data value of "0" is pure black and "255" pure white on the grey scale. The vertical scale shows the number of pixels for each data number on the horizontal scale. The peak toward the lower dark end of the grey scale in Figure 3 (left) illustrates the classical water pattern associated with a near infrared image. Figure 3 (right) shows where the histogram was sliced into two classes, water and land. A pixel count was recorded for each class. The slice point between the water and land classes was determined by ascertaining the pixel values at several different locations along the edge of the reservoir based on the near infrared image. This process created three classified image files, one for each data set.



*Lake Powell Megadrought: Image Simulation*

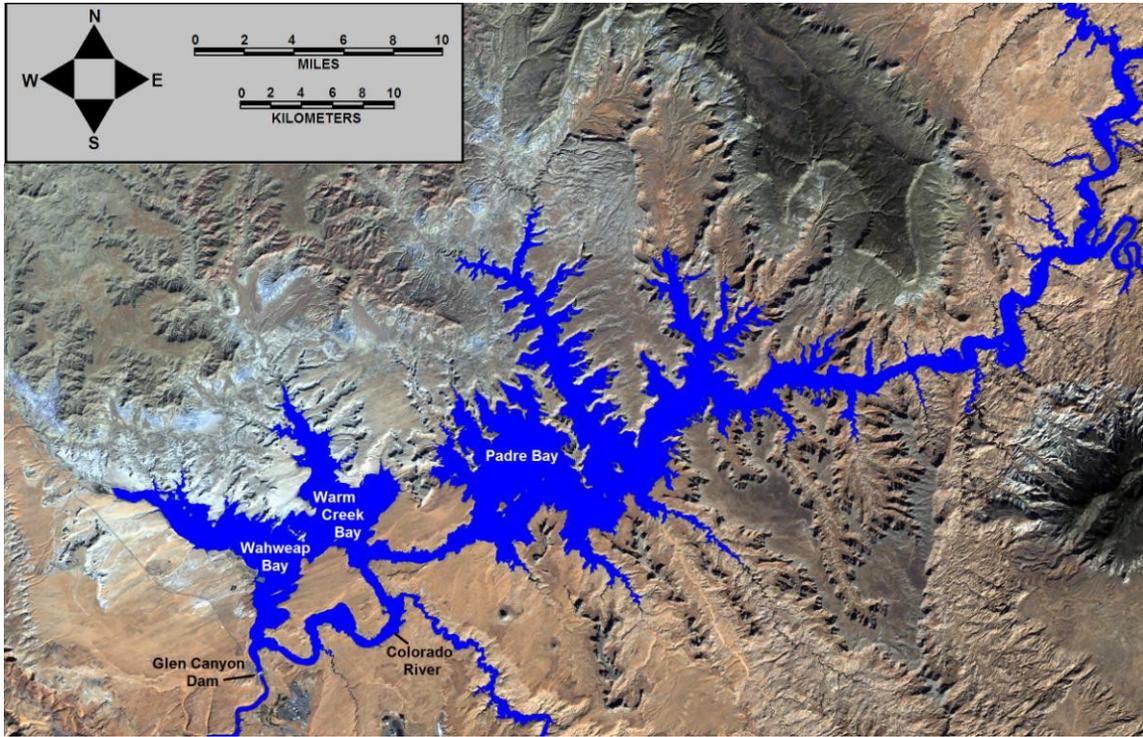


Figure 5. Lake Powell water surface October 18, 1999.

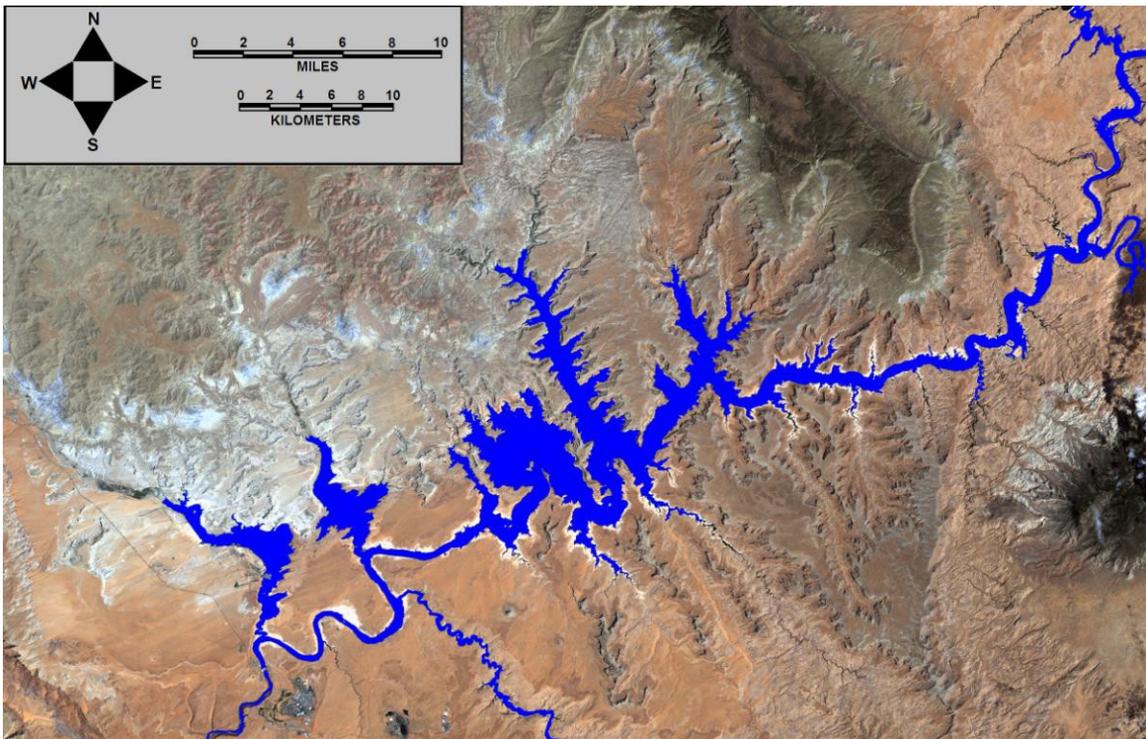


Figure 6. Lake Powell water surface, July 11, 2004.

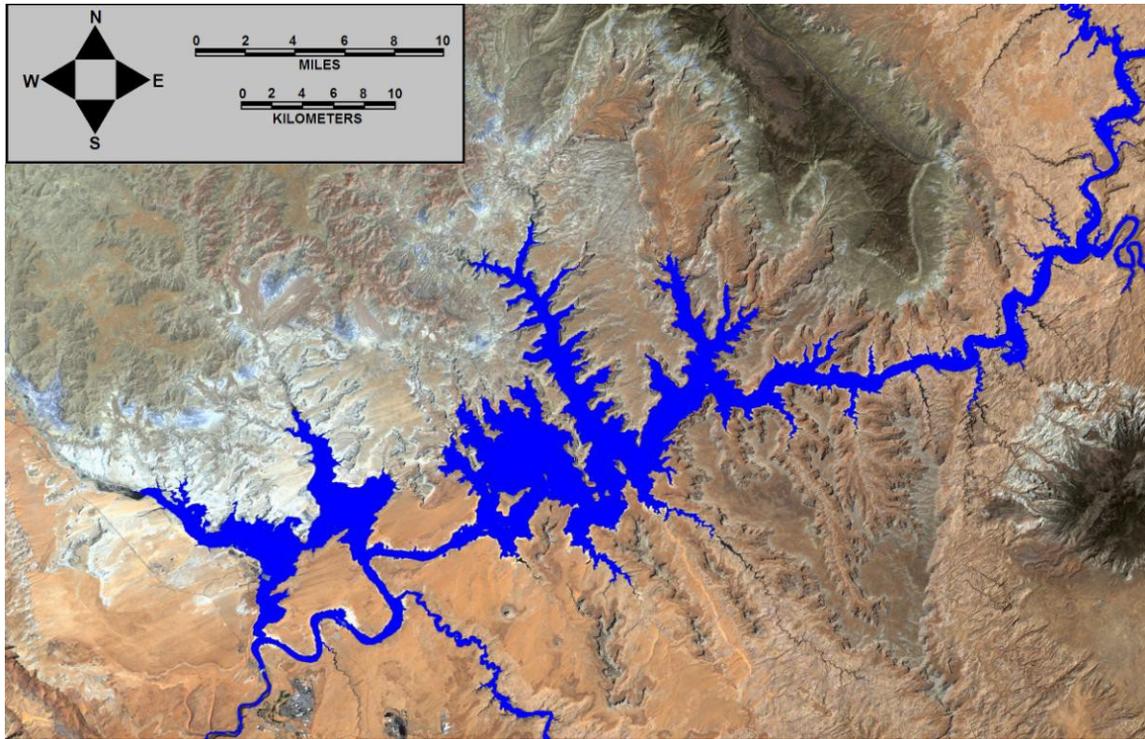


Figure 7. Lake Powell water surface, July 9, 2019.

Table 1. Water Surface Area Data

	<b>October 18 1999</b>	<b>July 11 2004</b>	<b>July 9 2009</b>	<b>Simulation 2009</b>
Number of Pixels	358,704	210,191	278,874	136,438
Number of Acres	79,774	46,745	62,020	30,343
Number of Hectures	32,283	18,917	25,099	12,279
Square Miles	124.64	73.04	96.90	47.41
Square Kilometers	200.59	117.54	155.94	122.79

## ANALYSIS

Figure 5 shows the amount of water surface in the lower portion of Lake Powell in October 1999. A continuous water surface existed between Wahweap Bay and Warm Creek Bay and a full Colorado River exhibited no sand bars. By July 2004 (Figure 6) the water surface had dropped 42 percent in comparison to 1999. A large land bridge existed between Wahweap Bay and Warm Creek Bay and the only way to get from one bay to the other bay was by the Colorado River. Sizeable sand bars can be detected along the river. A large land body appeared in Padre Bay, extending almost the entire width of the bay. The entire lower reservoir had shrunk considerably within the five year period of 1999 to 2004. The data in Table 1 confirm this shrinkage. In July 2009 (Figure 7) the water surface had increased by 25 percent in relationship to July 2004. A pathway between the two bays now existed again and the number of sand bars along the river had declined but the lower reservoir was still well below its 1999 level.

After 2009 Lake Powell slowly rebounded by about 70 feet (21.34 m) from 2008 to 2011; dropped by 60 feet (18.29 m) between 2012 and 2013; rose by about 40 feet (12.19 m) in 2014; and dropped again in 2017 by 64 feet (19.51 m). The Lake Powell Water Database shows that as of March 2019 the reservoir was at its lowest level in the last twenty years. Its elevation was 3574.82 feet (1089.61 m). Some of the up and down variation in the data is due to increased demand by Lake Mead that has also been impacted by the megadrought. Lake Powell was designed to maintain a certain water level in Lake Mead. With all of these variations in Lake Powell's water level the lake is nowhere near full capacity as it was in 1999. It will take at least a decade of large mountain snowfalls to start the process of moving the lake back to full capacity. Such an event might occur but based on the precipitation records over the last twenty years it appears unlikely for the near future. The reservoir's inflow of water versus its outflow is not moving the lake toward full capacity.

## IMAGE SIMULATION

Between 1999 and 2004 Lake Powell's water surface dropped 41.4 percent or 8.28 percent per year. Using the 8.28 percent annual decrease rate, the reservoir's size was calculated for each year from 2005 to 2009. This mathematical calculation has the reservoir's water level dropping by another 136,438 pixels: 30,342.98 acres (12,279.37 ha) or 47.41 square miles (122.79 sq. km.). Employing this pixel count a density slice classification followed by a 3 x 3 matrix convolution was conducted again on the 2004 image but rather than slicing out all of the water as shown in the Figure 4 histogram, only the lower portion of the water was sliced. This process created a pixel count of 136,076: 30,262.48 acres (12,246.79 ha) or 47.28 square miles (122.45 sq. km.). The upper portion of the water on the histogram was sliced into several small classes and each of these classes was assigned a land color in order to cover the remaining water areas shown in the 2004 image. This process resulted in the image shown in Figure 8, an image simulation of what the reservoir might have looked like if the 1999-2004 decrease had continued another five years to 2009. The major bays that were linked together now stand as separate lakes and the river does not exist over much of its course. The difference between the mathematical calculation and the image simulation was 362 pixels or .00265 percent.

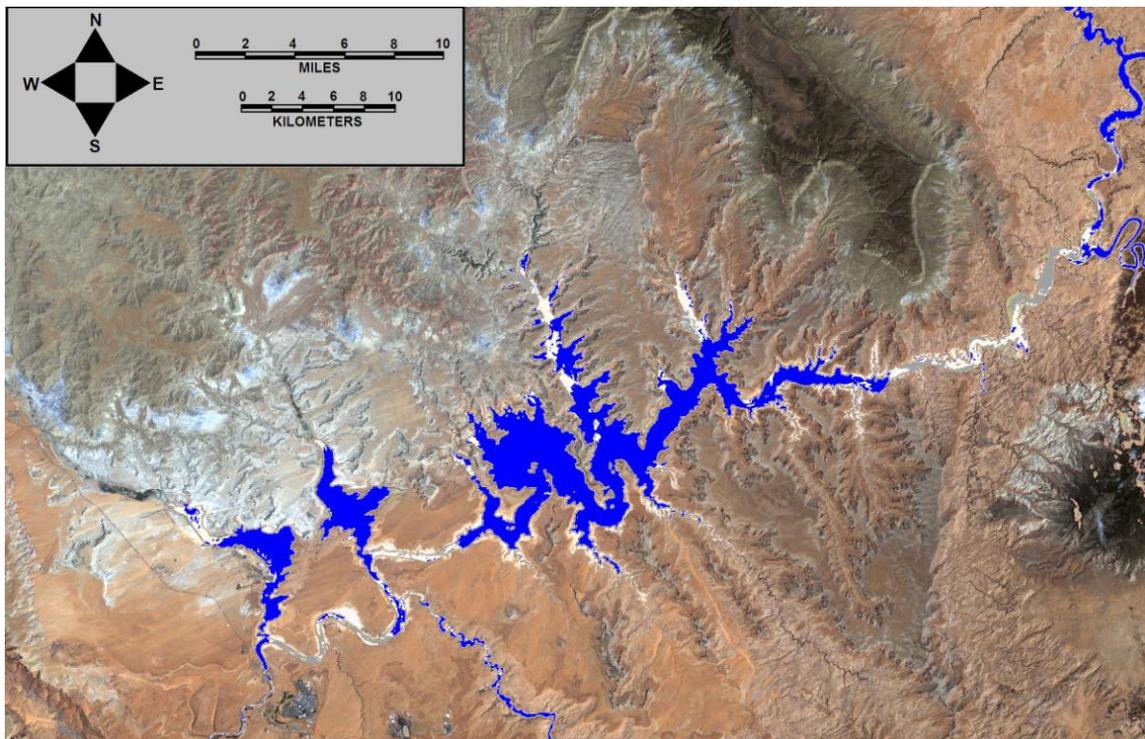


Figure 8. Image simulation of Lake Powell, 2009.

An ongoing study is being conducted by the State of Colorado's Colorado River District to determine what will occur if the water level in Lake Powell drops below certain levels. The district working in conjunction with the other water districts in the Upper Basin is concerned that if another 1999-2004 type drought occurs during this drought period, Lake Powell might become effectively empty as the simulation indicates. If a drought pushed the lake below 3,525 feet (1,074.42 m), almost 175 feet (53.34 m) below its maximum level, the other Upper Basin reservoirs would be required to deliver more water to Lake Powell in order for the Upper Basin to maintain its legal obligations to the Lower Basin and Mexico. This step would start the process of draining the other reservoirs that are also at low levels. It is not known how long this draining process can be maintained if the megadrought continues. Also, these reservoirs provide water to Upper Basin users who would have to reduce their water consumption.

In 2007 Eric Kuhn, General Manager of the Colorado River Water Conservation District, stated that "At 3,490 feet (1,063.75 m) power production at the (Glen Canyon Dam) dam will have to be terminated due to lack of water pressure to turn and cool the turbines. Also, the turbines could be damaged if oxygen started mixing with water, a cause known as cavitation. Without the revenue generated from the dam's power production, funds to pay for programs such as the endangered fish recovery, controlling salinity in the basin, and management of flows through

the Grand Canyon will be jeopardized. Also if not enough water can be released through the power plant, the water will have to be diverted through the bypass tubes but these tubes are not large enough to handle the required downriver delivery.” Using the water levels recorded on October 18, 1999 and July 11, 2004, dates that correspond to the first two Landsat data sets, it was determined that the water level for the image simulation would have been 3,479 feet (1,060.40 m). Thus, Lake Powell could no longer produce electricity (Gardner-Smith, 2016)

Although this simulation was designed to determine the reservoir’s water level after the five year period ending in 2009, it could be applied to any five year period during the current megadrought. Concern is growing about the future of the reservoir if the megadrought continues. The Colorado River District study has generated in the local and environmental news media such headlines as “Study: Drought like 2000-2006 would empty Lake Powell” (Davis, 2016), “Lake Powell could dry up in as little as six years, study says” (Gardner-Smith, 2016), and “Should Iconic Lake Powell Be Drained?” (Patterson, 2017).

## SUMMARY/REMARKS

The graphs presented on Figure 2 illustrate that Lake Powell is experiencing the current Southwest megadrought. Previous megadroughts within the region have lasted much longer than the current megadrought, suggesting that the region might have several more dry decades. Two of the earlier megadroughts brought about depopulation and outmigration within the Upper Basin. How will current populations within the region react if the present megadrought continues for several more decades? Figures 5 and 6 illustrate the dramatic drop in the reservoir’s water surface during the five year period associated with the beginning of the megadrought. Although considerable variation in the height of the reservoir’s water surface has occurred over the past two decades, Figure 7 provides an average view of the reservoir during this period. Figure 8 shows through a simulation what Lake Powell’s water surface might look like if another five year drop would occur. Great concern exists that such a drop might occur.

Local and state governments depending on Colorado River water are trying to address the issue of a potentially severe megadrought. Since multi-states are involved and the dams and reservoirs are controlled by the Federal Government, the Federal Government is the political body that needs to be proactive in developing a plan to handle this situation. Even if a severe megadrought does not materialize, the continuing demographic and economic growth in the region will place demanding strains on the available water resources. Some Federal agencies are examining and discussing the Southwest drought but no comprehensive regional policy has been formulated. The 1922 Colorado River Compact is out of date and needs to be revisited using current conditions.

Paleoclimatologist Edward Cook, director of the Tree Ring Laboratory at Columbia University’s Lamont-Doherty Earth Observatory in Palisades, N.Y., stated at a recent American Geophysical Meeting that the current Western megadrought might not be a product of human-caused climate change and could be just a natural event. “It’s tempting to blame radiative forcing of climate as the cause of the megadrought,” Cook said. “That would be premature. Why? There’s a lot of variability in the system that still can’t be separated cleanly from CO<sub>2</sub> forcing on climate. Natural variability still has a tremendous impact on the climate system.” (Magill, 2017) From the perspective of trying to motivate the appropriate political forces to develop a new regional water policy for the dry West, it might be desirable to separate the issue from the current debate about CO<sub>2</sub>. A problem exists; the cause(s) of the problem is unclear. Thus, address the problem rather than the cause(s). By the time the cause(s) is determined, it might be too late to address the problem.

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