Annual Snowpack Effect on Lake Powell

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CE 394K.3 GIS in Water Resources

Introduction

The proper study and management of the Colorado River is key to the sustainability of the American Southwest. The Colorado River serves as the main water supply for more than 30 million people and millions of acres of agriculture across seven states and Mexico. In addition to supplying water, the river serves as a major tourist attraction and hydroelectric power source. The resiliency of the water source is brought into question as increasing population and climate change continue to strain the river[1].

Traditionally, in periods of low precipitation, the reservoir capacity would be utilized to meet water demands. However, following years of drought and continued lower than average reservoir levels, it becomes increasingly important to understand the sourcing of the water in this watershed. The Upper Colorado River Basin sources 90% of the water in the Colorado River, with 50% coming directly from snow melt. This statement highlights the importance of understanding the impact snowpack levels on the entire Colorado River Basin[2].

The objective of this report is to estimate the amount of snowpack is required annually to ensure no elevation loss in Lake Powell and to observe relationships between snowpack and reservoir storage. This estimation will be completed using Snow Water Equivalent (SWE). SWE is the amount of water in the snowpack. It is the theoretical depth of water if the entire snowpack was melted instantaneously. SWE is calculated by multiplying the snow depth by the density. Typical density values range from 10-40%[3].

Figure 1: Image of Lake Powell taken from Glen Canyon Dam. Note the banding along the shoreline due to decreased water levels.[8]

Initial Research

The preliminary hypothesis of the project was that there should be a linear relationship between snowpack levels in the Upper Colorado River Basin and the storage in Lake Powell. In years of above average snowfall, the elevation of the surface of Lake Powell would rise and in years of below average snowfall, the surface elevation would decrease. However, the relationship is not as linear as one would imagine as the U.S. Bureau of Reclamation maintains 28 reservoirs in the Upper Colorado River Basin. In this report, two types of inflows may be referenced, unregulated and regulated. Regulated flow consists of all types of flows, virgin river flows, runoff, and outflows from other reservoirs, while unregulated flow doesn't account for dam releases or other human interference.

While researching this project, many news articles appear at the top of the search results. Most of them share the similar theme, something along the lines of "Lake Powell at Lowest Level in Recent History" drawing attention to the severity of the issue. These headlines create the questions, are these headlines true, why are these water levels at such lows?
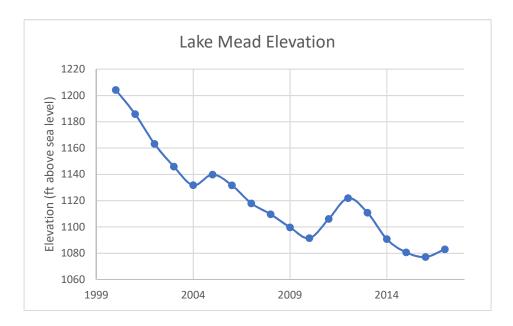

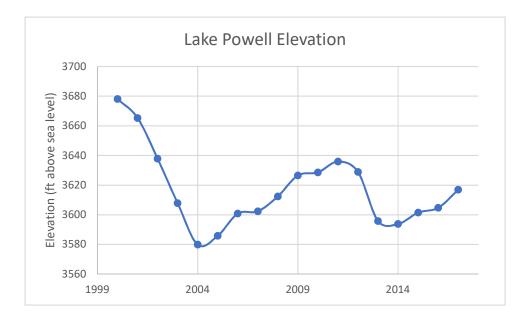**Figure 2: Change in Lake Mead Surface Elevation from 2000-2017[4]**

Figure 3: Change in Lake Powell Surface Elevation from 2000-2017[5]

Based on these two plots, there has been a decrease in water levels of both Lake Mead and Lake Powell since 2000. In Lake Powell alone, this decrease amounted to 8.67 million acre-feet of water. But what is causing this change? This change appears to be caused by several factors including climate, development and snowpack. However, in the Colorado River Compact of 1922 and The Mexican Water Treaty of 1944, 16.5 million acre-ft of water are allocated annually between the Upper Colorado River Basin, Lower Colorado River Basin and Mexico. It has been researched and proven that the Colorado River Basin can only supply approximately 14.5 million acre-ft annually. Additionally, many factors have changed since the creation of these treaties which require review for sustainable water resource management.[6]

Climate

The image below shows the current drought map of the United States as of late November. As seen, the seven states that make up the Upper and Lower Colorado River Basins all are currently experiencing drought conditions. Per the Upper Colorado River Commission, the Upper Colorado River basin has been experiencing drought conditions since 1999.[7]
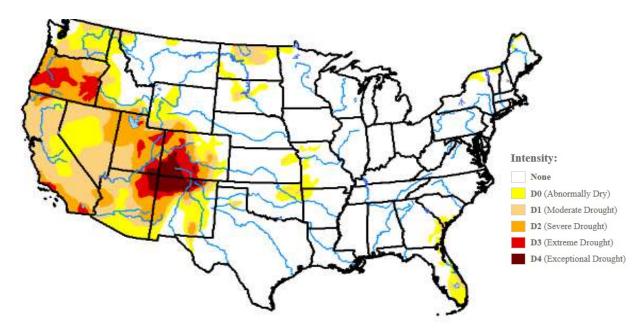

Figure 4: Drought map of the Continental US as of 27-Nov-18. Provided by The National Drought Mitigation Center, University of Nebraska.

Land Cover and Population Dynamics

In addition to drought conditions. Development and population dynamics seem to contribute to increased water usage. Information was sourced from USGS and compared between 2006 and 2011. A cell size of 30m was used. The Lower Colorado River Basin was used for this analysis due to evidence of stronger population trends in this area.
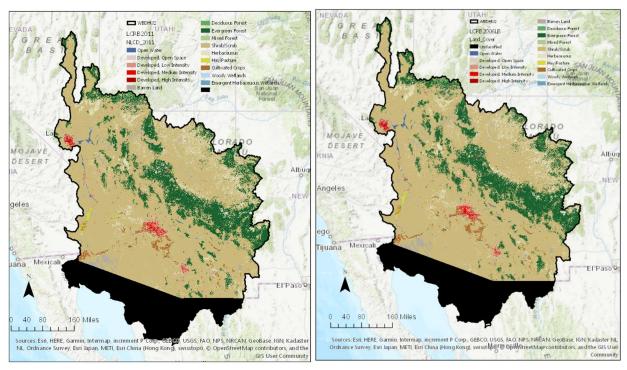

Figure 5: 2011 and 2006 National Land Cover Data obtained from USGS.

Between 2006 and 2011 there were some noticeable changes in the land cover. There was an increase of approximately 350km² of developed land, a decrease of 90km² of agricultural land, and a decrease of 50km² of open water. The large increase of developed land is indicative of a significant population change and therefore more water consumption. As expected, there was a decrease in the open water in the Lower Colorado River Basin. A decrease in the agricultural land was surprising but could be attributed to previously existing drought conditions. These results can be viewed in the below table.

	Developed Land (sq km)	Agriculture (sq km)	Open Water (sq km)
2011	8375.20	5872.01	1051.54
2006	8024.35	5961.90	1100.08
Change	350.85	-89.89	-48.53
Percent Change	4.37	-1.51	-4.41

Figure 6: Table of Changes between 2006 and 2011

The City of Las Vegas experienced rapid population growth in that late 1900's and early 2000's. Though the water usage has remained relatively constant at approximately 500,000 acre-ft annually since 2000, this continued draw from the reservoirs is only one example of many as population shifts towards the southwest United States. This increased water consumption is another contributing factor towards decreased water storage since 2000.
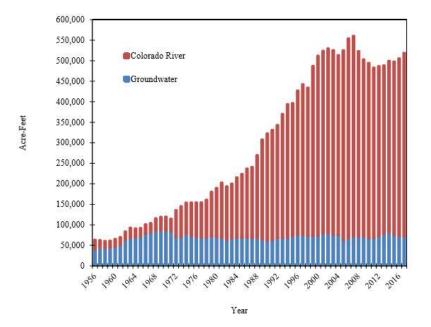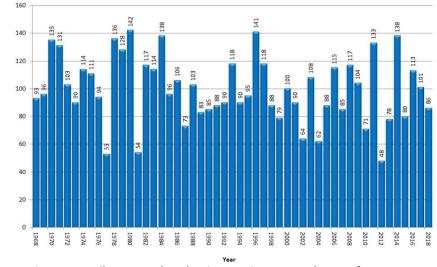

Figure 7: Las Vegas Valley Water usage. Data taken from water.nv.gov.

Snowpack

Looking at the data below, it shows that there seems to be a slight decline in snowpack in the Upper Colorado River Basin. The first plot uses a median instead of an average, this is beneficial as it discards outliers. Averaging the data since 2000, it shows that the Upper Colorado River Basin has only achieved 94% of the median snowfall. This is potentially contributing to decreased storage in Lake Powell. The month of April was chosen for this plot as the snowpack typically peaks around April 10-15th.

Figure 8: April Upper Colorado River Basin Snowpack. Data from USDA.

This next plot shows the percent average of the SWE from 2013 to 2018. Data from 2013, 2015, and 2018 show below average years, while 2014 and 2016 appear to be average and 2017 is above average. This plot also shows that in the last few years snowpack has usually been average or below average with three of six years below average.
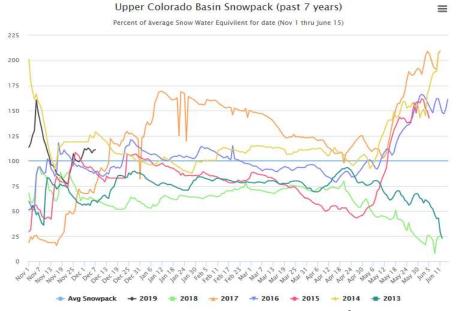

Figure 9: Upper Colorado Basin Snowpack based on percent of average SWE.[9]

SWE and Stream Gage Correlation

      The first step was to plot the Upper Colorado HUC2 Region and then plot the HUC4 Subregions to divide it into useable sizes. One SNOTEL site was picked for each HUC4 Subregion to see if any spatial variation existed. In the future, for a full analysis, more sites should be used.
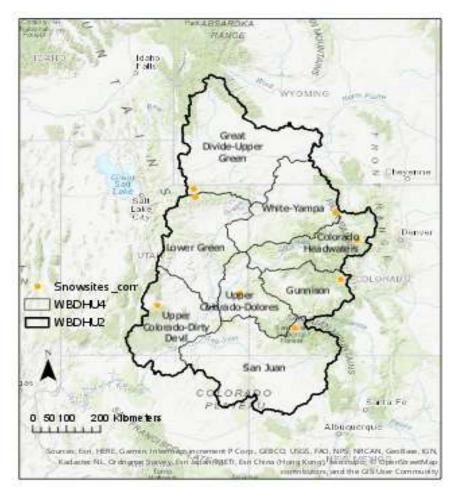

Figure 10: Location of SNOTEL sites

SNOTEL sites:

1401-Rabbit Ears, Colorado Headwaters

1402-Cascade, Gunnison

1403-Lasal Mountain, Dolores

1404-Five Points Lake, Upper Green

1405-Steel Creek Park, White-Yampa

1406-Summit Ranch, Lower Green

1407-Donkey Reservoir, Dirty Devil

1408-Park Cone, San Juan

The below image represents the unregulated inflow into Lake Powell from 2000-2017. This data was gathered from the Upper Colorado River Basin Commission. SNOTEL data from the USDA for each site exists in plot form for 2014-2018 so those years will be focused on. In the interest of space, data from only two SNOTEL sites is included. Based on the Unregulated Inflow, it appears that in both 2014 and 2017, there should be near or above average levels of snowpack.
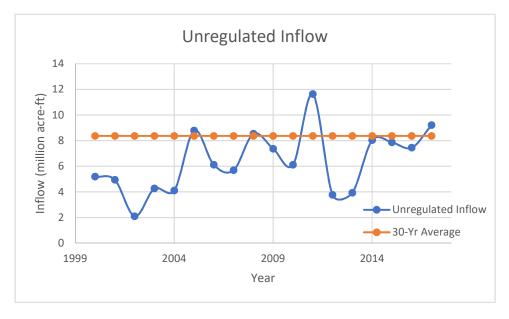

Figure 11: Lake Powell Unregulated Inflow 2000-2017

Analyzing the change in monthly elevation, it appears that 2014 and 2017 should have higher levels of snowpack than 2015 and 2016, based on the steepness and length of the incline slope. This plot also shows that there could be a below average snowpack for 2018.
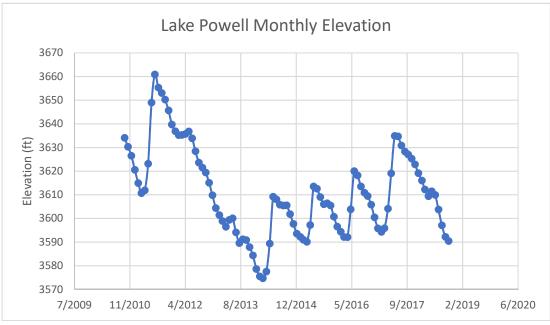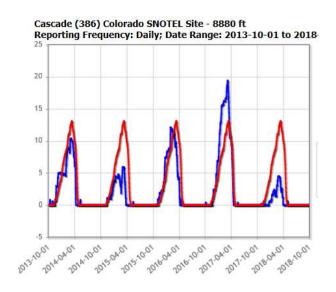

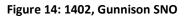**Figure 12: Lake Powell Monthly Elevation 2010-2018**

Though not all attached to this report, all eight SNOTEL sites show below average readings for 2018., corroborating what is seen on the elevation plot. Across the entire Upper Colorado River Basin, 2018 did not provide much snow, and it makes sense that SNOTEL and Lake Powell Elevation agrees. Similarly, 2017 provided a lot of snow for the area, and seven of the eight SNOTEL sites showed above average readings which agreed with the monthly elevation and unregulated inflow plots. However, 2014, 2015, and 2016 all seem to be average years, and many more SNOTEL sites would be needed to determine whether it was an above or below average year as there is a mix of sites, both above and below average.

Drawing from this analysis, it can be seen in years with high deviation from the average, either above or below, it might be possible to make hydrologic assumptions with only a few SNOTEL sites. With smaller deviations from the average, it takes a much wider data set to see if the year was above or below average. It is difficult to predict trends within the Upper Colorado River Basin due to the high geographic and hydrologic variability.

Rabbit Ears (709) Colorado SNOTEL Site - 9400 ft
Reporting Frequency: Daily; Date Range: 2013-10-01 to 2018-

Cascade (386) Colorado SNOTEL Site - 8880 ft
Reporting Frequency: Daily; Date Range: 2013-10-01 to 2018-

Figure 13: 1401, Colorado Headwaters **Figure 14: 1402, Gunnison SNO**

It was initially hypothesized that there would be a linear relationship between storage in Lake Powell and snowpack. However, the Colorado River is an extremely complex water resource. Though SNOTEL sites may be able to predict how much water will be entering a reservoir through SWE, we don't know the demands of other areas in the watershed. It appears that the average outflow is a function of the regulated average inflow and is difficult to predict around precipitation because it includes releases from other reservoirs. Lake Powell is used to fill Lake Mead, and the 28 other reservoirs in the Upper Colorado Basin are metered to ensure Lake Powell is filled and provide some drought stability to the Lower Colorado Basin. Though snowpack plays a key part in the storage of Lake Powell there is no linear relationship, as the storage of Lake Powell is a function of the regulated inflow.
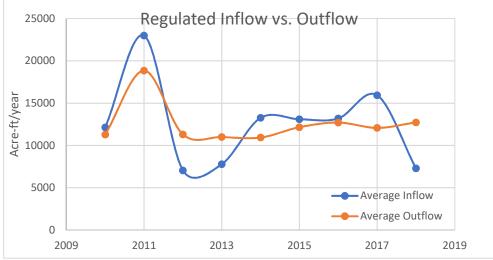

Figure 15: Regulated Inflow vs. Outflow

Lake Powell

Using the elevation from June 2011, the extent of Lake Powel was plotted using the Raster Calculator. All values beneath the surface elevation were exported as a raster to show the surface area and extent of Lake Powell at such a high surface elevation.
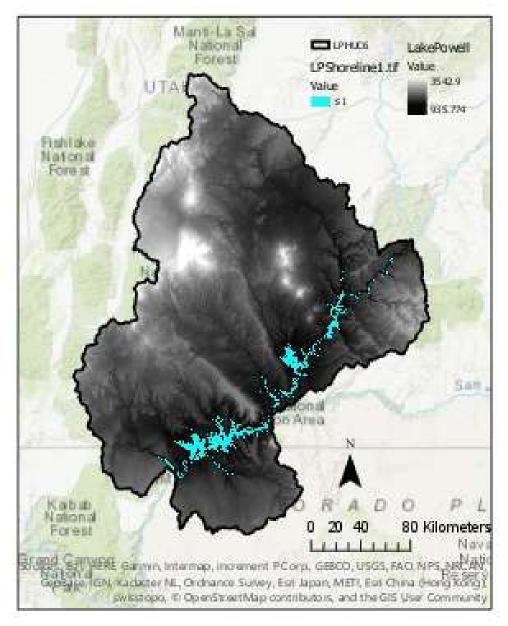

Figure 16: Lake Powell at peak, June 2011

The Surface Volume tool was used to calculate the volume using the DEM to compare against the data online to see if there were any differences, However, in this instance, using the Surface Volume tool calculated a value between 5-7 times smaller than the actual data online.

Data Analysis

The drainage area of the Upper Colorado region is 293,569km² or 72,542,421 acres, and snowpack contributes to 50% of the flow of the Colorado River. From the 69th Annual Report of the Upper Colorado River Commission, the average annual unregulated inflow into Lake Powell is 8.37 million acre-ft. If the average unregulated flow is 8.37 million acre-ft, then snowpack contributes 4.185 million acre-ft a year of water.

To determine how much SWE was necessary to meet this goal, the Upper Colorado HUC2 Region was divided into its 8 HUC4 Subregions. Due to computing memory restrictions, they were mosaiced into their HUC 4 Subregions instead of the HUC2 Region. USGS 1/c arc-second DEMs were used and converted to the NAD 1983 2011 Contiguous USA Albers with 30m cell size. The DEMs were then filled.
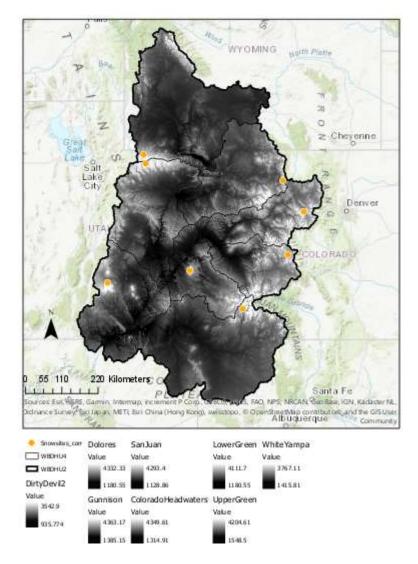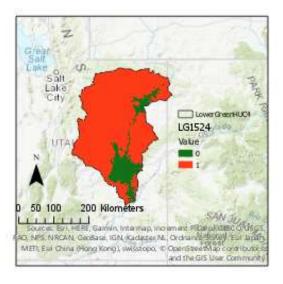

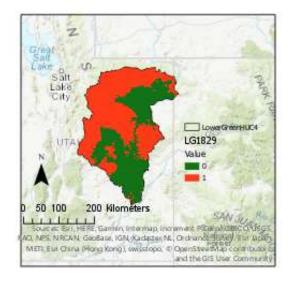**Figure 17-Filled DEM of Upper Colorado HUC2 Region**

The DEMs were then individually analyzed by each HUC4 Subregion. As an example, the Lower Green Subregion is analyzed in the figures below. To accomplish this analysis, it was necessary to find the surface area above several different elevations as the exact elevation of the contributing snowpack varies. The desired unregulated inflow of 4.185 million acre-feet is then divided by this calculated surface area. This amount equals the average SWE value for the surface area above that selected elevation to achieve the desired inflow.
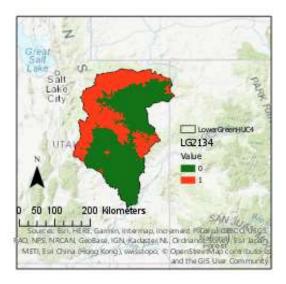
For example, if above an elevation of 2000ft, there was a contributing area of 72.5 million acres and a desired volume of 8.23 million acre-ft, the SWE could be calculated by dividing 8.23 million acre-ft by 72.5 million acres. This results in a SWE of 0.11 ft, or 1.35 inches, across all surface area above 2000ft of elevation locations for the desired unregulated inflow.

The Raster Calculator tool was utilized to determine the number of cells above each input elevation. Once the number of cells was determined, the area above each elevation was calculated. Five elevations were chosen: 1524m (5000ft), 1829m (6000ft), 2134m (7000ft), 2434m (8000ft), and 2743m (9000ft). Multiple elevations were chosen because the contributing snowpack elevation will vary year to year, and most of the SNOTEL sites are between 8000ft and 10000ft. In the images below, the red cells are the cells above the input elevation and green cells are below the calculated elevation.

Several assumptions were used in these calculations. The first assumption is that there was no contributing snowpack beneath these chosen elevations. Secondly, it was assumed that all snowpack above the chosen elevation contributed directly towards the unregulated flow in the Colorado, rather than accounting for melting, infiltration or storage in another waterbody.

Figures 18-22: Raster Calculations of Lower Green HUC4 from 5000ft -9000ft above sea level.

Looking at the images above, as the elevation increases, the number of red cells decreases, meaning there is less contributing surface area at higher elevations.

After finding the number of cells above each elevation, they were converted into an area in acres, seen in the table below.

	Col. Headwaters	Gunnison	Dolores	Upper Green	White-Yampa	Lower Green	Dirty Devil	San Juan
5000ft	6028212	5075624	4496482	13283698	8392489	7952694	6463529	14702023
6000ft	5548895	4578514	3494677	13172927	7500570	5329997	3620461	9698302
7000ft	4853981	4122791	2186405	6745451	3771076	3617812	1661035	4075408
8000ft	3886340	3455616	1284231	2052202	1641282	2162163	948770	1690602
9000ft	2557856	2346604	595150	1012480	713869	1034561	442659	1005487

Figure 23: Shows the area in acres of each HUC4 above the calculated elevation.

This area was then summed between all the HUC4 Subregions at each individual elevation. The unregulated inflow was then divided by the sum at each elevation, to find the average SWE. In this case the answer was multiplied by 12 to convert to inches. It was calculated that it would take a SWE of 0.76 inches across all area above 5000ft to meet the desired unregulated inflow. For the area above 9000ft, it would take 5.17 inches of SWE. To calculate the depth of snow, the SWE can be divided by the density. However, these values seem very low.

Sum	Acres	Unreg Inflow (acre-ft)		SWE (in)	Powder 10% (in)	Spring Snow 40% (in)
Above 5000ft	66394751	4185000	SWE 5000ft	0.76	7.56	1.89
Above 6000ft	52944342		SWE 6000ft	0.95	9.49	2.37
Above 7000ft	31033960		SWE 7000ft	1.62	16.18	4.05
Above 8000ft	17121207		SWE 8000ft	2.93	29.33	7.33
Above 9000ft	9708665		SWE 9000ft	5.17	51.73	12.93

Figure 24: Shows the Sum of the acres at each elevation and the SWE values.

Analysis and Conclusion

Snowpack plays an important role in the Colorado River Basin. However, equally important are climate change, drought and population dynamics. Based on the high levels of human interference, with dams and reservoirs, there is no linear relationship between snowpack and the storage of Lake Powell. In years of above average snowpack, the storage does increase, but it is usually accompanied by above average outflows to assist other areas in the basin still struggling with drought.

The calculated SWE values of 0.76 through 5.17 seem artificially low as most SNOWTEL gages get more than 12-24 inches of SWE in the Upper Colorado River Basin. I believe they are low for a few reasons. First, my model accounts for no loss, and assumes all snow instantaneously melts and contributes to the Colorado River without evaporation. Most SNOTEL gages are at 8000ft to 1000ft, so I could have continued calculations at higher elevations to see if answers were more reasonable. However, operating with so many assumptions, it would have been difficult to get close to an accurate answer. Converting to higher resolution data, incorporating evaporation, infiltration with a higher processing ability would also improve these results.

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