Lake Tahoe

Response to 2016-2017 Winter Rain Events

CE 394K – GIS in Water Resources
Fall 2017
University of Texas at Austin

PREPARED FOR

Dr. David Maidment
University of Texas at Austin

Dr. David Tarboton
Utah State University

PREPARED BY

Joel Lagade Jr., EIT
University of Texas at Austin | CAEE - EWRE

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLOTS

APPENDICES

ACRONYMS/ABBREVIATIONS

amsl	above mean sea level
bgs	below ground surface
cfs	cubic feet per second
°F	degrees Fahrenheit
DM	Drought Monitor
HUC	Hydrologic Unit Code
LA Times	Los Angeles Times
NLCD	National Land Cover Dataset
NHDPlusV2	USA National Hydrography Dataset Plus Version 2
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRCS	Natural Resources Conservation Service
SNOTEL	Snow Telemetry
sq-mi	square miles
USDM	United States Drought Monitor
USGS	United States Geologic Survey

EXECUTIVE SUMMARY

California has experienced one of its most severe and prolonged droughts from December 2011 to October 2016. According to the United States Drought Monitor (USDM), approximately 90 percent of California was in a drought from 2013 to 2016. At its worst, more than 60 percent of California was experiencing at least a level of Extreme Drought D3 forcing Governor Jerry Brown to declare a drought state of emergency in January 2014 (See Figure 1; United States Geologic Survey (USGS), 2017). Governor Brown ordered a 25% reduction in urban water use enforcing people to take shorter showers and replanting of their lawns. This forced California to rely heavily on groundwater and inevitably create its first groundwater regulations and laws. The last prolonged drought of similar magnitude and policy change was from 1987-1992 when California responded by building several reservoirs (Los Angeles Times (LA Times), 2017).

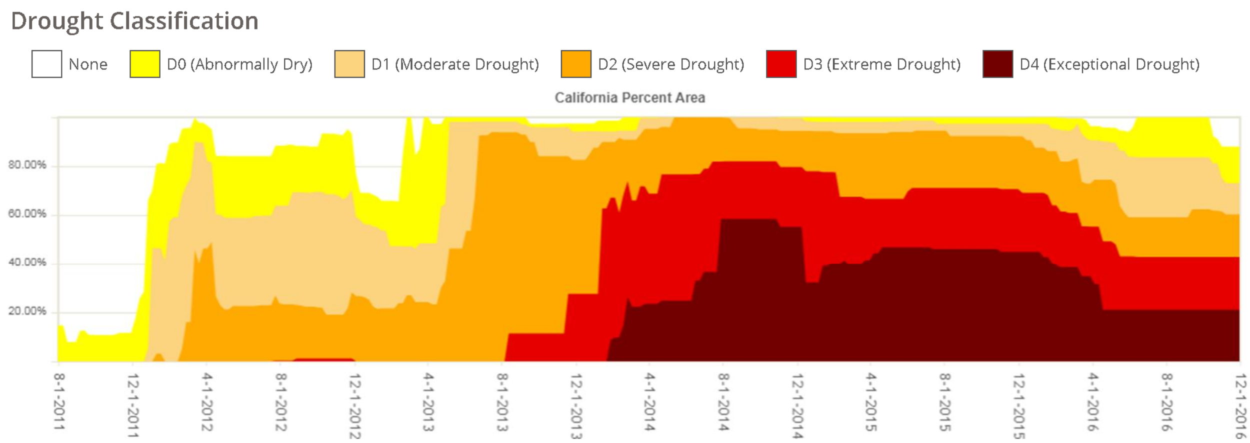


Figure 1 – Percent Area Time Series of California Drought 2011-2017 (USDM, 2017)

During the 2011-2016 drought, California fell to historic hydrologic lows due to the amount of precipitation and snow that did not fall. This was particularly evident in the Northern Sierra 8-Station precipitation index and the recorded California Snow Water Content, which the former measures the precipitation of the Sacramento River Watershed – a major component of the state's water supply. Since 1966, the Sacramento River Watershed has received a maximum daily average of 51.8 inches of precipitation a year and California as a whole recorded a maximum daily average of 100 inches of snow water content a year. However, from December 2011 to October 2016, the Sacramento River watershed dropped to a maximum daily average of 37.2 inches of precipitation and the State of California recorded its lowest maximum daily average of approximately 20 inches of snow water content in the driest and warmest year on record, 2014-2015 (Appendix A; California Department of Water Resources, 2017).

The Lake Tahoe Watershed, located in the Sierra Nevada, was no different and exhibited extremely low conditions from the end of 2011 through 2016. This was determined by disseminating data from active USGS gage and Natural Resources Conservation Service (NRCS) – Snow Telemetry (SNOTEL) stations. In the seven years prior to the drought (2004-2011), the Lake Tahoe Watershed received a maximum daily average of 35.7 inches in precipitation, 20.1 inches in snow water equivalent, and 68.9 inches in snow depth. The maximum daily total average mean discharge into Lake Tahoe was 2,262 cubic feet per second (cfs) and the maximum daily average lake gage height was 6.52 feet (6,226.52 feet above mean sea level (amsl)). To identify the drought frequency and severity of the Lake Tahoe Watershed, relative drought severity maps were developed utilizing the same methodology as John Nelson in his Esri ArcGIS "Five Year Drought" story map (Esri, 2017). During this time period, the Lake Tahoe Watershed averaged drought levels between Severe Drought D2 to Extreme Drought D3. From the winter of 2011 to the winter of 2016, the Lake Tahoe Watershed maximum daily averages dropped to 27.8 inches in precipitation, 9.0 inches in snow water equivalent, and 36.0 inches in snow depth. The maximum daily total average mean discharge into Lake Tahoe decreased to 1,115 cfs and the maximum daily average lake gage height decreased to 5.14 feet (6,225.14 feet amsl). The drought levels in the Lake Tahoe Watershed averaged an Extreme Drought D3 to Exceptional Drought D4 during this time.

Fortunately for Lake Tahoe and California as a whole, the historical high levels of precipitation and snow of winter 2016-2017 brought California out of the strenuous five year drought. As such, Governor Brown declared the drought state of emergency over in April 2017. The Sacramento Watershed experienced its wettest year on record with a maximum daily precipitation of 94.7 inches. The State of California recorded its second highest maximum daily snow water content measurements of approximately 160, 180, and 175 inches in Northern, Central, and Southern California, respectively (Appendix A; California Department of Water Resources, 2017). Similarly, the Lake Tahoe Watershed received a maximum average daily precipitation of 71.7 inches, water equivalent of 36.4 inches, and snow depth of 105 inches. The maximum daily total average mean discharge into Lake Tahoe increased to 4,017 cfs and the maximum daily average lake gage height increased to 8.97 feet (6,228.97 feet amsl) – short of its maximum legal gage height of 9.1 feet (6,229.1 feet amsl). Through 2017, Lake Tahoe has not averaged any drought level. This historic response to the 2016-2017 winter rain events is seen in Figure 2a-b. See Plots 1-12 and Table 2 for hydrologic measurements and Figures 12-14 for relative drought severity levels.

Figure 2a-b – Lake Tahoe Dam Before (2015) and After (2017) Photos (Truckee River Guide, 2015; Northern Nevada Business Weekly, 2017)

At the conclusion of this term project, the Lake Tahoe Watershed and the majority of California has fully receded from their drought statuses. The only portion of California experiencing the drought and/or its side effects is central and southern California. While this has been a historic year, history and Governor Brown reminds us that "…the next drought could be around the corner. Conservation must remain a way of life" (LA Times, 2017).

1.0 INTRODUCTION

1.1 LAKE TAHOE BACKGROUND

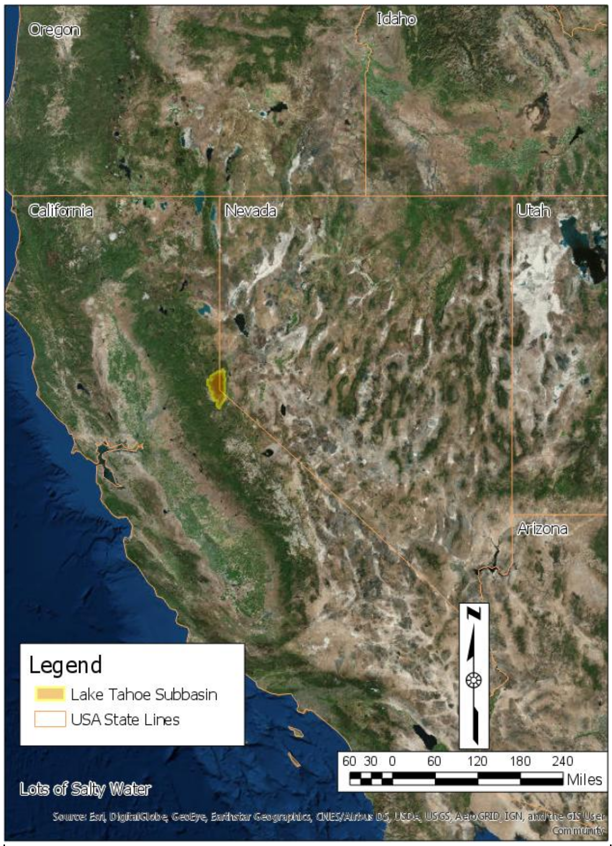


Figure 3 – Lake Tahoe Site Location Map

Lake Tahoe is located in the Sierra Nevada and is the sixth largest natural lake in the United States, behind the five Great Lakes (See Figure 3). At an elevation of 6,225 feet above mean sea level (amsl), Lake Tahoe straddles the California and Nevada state line. The surrounding Lake Tahoe watershed is approximately 314 square miles (sq-mi), which is situated in the greater Lake Tahoe subbasin (507 sq-mi). The lake itself, is approximately 21.2 miles north-south, 11.9 miles east-west, with an approximate surface area of 192 square miles. The average depth is approximately 1,000 feet with a maximum depth of 1,645 feet. Lake Tahoe can hold about 39 trillion gallons of water with a regulated variation of 243 billion gallons. The only outlet is a dam located at Tahoe City, which controls the release of water into the Truckee River. The water is reported to be 99.994% pure – versus commercially distilled water at 99.998% purity (Tahoe Fund, 2017).

Approximately 65% of the water that enters Lake Tahoe is rain and snow melt runoff from 63 tributaries within the watershed. The remaining 35% of water is precipitation that directly falls on the lake – typically 212 billion gallons of water a year. In a normal year, about one-third of the lake water flows into the Truckee River for downstream use and ultimately to Pyramid Lake in Nevada. The remaining water is lost to evaporation at an annual average rate of 0.1 inch per day or 36 inches per year. Every 24 hours about 1.4 million tons of water evaporates from Lake Tahoe, which is enough to serve 3.3 million people (Tahoe Fund, 2017).

1.2 2011-2016 CALIFORNIA DROUGHT BACKGROUND

The State of California recorded its worst drought from December 2011 to October 2016 since the drought of 1987 to 1992. From the onset of the drought, the drought status of California became progressively worse. From 2013 to 2016, approximately 90 percent of California was in a drought. In California's warmest year on record, 2014-2015, approximately 60 percent of California was experiencing at least a level of Extreme Drought D3 (See Figures 1 and 4; USDM, 2017). As a result, Governor Jerry Brown declared a drought state of emergency in January 2014 ordering a 25% reduction in urban water use and increased reliance on groundwater aquifers. The creation of groundwater regulations and policies followed soon after. This all lead to several permanent changes in people's habits such as shorter showers and drought resistant landscape replanting of homes and businesses.

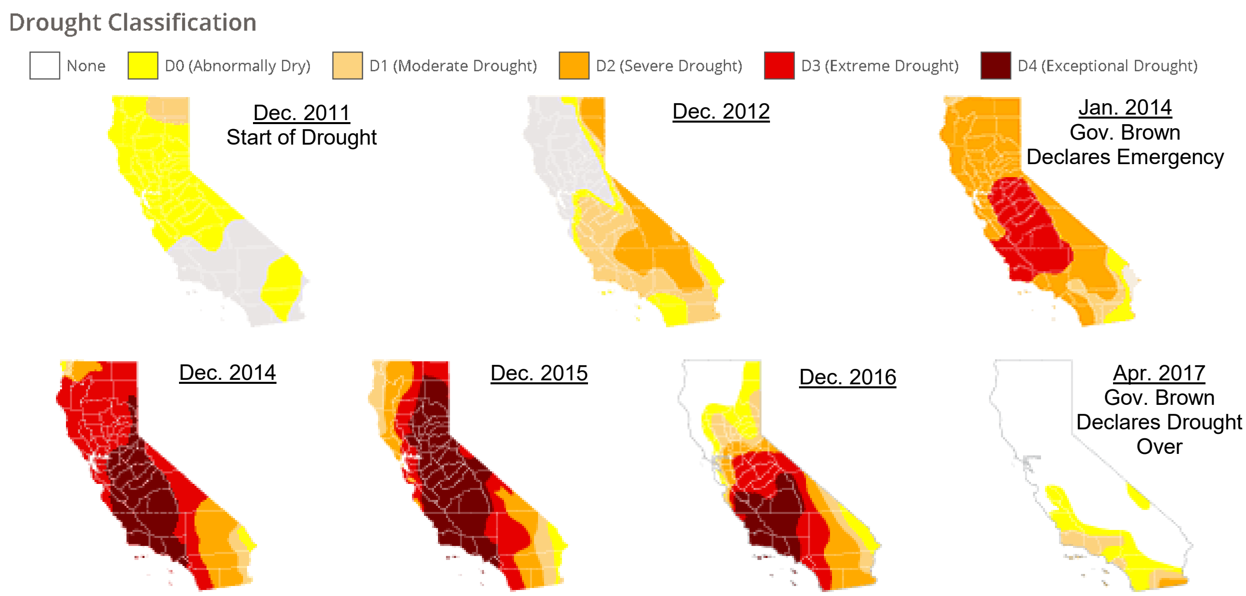


Figure 4 – California Drought Maps 2011-2017 (USDM, 2017)

During the 2011-2016 drought, the average amount of precipitation and snowpack decreased dramatically. This was particularly evident in the Northern Sierra 8-station precipitation index and the recorded California Snow Water Content, which the former measures the precipitation of the Sacramento River Watershed – a major component of the state's water supply. Since recording began in 1966, the Sacramento River watershed has received a maximum daily average of 51.8 inches of precipitation a year and California as a whole recorded a maximum daily average of 100 inches of snow water content a year. However, from December 2011 to October 2016, the Sacramento River watershed dropped to a maximum daily average of 37.2 inches of precipitation and the State of California recorded its lowest maximum daily average of approximately 20 inches of snow water content in the driest and warmest year on record, 2014-2015. (Appendix A; California Department of Water Resources, 2017).

In the winter of 2016-2017, the State of California recorded historical high levels of precipitation and snow which ultimately brought California out of the drought. The Sacramento Watershed experienced its wettest year on record with a maximum daily precipitation of 94.7 inches. The State of California recorded its second highest maximum daily snow water content measurements of approximately 160, 180, and 175 inches in Northern, Central, and Southern California, respectively (Appendix A; California Department of Water Resources, 2017). As such, Governor Brown declared the drought state of emergency over in April 2017.

1.3 OBJECTIVE

To analyze how the recent rain events of the winter season of 2016-2017 impacted Lake Tahoe, the Lake Tahoe Watershed, and surrounding snow packs against California's drought severity level via the parameters described and depicted below:

1. Precipitation / Snow Accumulation
2. Snow Water Equivalent / Depth
3. Surface / Snowmelt Runoff
4. Lake Tahoe Water Level
5. State and Local Drought Severity

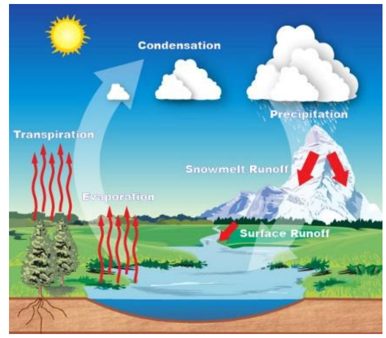


Figure 5 – Hydrologic Cycle
(NOAA - National Weather Service, 2010)

Cartography and data collection was completed via ArcGIS Pro, United States Geologic Survey (USGS), National Resources Conservation Service – Snow Telemetry (NCRS-SNOTEL), National Weather Service – National Operational Hydrologic Remote Sensing Center (NOHRSC), and United States Drought Monitor (USDM). Methodology is detailed below in Section 2.

2.0 METHODS AND DATA COLLECTION

2.1 GAGE STATION IDENTIFICATION AND DATA EXTRACTION

To identify pertinent gage stations for hydrologic analysis, the Lake Tahoe Subbasin, associated watershed, subwatersheds, catchments, and stream flowlines were extracted from the USA National Hydrography Dataset (NHDPlusV2, 2017) and delineated in ArcGIS Pro. The Lake Tahoe Subbasin was identified as Hydrologic Unit Code 12 (HUC 12) 16050101 with a total of four subwatersheds, 478 catchments, and 483 streams – as seen in Figure 6a. To assist in visually determining streams and areas with gage stations, the flowlines were recolored to the Best Estimate of Actual Mean Flow Attribute and land cover rasters for were extracted from the National Land Cover Database (NLCD, 2011) onto the Lake Tahoe Watershed (See Figure 6b). This cartographic process was cross referenced with the USGS and SNOTEL databases to plot all the relevant and active gaging stations: one lake gage, eight stream gages, and five SNOTEL stations. See Figures 6a/b and Table 1.

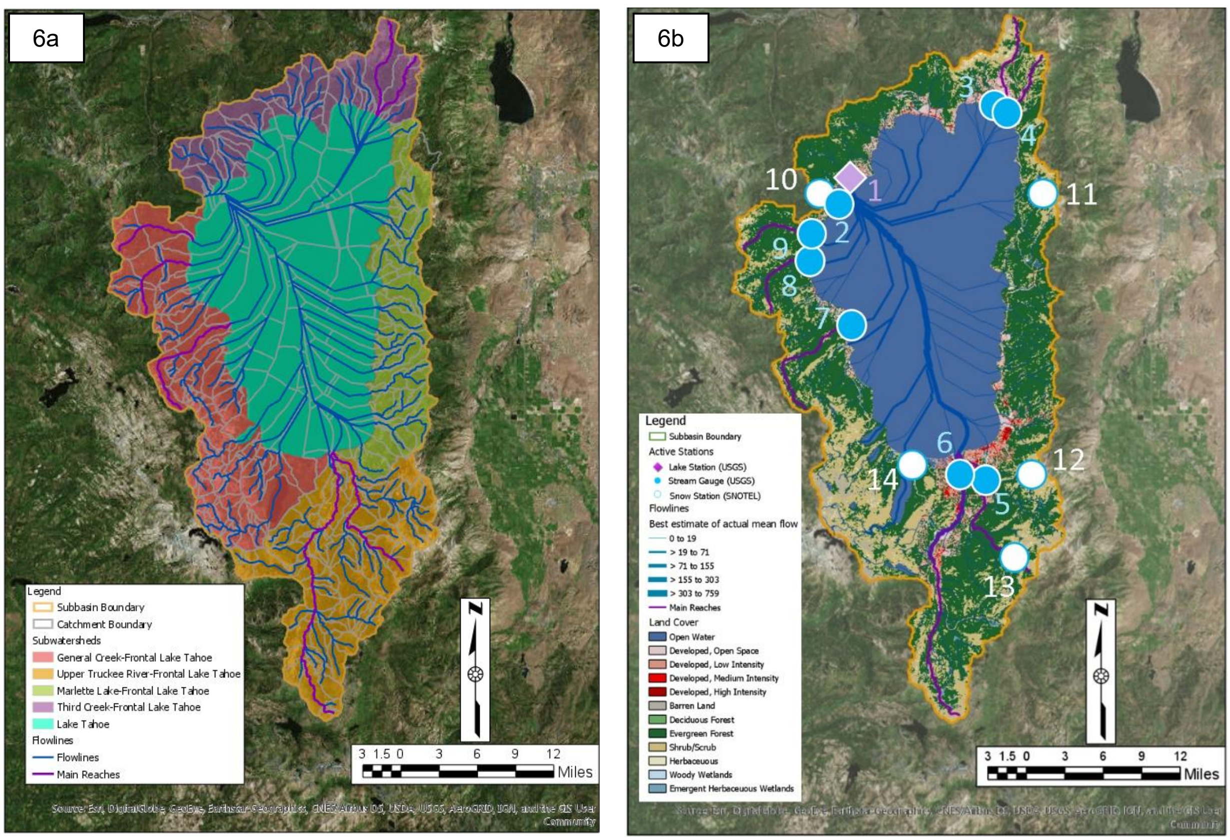


Figure 6a – Lake Tahoe Watershed with Subwatersheds, Catchments, and Flowlines
Figure 6b – Lake Tahoe Watershed with Land Cover and Gaging Stations

Table 1 – List of Gaging Stations

	Site #	Name	Agency	Latitute	Longtitude
1	10337000	Lake Tahoe at Tahoe City, CA	USGS	39.180740	-120.119358
2	10337500	Truckee River, CA	USGS	39.166389	-120.143333
3	10336698	Third Creek near Crystal Bay, NV	USGS	39.240463	-119.946577
4	10336700	Incline Creek near Crystal Bay, NV	USGS	39.240186	-119.944911
5	10336780	Trout Creek near Tahoe Valley, CA	USGS	38.919908	-119.972404
6	10336610	Upper Truckee River at South Lake Tahoe, CA	USGS	38.922408	-119.991571
7	10336645	General Creek near Meeks Bay, CA	USGS	39.051852	-120.118521
8	10336660	Blackwood Creek near Tahoe City, CA	USGS	39.107407	-120.162135
9	10336676	Ward Creek at Hwy 89 near Tahoe Pines, CA	USGS	39.132129	-120.157691
10	809	Tahoe City Cross	NRCS-SNOTEL	39.166667	-120.150000
11	615	Marlette Lake	NRCS-SNOTEL	39.166667	-119.900000
12	518	Heavenly Valley	NRCS-SNOTEL	38.916667	-119.916667
13	508	Hagans Meadow	NRCS-SNOTEL	38.850000	-119.933333
14	473	Fallen Leaf	NRCS-SNOTEL	38.933333	-120.050000

Once the stations were identified and plotted, specific hydrologic data were downloaded for each type of station from October 2004 through November 2017: 1) Lake Tahoe daily lake gage height (Station 1, USGS); 2) daily mean discharge for stream gages (Stations 2-9, USGS); and 3) daily mean precipitation, snow water equivalent, snow depth, soil moisture content, and soil moisture temperature (Stations 10-14; NRCS-SNOTEL). Due to the size of the Lake Tahoe Watershed and locale variation of the gaging stations, the hydrologic characteristics were averaged in order to analyze the watershed as a whole. Caution was exercised in making sure not to apply these averaged values toward single gaging stations. This data is detailed and analyzed in Section 3.

2.2 NOHRSC SUPPLEMENTAL MAPS

As supplemental and visual material in comparing the three time periods, NOHRSC maps for snow water equivalent were extracted from the online interactive maps. They are depicted below in Section 3.

2.3 USDM SUPPLMENTAL MAPS AND PLOTS

Similar to the NOHRSC supplemental material, USDM maps and plots were extracted from the online database for analysis. Additionally, GIS shapefiles were downloaded and used to develop relative drought severity maps. The extracted maps and plots are displayed through this project. The methodology in developing the relative drought severity maps is described below in Section 2.4.

2.4 RELATIVE DROUGHT SEVERITY CARTOGRAPHY

In order to analyze the impact of the 2016-2017 winter rain events on the Lake Tahoe Watershed and the five year drought, relative drought severity maps were developed to depict the combined frequency and severity that Lake Tahoe experienced. This methodology was reproduced based on the Esri "Five Years of Drought" Story Map created by John Nelson (Esri, 2017). John Nelson outlined this process in his ArcGIS blog post, "Six Months of Drought in the American Southeast" (Nelson, 2016), which is described below with respect to the maps created for the Lake Tahoe Watershed.

2.4.1 USDM Drought Data Download and Extraction

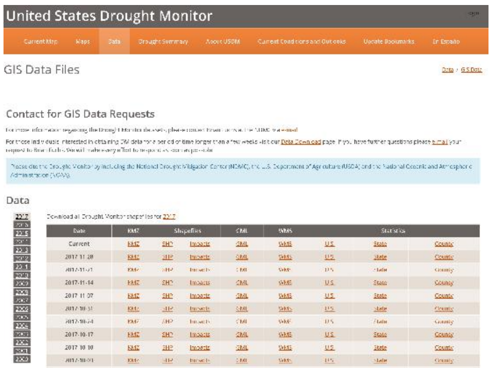


Figure 7 – USDM GIS Data Files Page

On their website, USDM provides a plethora of data files ranging from statistics to GIS shapefiles dating back to 2000 (See Figure 7). For this term project, weekly drought perimeter shapefiles were downloaded per bulk year from 2004 through 2017.

The shapefiles were then extracted into the ArcGIS Pro project location, opened in the software, and merged (Geoprocessing tool) together into one single shapefile. Each polygon in the shapefile produced has a single drought severity attribute based on the USDM drought levels: 0 (Abnormally Dry), 1 (Moderate Drought), 2 (Severe Drought), 3 (Extreme Drought), and 4 (Exceptional Drought). Figure 8 below depicts the merging of the USDM drought shapefiles into a single shapefile and its visual output.

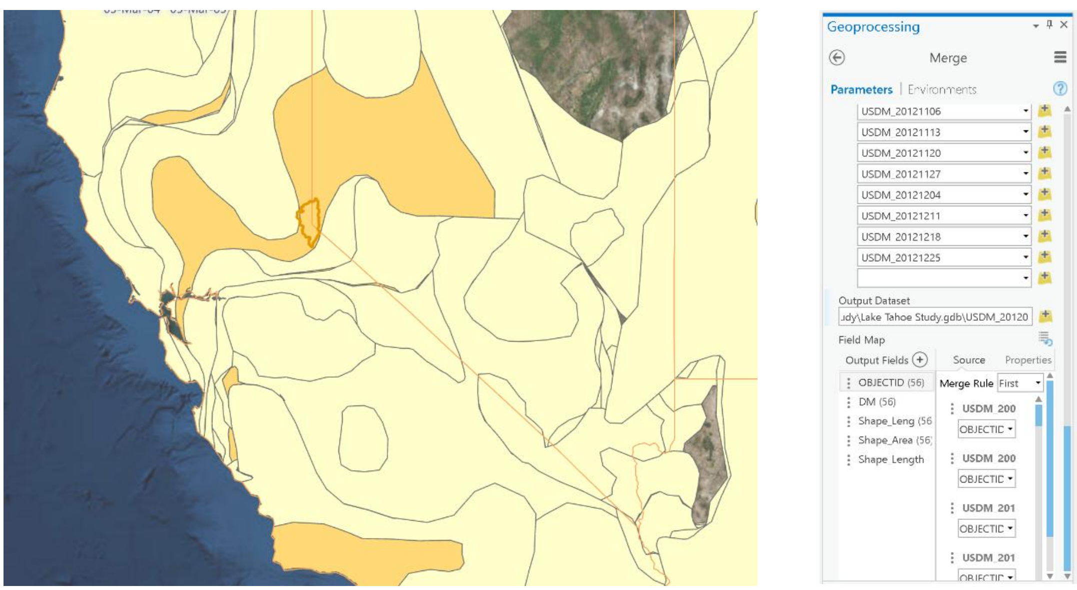


Figure 8 – Merged USDM Shapefiles

2.4.2 Data Organization and Transformation

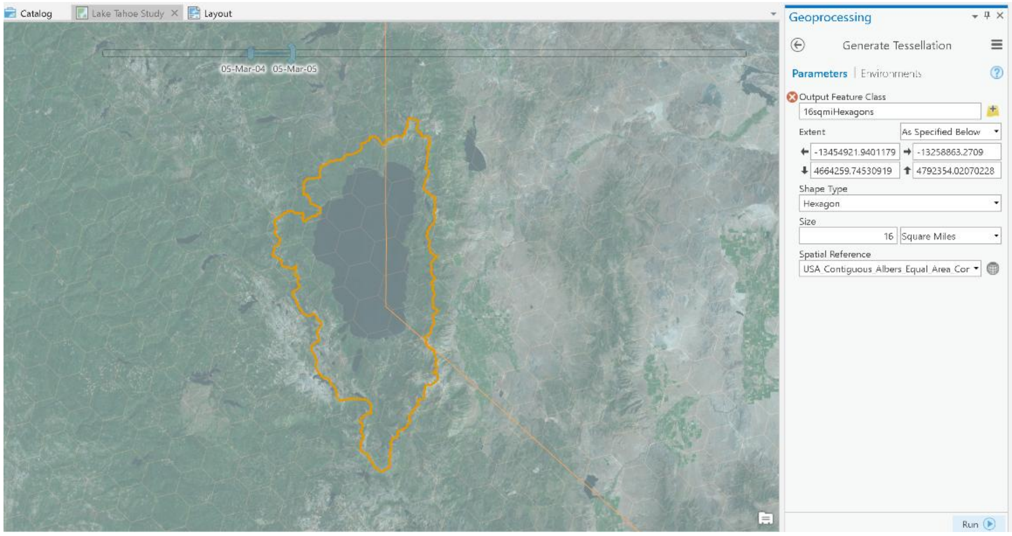


Figure 9 – Lake Tahoe Watershed Hexagon Grid

To begin organizing the data within the single drought shapefile, the Lake Tahoe Watershed was divided into an evenly spaced grid via hexagonal tessellation. The project file was set to an equal area projection and the Lake Tahoe Subbasin and its surrounding area were carved into approximately 16 sq-mi hexagonal cells (See Figure 9 above).

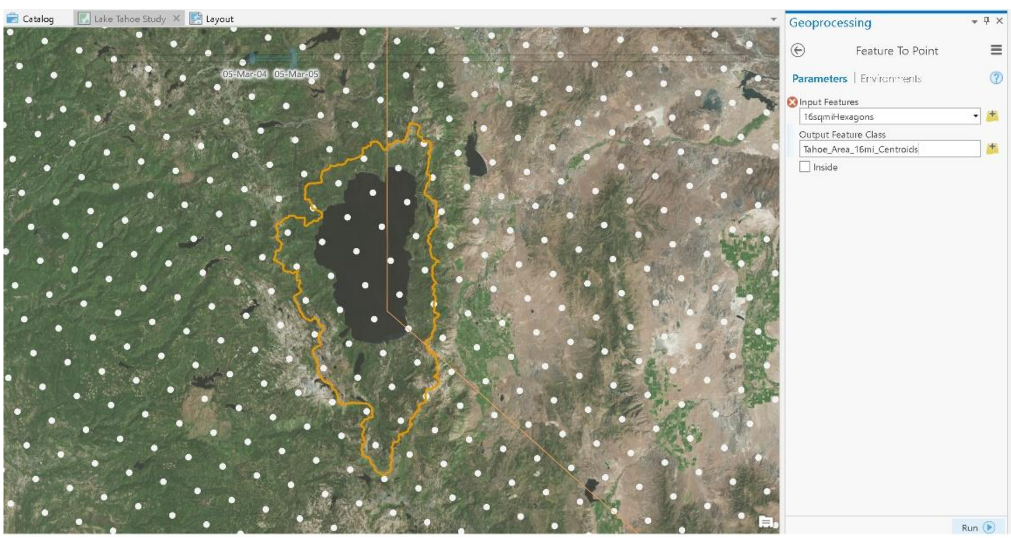


Figure 10 – Lake Tahoe Watershed Centroids

The hexagonal polygons were then converted to point centroids via the *Feature to Point* geoprocessing tool to have precisely only one location per point to account for overlapping drought polygons (See Figure 10 above).

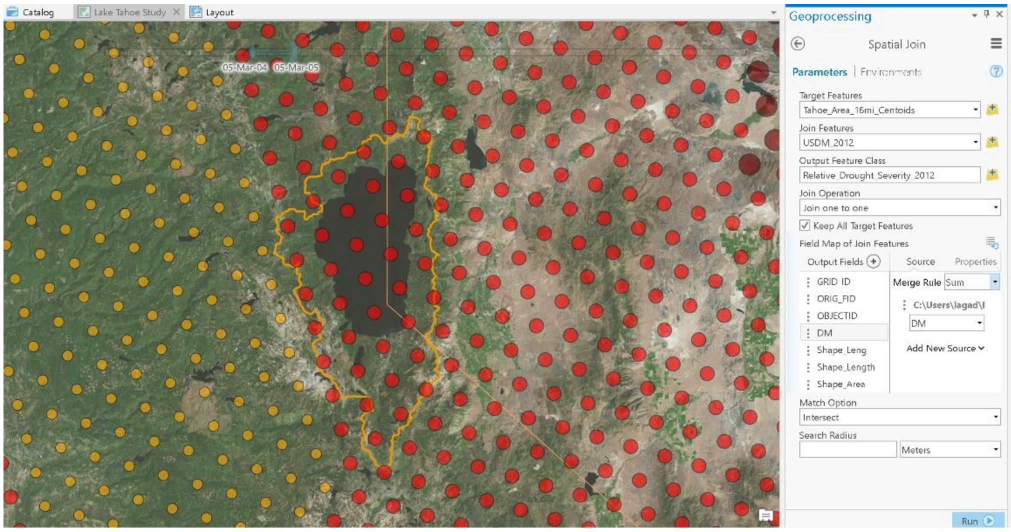


Figure 11 – Lake Tahoe Watershed Spatially Joined Centroids and Drought Polygons

The centroid layer was then spatially joined (Geoprocessing tool) to the single drought shapefile merged in Section 2.4.1. Figure 11 above depicts spatially joined centroids and drought polygons broken into three drought severity groups: DM2 Severe Drought (orange, left side), DM3 Extreme Drought (bright red, center➔right), and DM3 Exceptional Drought (dark red, top right). Each group was separated into its own layer in order to assign a specified color and size.

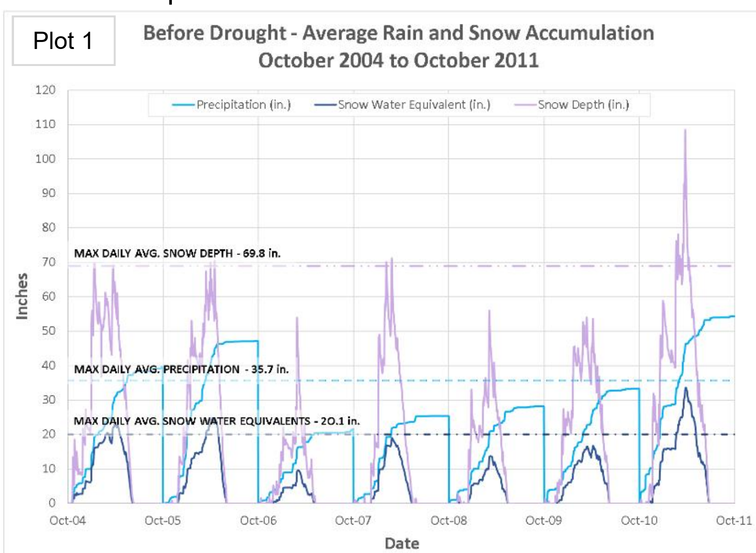
This process took into account all the drought polygons that overlapped at each centroid point via the DM attribute. As reminded by John Nelson, the DM attribute is a categorical scale and is not intended to be quantifiable. However, similarly to John Nelson's work, this term project uses this relative, cumulative DM value per point to depict the frequency (centroid size) and severity (centroid color) of the Lake Tahoe Watershed. Analysis of these maps are detailed in Section 3.

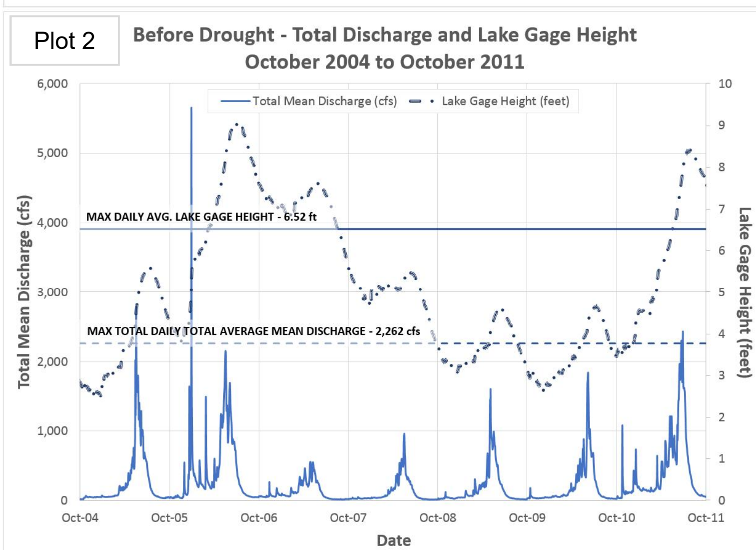
3.0 RESULTS

3.1 PRIOR TO THE DROUGHT (2004-2011)

To get a cumulative sense of the severity of the 2011-2016 drought and the impact of the subsequent 2016-2017 winter rains, hydrologic data prior to the drought was analyzed. The time period of 2004 through 2011 was selected as an arbitrary, but suitable time period for comparison.

During the seven years prior to the drought, Lake Tahoe exhibited cyclical behavior expected from a large and historical natural system – winter / wet seasons beginning on October 1. As detailed in Plots 1 and 2 and Table 2, there were expected hydrologic highs and lows. Interestingly enough, Lake Tahoe received its highest precipitation and snowpack levels from October 2010 to October 2011, immediately before the start of the drought. From 2004-2011, the Lake Tahoe Watershed received a maximum daily average of 35.7 inches in precipitation, 20.1 inches in snow water equivalent, and 68.9 inches in snow depth. The maximum daily total average mean discharge into Lake Tahoe was 2,262 cubic feet per second (cfs) and the maximum daily average lake gage height was 6.52 feet (6,226.52 feet amsl). See Figure 12 for a visual representation of the accumulated snow water equivalent in California.





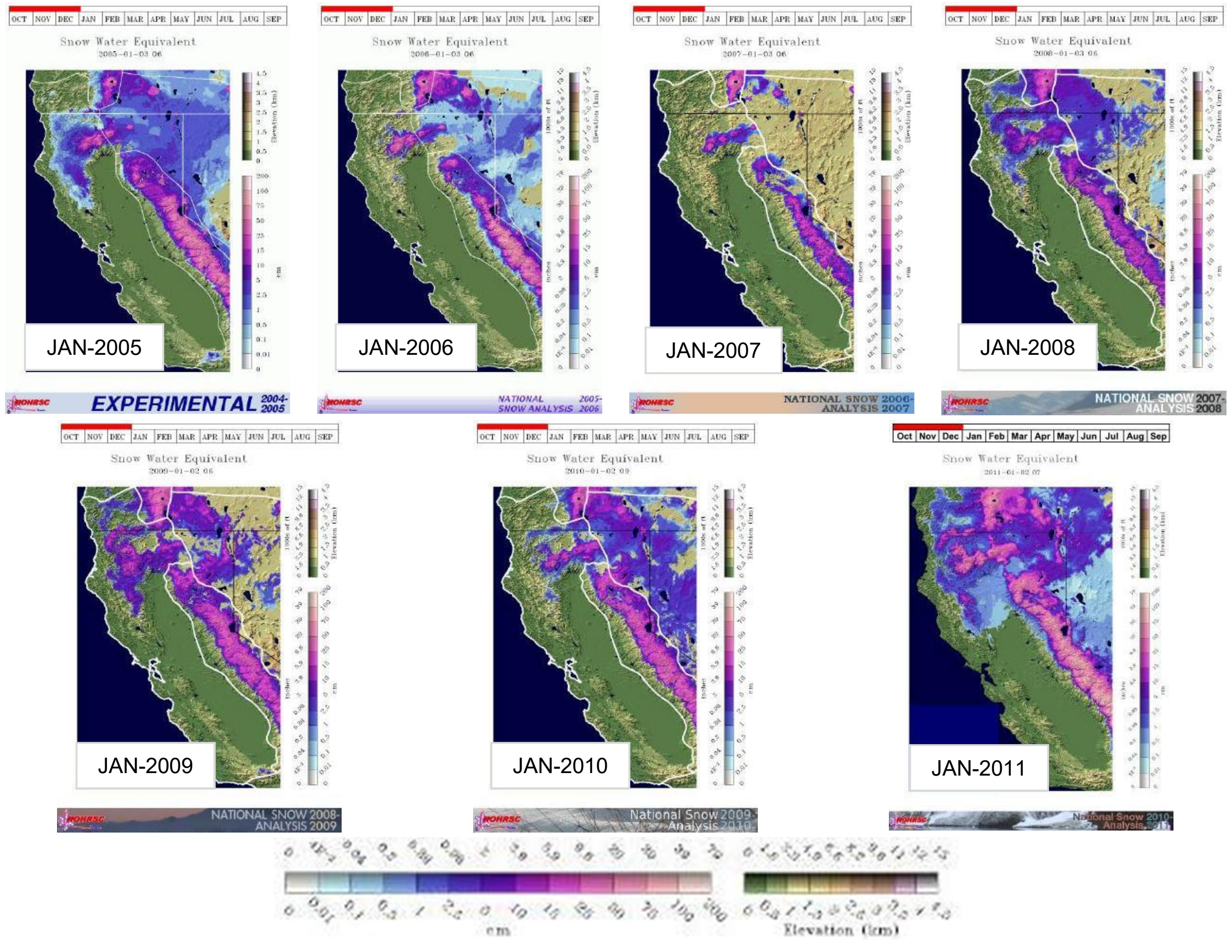
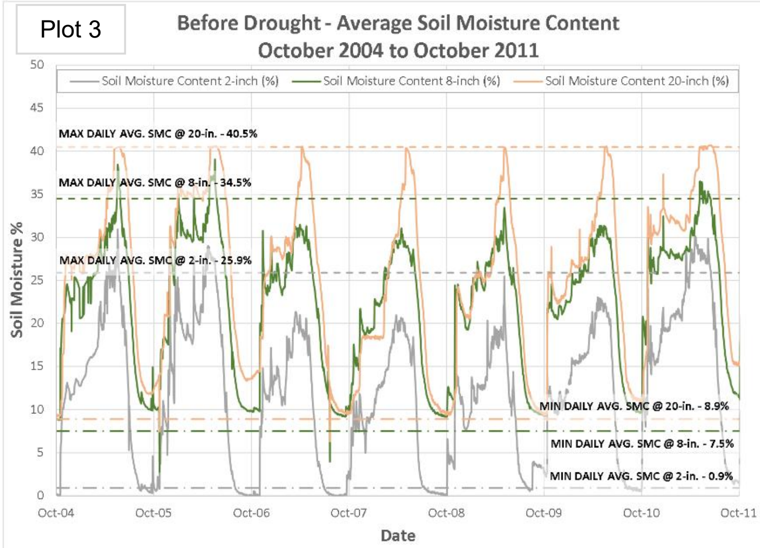
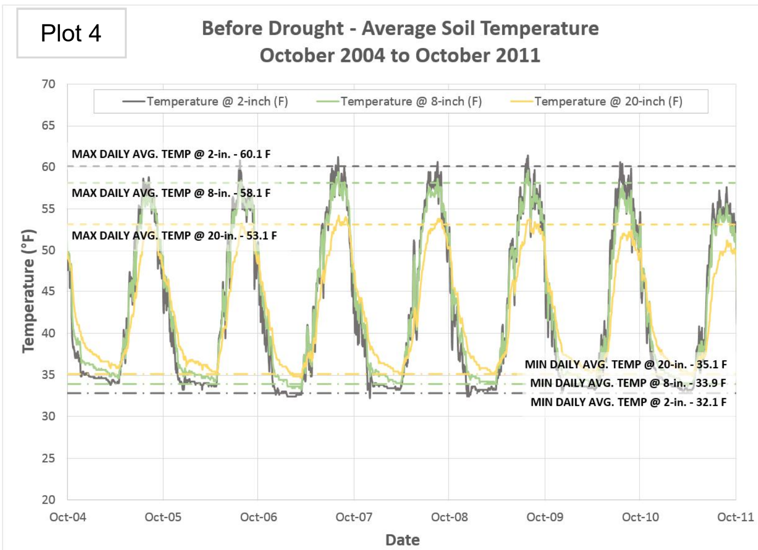
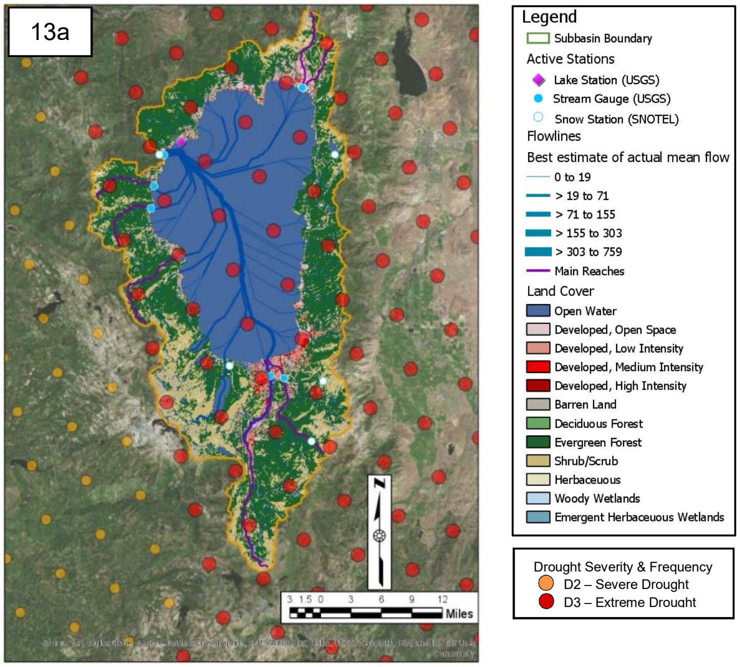


Figure 12 – California Snow Water Equivalent – 3 Jan 2005 to 3 Jan 2011 (NOHRSC, 2017)
Note: January 3 for Lake Tahoe is the center date for the most snow.

Soil moisture content and associated temperatures are measured at the SNOTEL stations at 2-inches, 8-inches, and 20-inches below ground surface (bgs). From 2004 to 2011, the maximum daily average soil moisture content measured in the Lake Tahoe Watershed were 25.9%, 34.5%, and 40.5%, at 2-, 8-, and 20-inches, respectively. The associated measured maximum daily average temperatures were 60.1 degrees Fahrenheit (°F), 58.1 °F, and 53.1 °F, respectively. Conversely, the minimum daily average soil moisture content measured in the Lake Tahoe Watershed were 0.9%, 7.5%, and 8.9%, at 2-, 8-, and 20-inches bgs, respectively. The associated measured minimum daily average soil temperatures were 32.8 °F, 33.9 °F, and 35.1 °F, respectively. As a result, the Lake Tahoe Watershed averaged drought levels between Severe Drought D2 to Extreme Drought D3 going from the southwest to the northwest. See Plots 3 and 4, and Figure 13a-b.


Plot 3
Before Drought - Average Soil Moisture Content
October 2004 to October 2011
Soil Moisture Content 2-inch (%)
Soil Moisture Content 8-inch (%)
Soil Moisture Content 20-inch (%)
MAX DAILY AVG. SMC @ 20-in. - 40.5%
MAX DAILY AVG. SMC @ 8-in. - 34.5%
MAX DAILY AVG. SMC @ 2-in. - 25.9%
MIN DAILY AVG. SMC @ 20-in. - 8.9%
MIN DAILY AVG. SMC @ 8-in. - 7.5%
MIN DAILY AVG. SMC @ 2-in. - 0.9%
Soil Moisture %
Date
Oct-04
Oct-05
Oct-06
Oct-07
Oct-08
Oct-09
Oct-10
Oct-11


Plot 4
Before Drought - Average Soil Temperature
October 2004 to October 2011
Temperature @ 2-inch (F)
Temperature @ 8-inch (F)
Temperature @ 20-inch (F)
MAX DAILY AVG. TEMP @ 2-in. - 60.1 F
MAX DAILY AVG. TEMP @ 8-in. - 58.1 F
MAX DAILY AVG. TEMP @ 20-in. - 53.1 F
MIN DAILY AVG. TEMP @ 20-in. - 35.1 F
MIN DAILY AVG. TEMP @ 8-in. - 33.9 F
MIN DAILY AVG. TEMP @ 2-in. - 32.1 F
Temperature (°F)
Date
Oct-04
Oct-05
Oct-06
Oct-07
Oct-08
Oct-09
Oct-10
Oct-11



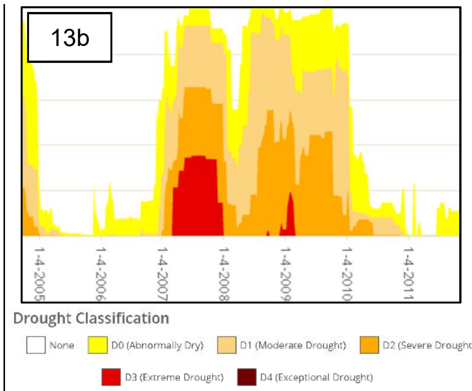
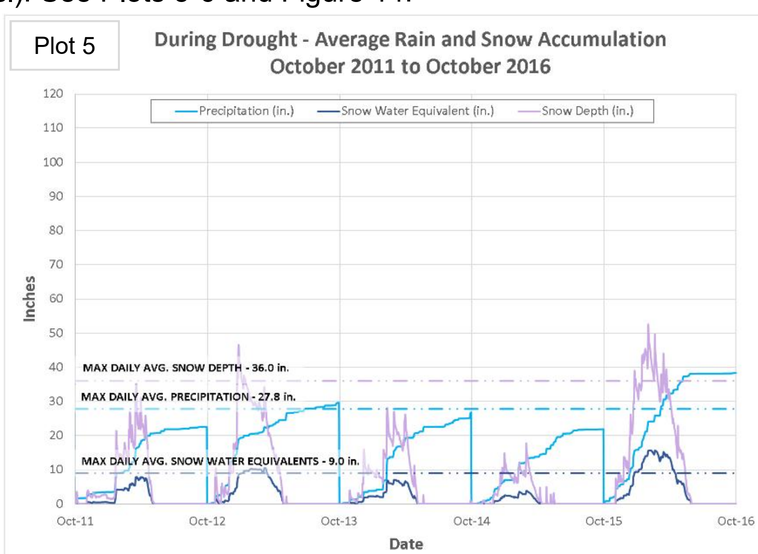
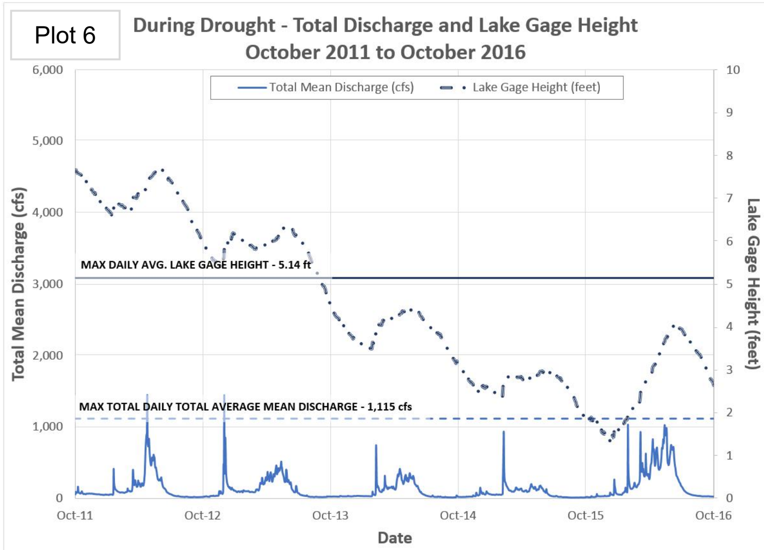


Figure 13a – Before Drought - Relative Drought Severity Map (Oct 2004 to Oct 2011)
Figure 13b – California Drought in Percent Area (USDM, 2017)

3.2 DURING THE DROUGHT (2011-2016)

Identical to the entire State of California, Lake Tahoe experienced hydrologic record lows at all its gaging stations. During this exceptionally dry period, the maximum daily average precipitation, snow water equivalent, and snow depth dropped to 27.8 inches, 9.0 inches, and 36.0 inches, respectively. Likewise the maximum daily total average mean discharge into Lake Tahoe dropped 1,115 cfs and the maximum daily average lake gage height dropped to 5.14 feet (6,225.14 feet amsl). See Plots 5-6 and Figure 14.





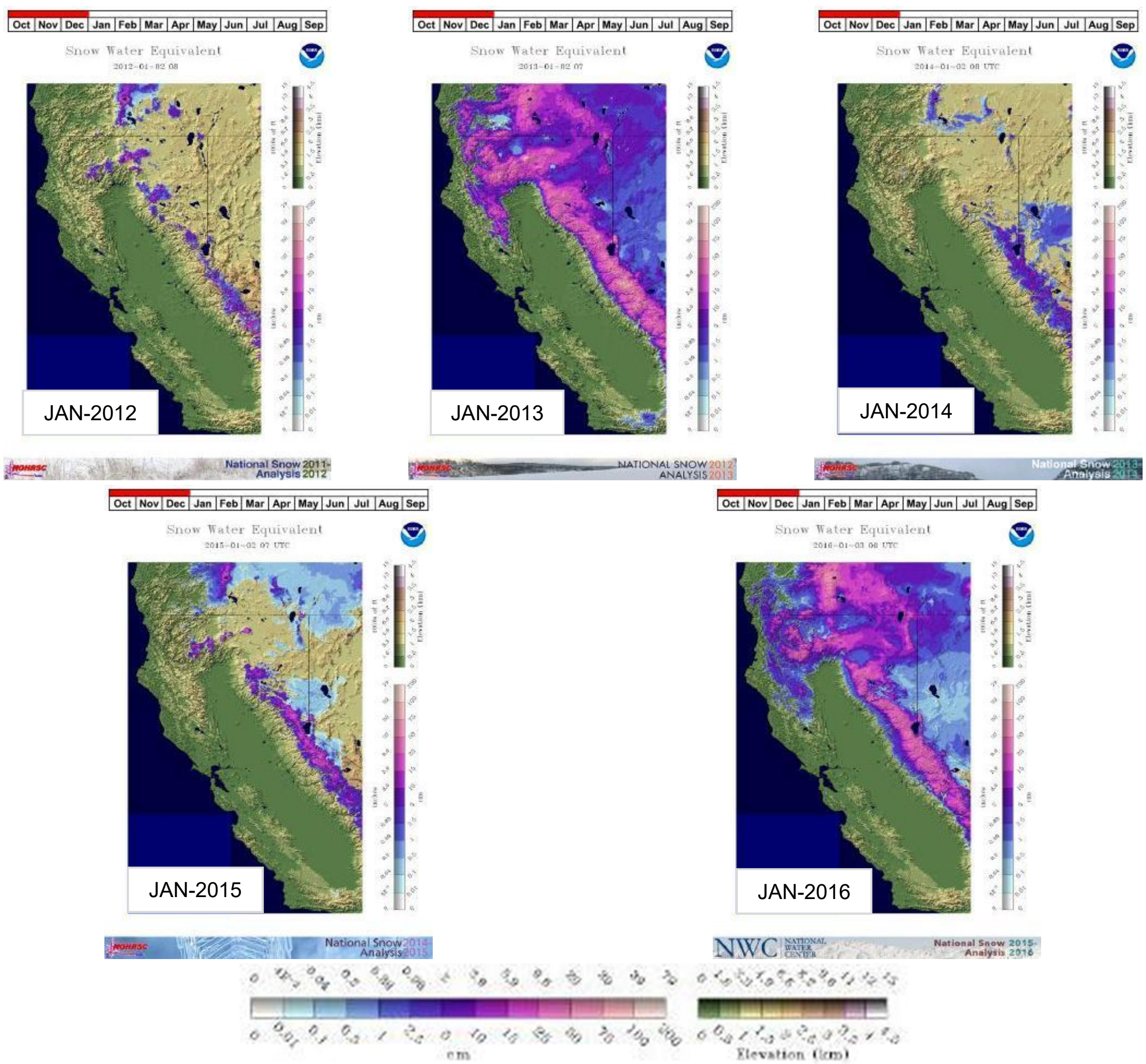
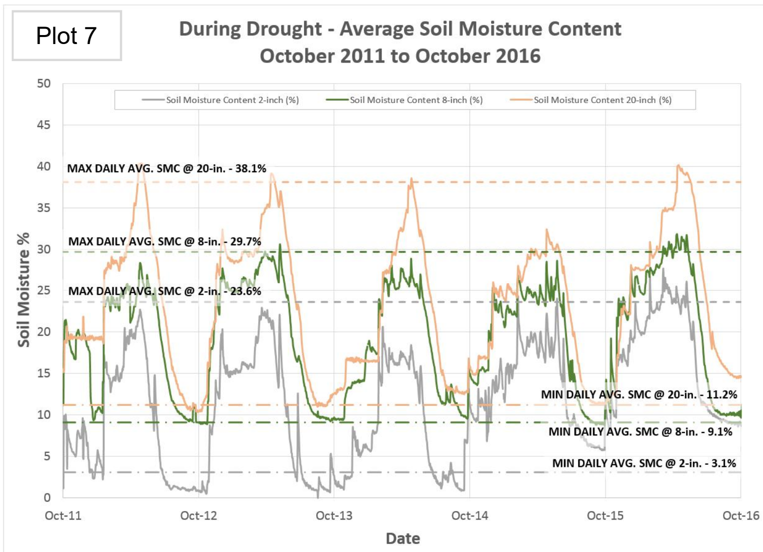
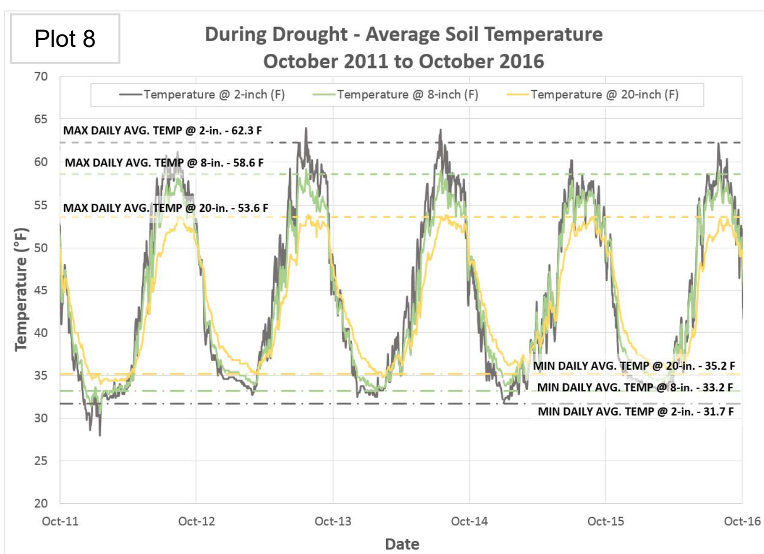


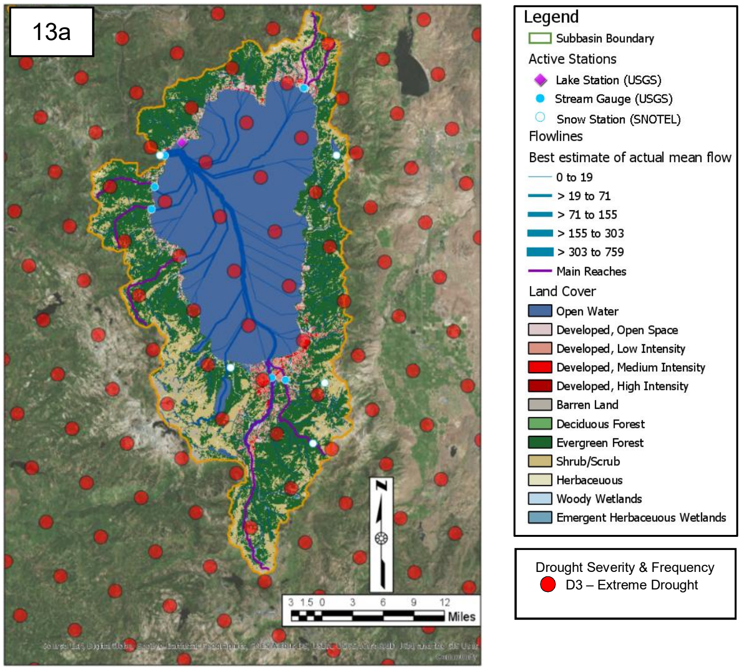
Figure 14 – California Snow Water Equivalent – 3 Jan 2012 to 3 Jan 2016 (NOHRSC, 2017)

Note: January 3 for Lake Tahoe is the center date for the most snow.

During the drought, the maximum daily average soil moisture content measured at 2-, 8-, and 20-inches bgs decreased to 23.6%, 29.7%, and 38.1%, respectively. The associated measured maximum daily average temperatures increased 62.3 °F, 58.6 °F, and 53.6 °F. On the other end of the spectrum, the minimum daily average soil moisture content measured increased to 3.1%, 9.1% and 11.2%, respectively. The associated measured minimum daily average temperatures decreased to 31.7 °F, 33.2 °F, and 35.2 °F, respectively. Thus the Lake Tahoe Watershed averaged drought between Extreme Drought D3 and Exceptional Drought D4. See Plots 7 and 8, and Figure 13 a-b.







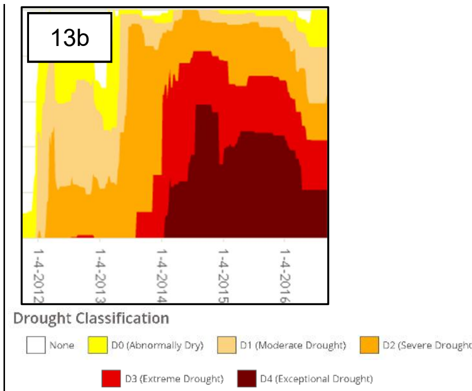
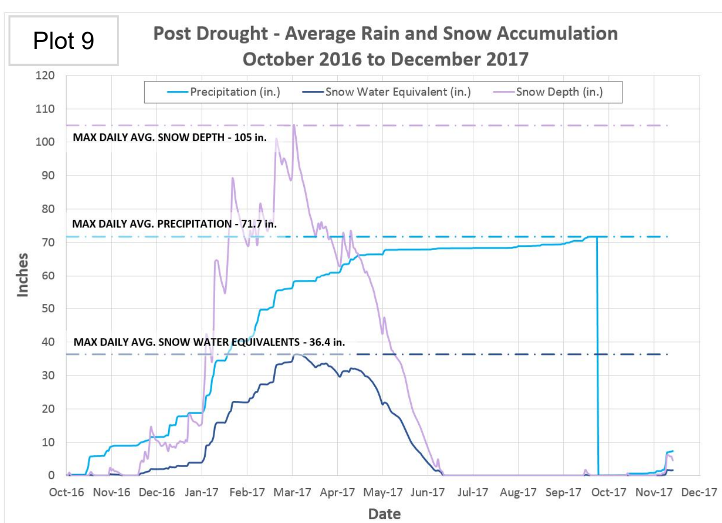
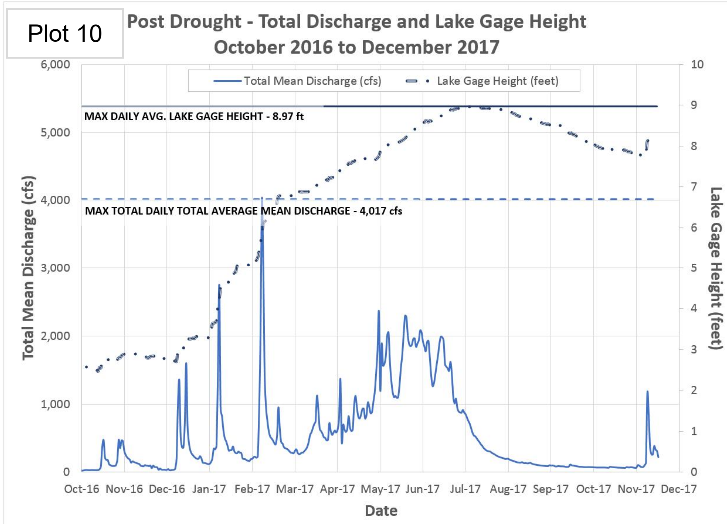


Figure 15a – During Drought - Relative Drought Severity Map (Oct 2011 to Oct 2016)
Figure 15b – During Drought - California Drought in Percent Area (Oct 2011 to Oct 2016; USDM, 2017)

3.3 RESPONSE TO DROUGHT (2016-2017)

For the Lake Tahoe Watershed, the drought began to diminish at the beginning of the 2016-2017 winter / wet season as the region experienced record highs for a single winter. As detailed in the following Plots 9-10 and Figure 16, precipitation and snow accumulation and the lakes response measurements increased dramatically. The recorded maximum daily average precipitation, snow water equivalents, and snow depth were 71.7 inches, 36.4 inches, and 105 inches, respectively. The maximum daily total average mean discharge into Lake Tahoe rose to 4,017 cfs and the resultant maximum daily average lake gage height rose to 8.97 feet (6,228.97 feet amsl) – 0.13 feet shy of the legal maximum limit of 9.1 feet (6,229.1 feet amsl). The winter and wet seasons ensuing extension pushed observed received precipitation into September 2017 and snow accumulation into June 2017.





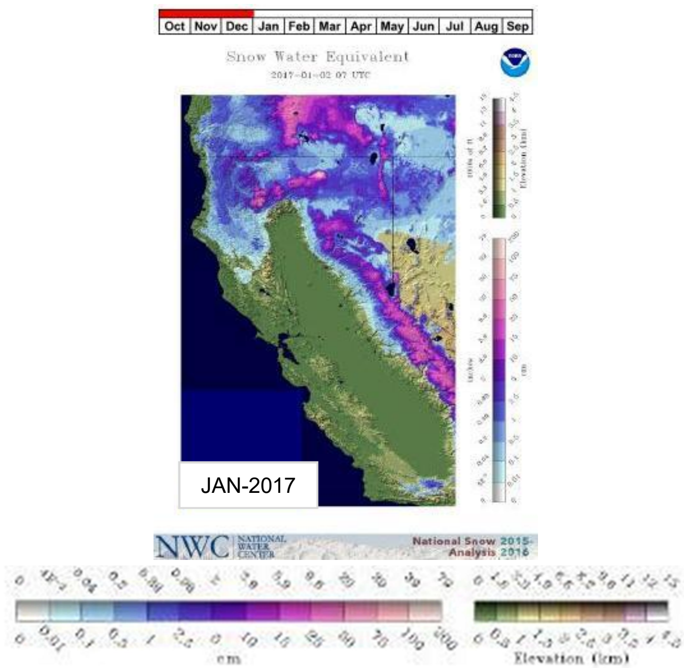
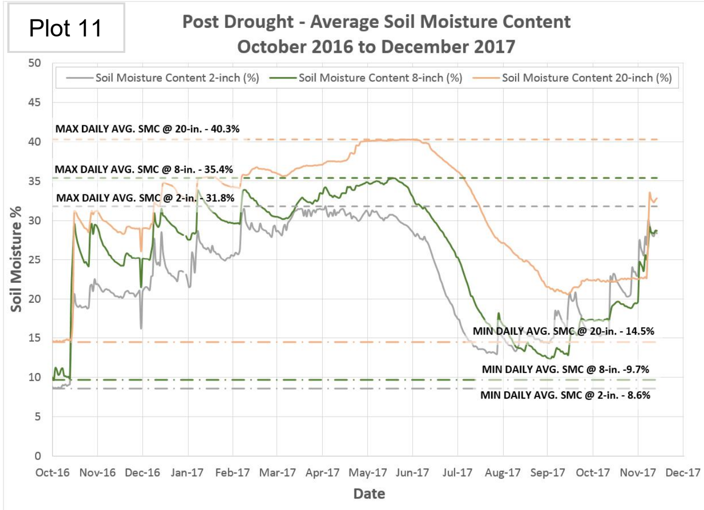
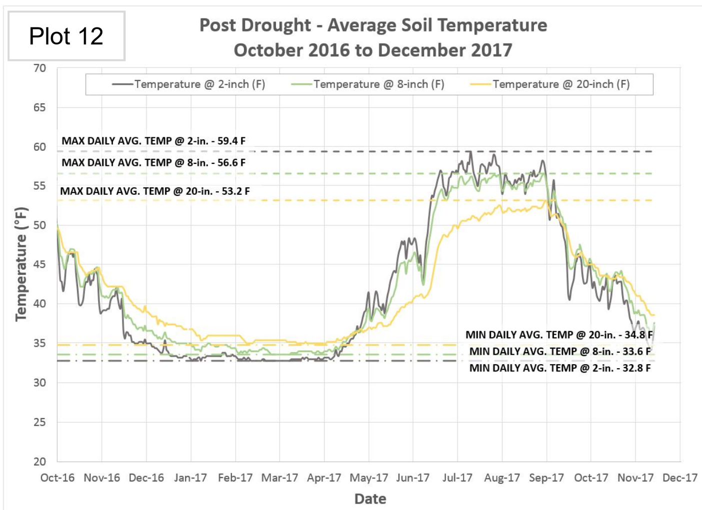


Figure 16 – California Snow Water Equivalent – 3 Jan 2017 (NOHRSC, 2017)
Note: January 3 for Lake Tahoe is the center date for the most snow.

As expected from the increase in precipitation and snow, the measured maximum daily average soil moisture content increased at all depths to 31.8%, 35.4%, and 40.3% - at 2-, 8-, and 20-inches bgs, respectively. The measured minimum daily average soil moisture content increased to 8.6%, 9.7%, and 14.5%, respectively. The measured maximum daily average soil temperatures decreased to 59.4 °F, 56.6 °F, and 53.2 °F, respectively. The measured minimum daily average soil temperatures increased to 32.8 °F (2-inches) and 33.6 °F (8-inches), with the exception of the soil temperature at 20-inches, which decreased to 34.8 °F. Since the beginning of the 2016-2017 winter season to December 2017, the Lake Tahoe Watershed has not averaged in any drought level. See Plots 11 and 12, and Figure 17 a-b.





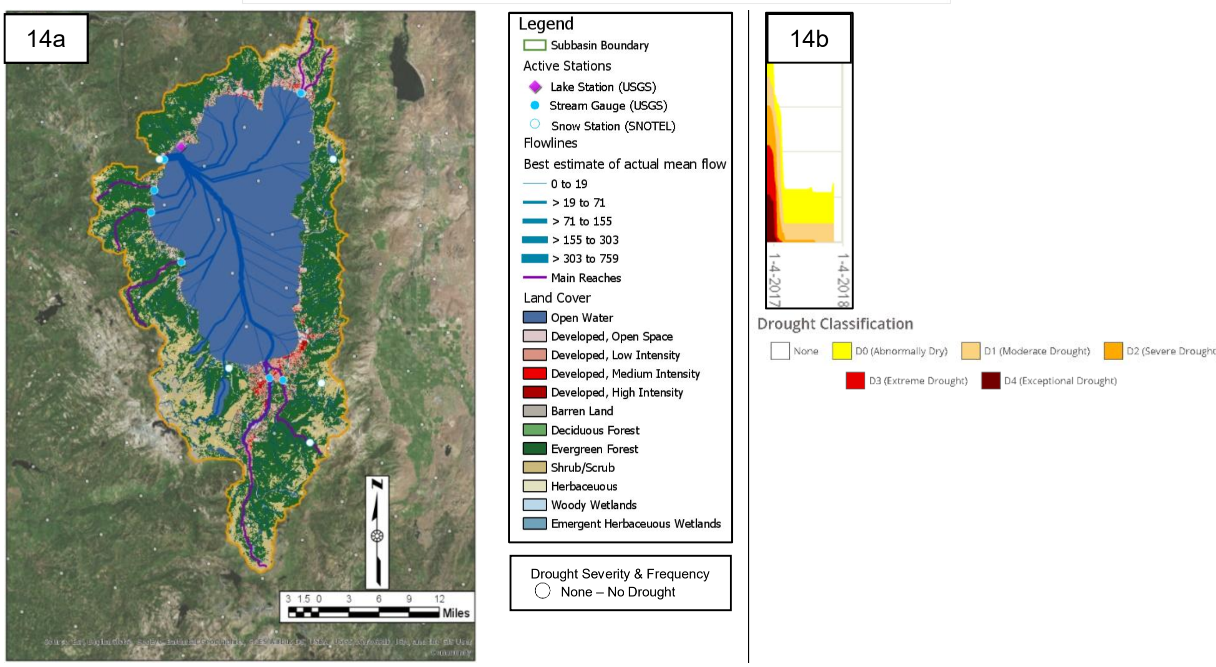


Figure 14a – Post Drought - Relative Drought Severity Map (Oct 2016 to Dec 2017)
Figure 14b – Post Drought - California Drought in Percent Area (Oct 2016 to Dec 2017; USDM, 2017)

4.0 SUMMARY AND CONCLUSIONS

As detailed in Section 3 above and Table 2 below, from October 2004 to December 2017, Lake Tahoe behaved in an expected cyclical behavior from a large and established natural ecosystem. While not the ideal and statistical analytical methodology, averaging the hydrologic parameters and identifying the maximum and minimum averaged values provided an ample comparative picture of the impact of the 2016-2017 winter rain events.

Table 2 – Hydrologic Parameters

	Before Drought 2004-2011	*Difference* Increase / Decrease	During Drought 2011-2016	*Difference* Increase / Decrease	Post Drought 2016-2017
Precipitation (in.)	35.7	7.85	27.8	43.8	71.7
Snow Water Equivalent (in.)	20.1	11.03	9.0	27.3	36.36
Snow Depth (in.)	68.9	32.98	36.0	69.0	105
Total Mean Discharge (cfs)	2,262	1,031	1,115	2,901	4,017
Lake Gage Height (feet)	6.52	4.05	5.14	3.83	8.97
Soil Moisture Content @ 2-in. (%) [Max / Min] ***Variance (Max-Min)***	25.9 / 0.19 *25.7*	2.20 / 2.89 *5.10*	23.6 / 3.1 *20.6*	8.18 / 5.54 *2.64*	31.8 / 8.6 *23.2*
Soil Moisture Content @ 8-in. (%) [Max / Min] ***Variance (Max-Min)***	34.5 / 7.5 *26.9*	4.81 / 1.60 *6.41*	29.7 / 9.1 *20.5*	5.7 / 0.56 *5.14*	35.4 / 9.7 *25.7*
Soil Moisture Content @ 20-in. (%) Max / Min ***Variance (Max-Min)***	40.5 / 8.86 *31.7*	2.39 / 2.29 *4.68*	38.1 / 11.1 *27.0*	2.17 / 3.37 *1.2*	40.3 / 14.5 *25.8*
Soil Temp. @ 2-in. (°F) [Max / Min] ***Variance (Max-Min)***	60.1 / 32.8 *27.3*	2.13 / 1.18 *3.31*	62.3 / 31.7 *30.6*	2.87 / 1.15 *4.02*	59.4 / 32.8 *26.6*
Soil Temp. @ 8-in. (°F) [Max / Min] ***Variance (Max-Min)***	58.1 / 33.9 *24.1*	0.58 / 0.71 *1.30*	58.6 / 33.2 *25.4*	2.04 / 0.4 *2.44*	56.6 / 33.6 *23.0*
Soil Temp. @ 20-in. (°F) [Max / Min] ***Variance (Max-Min)***	53.1 / 35.1 *17.9*	0.54 / 0.09 *0.46*	53.6 / 35.2 *18.4*	0.4 / 0.4 0	53.2 / 34.8 *18.4*

As detailed in Table 2 and depicted throughout Section 3, the precipitation and snow accumulation received by Lake Tahoe decreased from before the drought and increased after the drought. As a result, the total mean discharge into the lake and the water level of the lake decreased and increased. Comparing Plots 1 and 2 (before drought) to Plots 5 and 6 (during drought), it is observed that while precipitation levels generally were around the same range, the difference in received snow and measured snow water equivalent had immediate effects on the lake and the surrounding watershed. In particular, there is a downward trend in the lake gage height in Plot 6 until the 2016-2017 winter rain events.

Additionally, it is observed that due to less rain and snow during the drought, the variance (maximum minus minimum values) in soil moisture content decreased, which resulted in a higher variance in soil temperature. From before the drought and into the drought time period, the drought in Lake Tahoe worsened from a D2-D3 (Severe to Extreme Drought) to a D3-D4 (Extreme to Exceptional Drought). With the 2016-2017 winter rain events, the soil moisture content and associated soil temperature rebounded close to levels prior to the drought. Similar to the impact of the drought on the soil, it will take time and more rain and snow for Lake Tahoe to regain its typical characteristics. At the very least, Lake Tahoe has not averaged a drought this year.

In conclusion, the 2016-2017 winter rain events not only brought Lake Tahoe out of the drought, but also the majority of California. This drought forced California and its people to be more water conscious than they have ever been. However, in looking at the history of California and Lake Tahoe, a drought could be right around the corner – as was experienced in 2011, prior to the five year drought.

5.0 REFERENCES

California Department of Water Resources – California Data Exchange Center (CDEC). 2017.

Esri. 2017. “Five Years of Drought” – Story Map. Created by John Nelson. (http://www.esri.com/products/maps-we-love/five-year-drought).

Los Angeles Times (LA Times). 2017. “Gov. Brown declares California drought emergency is over”. (http://www.latimes.com/local/lanow/la-me-brown-drought-20170407-story.html). April 7.

National Land Cover Database (NLCD). 2011. USGS. (https://viewer.nationalmap.gov/launch/).

National Oceanic and Atmospheric Administration (NOAA) – National Weather Service. 2010. (https://forecast.weather.gov/jetstream/atmos/hydro.htm).

National Operational Hydrologic Remote Sensing Center (NOHRSC) – National Weather Service. 2017. (https://www.nohrsc.noaa.gov/nsa/).

Nelson, John. 2016. “Six Months of Drought in the American Southeast”. Esri – ArcGIS Blog. (https://blogs.esri.com/esri/arcgis/2016/12/06/six-months-of-drought-in-the-american-southeast/). December 6.

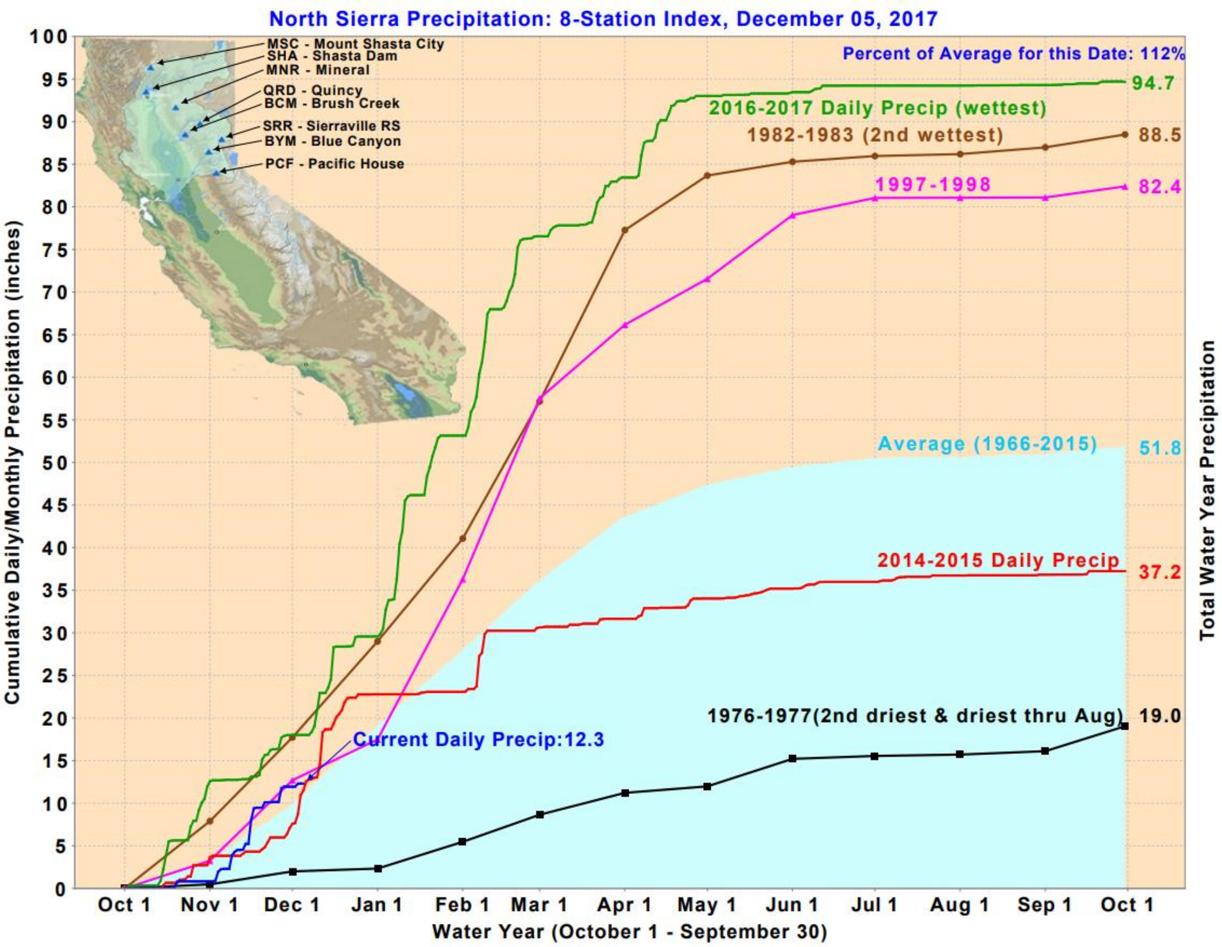
Tahoe Fund. 2017. (http://www.tahoefund.org/).

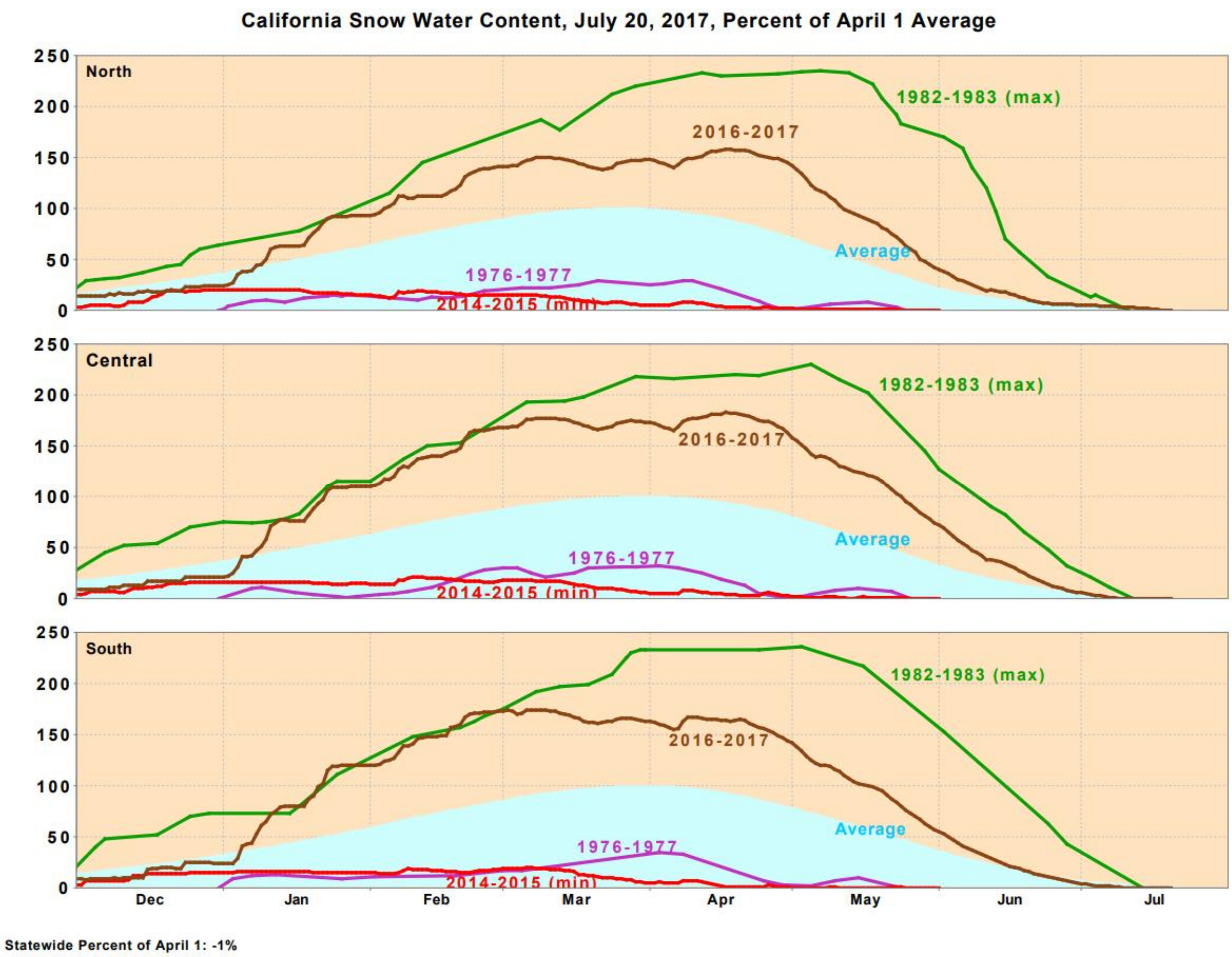
United States Drought Monitor (USDM). 2017. *The U.S. Drought Monitor is jointly produced by the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Map courtesy of NDMC-UNL.*

United States Geologic Survey (USGS). 2017.

USA National Hydrography Dataset Plus Version 2 (NHDPlusV2). 2017.

APPENDIX A Precipitation and Snow Water Content (CDEC, 2017)


North Sierra Precipitation: 8-Station Index, December 05, 2017
Percent of Average for this Date: 112%
MSC - Mount Shasta City
SHA - Shasta Dam
MNR - Mineral
QRD - Quincy
BCM - Brush Creek
SRR - Sierraville RS
BYM - Blue Canyon
PCF - Pacific House
2016-2017 Daily Precip (wettest)
94.7
1982-1983 (2nd wettest)
88.5
1997-1998
82.4
Average (1966-2015)
51.8
2014-2015 Daily Precip
37.2
1976-1977(2nd driest & driest thru Aug)
19.0
Current Daily Precip:12.3
Cumulative Daily/Monthly Precipitation (inches)
Total Water Year Precipitation
Water Year (October 1 - September 30)
Oct 1
Nov 1
Dec 1
Jan 1
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1



California Snow Water Content, July 20, 2017, Percent of April 1 Average
North
Central
South
1982-1983 (max)
2016-2017
Average
1976-1977
2014-2015 (min)
250
200
150
100
50
0
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Statewide Percent of April 1: -1%