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EXAMINING THE RELATIONSHIP BETWEEN SNOW COVER AND RESERVOIR STORAGE IN THE AMERICAN RIVER BASIN

A Thesis
Presented to
The Faculty of the Department of Geography
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In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

by
Karen McGillis-Moskaluk
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The Designated Thesis Committee Approves the Thesis Titled

EXAMINING THE RELATIONSHIP BETWEEN SNOW COVER AND RESERVOIR STORAGE IN THE AMERICAN RIVER BASIN

by

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APPROVED FOR THE DEPARTMENT OF GEOGRAPHY

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May 2013

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ABSTRACT

EXAMINING THE RELATIONSHIP BETWEEN SNOW COVER AND RESERVOIR STORAGE IN THE AMERICAN RIVER BASIN

by Karen McGillis-Moskaluk

This study focused on finding evidence of a relationship between snow cover and reservoir storage in the American River basin. Water availability is very important to the future of California. Landsat Thematic Mapper images of the area taken from 1985-2011 were analyzed by calculating Normalized Difference Snow Index and calculating snow acres. The peak storage data were obtained for Folsom Lake for the same time period as the satellite images. The evaluation of these methods showed that over time there was a correlation between snow cover and reservoir storage downstream.

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Introduction

Understanding the process by which Sierra Nevada's snow becomes surface water, and the degree to which this water is being impounded in lakes, will be critically important in maintaining water availability under climate change. This study used satellite and hydrologic data to examine the relationship between snow cover and reservoir storage in the American River Basin. Are they positively correlated, and if so, can we use this correlation to plan for future water needs?

California depends on the snow pack in the Sierra Nevadas to provide water during the summer and fall. During an average year, 75% of California's average annual precipitation falls between November and March and half of that occurs between December and February (DWR 2012). The state uses a system of reservoirs and aqueducts to move the water to areas that need the water such as agricultural and urban areas. This study analyzed the snow cover for the years 1985-2011 in a Landsat image using path 43 row 33 (Figure 1) and the maximum storage at Folsom Lake to see if climate change has had an impact. The American River basin begins in this section of the Sierra Nevada and is stored in the reservoir at Folsom Lake.

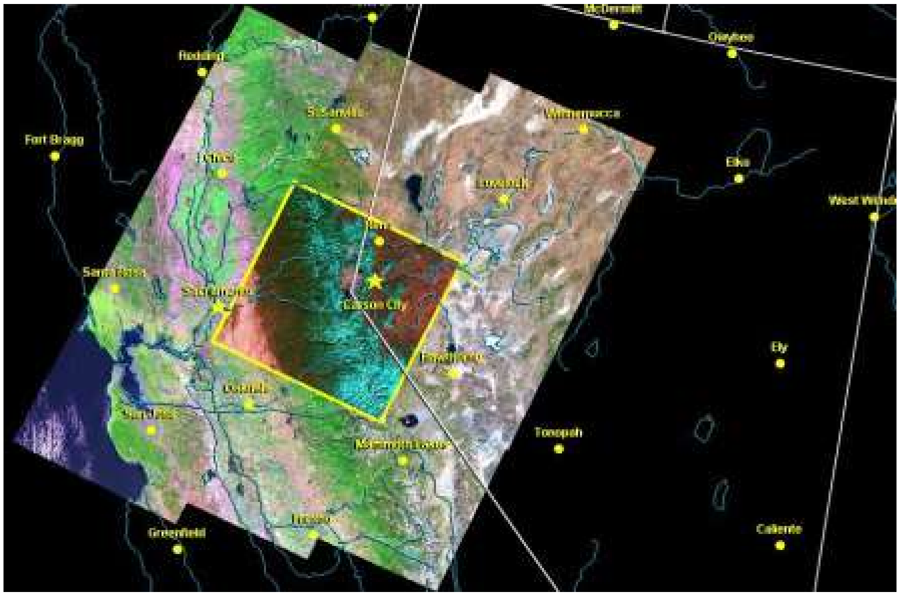

Figure 1- Landsat image of Path 43 Row 33, outlined in yellow, in relation to cities in California and Nevada. Image generated using the USGS Global Visualization Viewer.

The snowpack in the Sierra Nevada provides about one-third of California's water supply. Groundwater provides 30-60 % of water in California. About 75% of California's water supply comes from north of Sacramento, while 80% of the demand occurs in the southern two-thirds of the state. About 80% of this water is used for agricultural purposes while urban users consume about 10% of the water (DWR, 2012).

Area of study

The area of study extended from east of Lake Tahoe in Nevada to just outside of Sacramento. Folsom Lake can be seen in the lower left of Figure 2 next to the red arrow, just east of Sacramento. Figure 3 shows the relationship of this area to the states of California and Nevada.

Figure 2-Landsat image Path 43 Row 33 from March 15, 1998 showing the location of Folsom Lake at the red arrow. Image generated using the USGS Global Visualization Viewer.

Figure 3--Landsat Path 43 Row 33 in relation to the western US. Image generated using the USGS Global Visualization Viewer.

Folsom Lake and the American River

The water levels of the snowpack help determine how much water local agencies receive from the State Water Project, which begins at the Lake Oroville reservoir in Northern California and is channeled through the Sacramento-San Joaquin Delta to millions of people in Southern California (DWR, 2012). Since the last large dam project in the state was completed in 1975, learning to manage reservoirs is extremely important to the future of the state.

Folsom Lake is part of the State Water Project and the Central Valley Project. The California Water Project is a water-storage and delivery system containing reservoirs, aqueducts, and power plants throughout the state (DWR, 2012). The Central Valley Project is part of the California Water Project, and Folsom Dam and Reservoir are part of the Central Valley Project (California State Parks, 2012). The Central Valley Project was initially built to protect the Central Valley from water shortages and floods, but today the Central Valley Project is a multipurpose project that provides flood control, hydroelectricity, irrigation, and municipal water supplies.

Folsom Lake gets most of its inflow from the American River watershed (Figure 4). Folsom Dam is located about 25 miles northeast of Sacramento. Although its primary function is flood control, Folsom Lake stores water for irrigation and domestic use and for electrical power generation. Additional important activities include preservation of the American River fishery, downstream control of salt water intrusion in the Sacramento-San Joaquin Delta, and water-related recreation.

Figure 4-American River Watershed from UC Davis Center for Watershed Sciences

Folsom Dam is 340 feet high and 1,400 feet long. When Folsom Lake (Figure 5) is full it holds 1,010,000 acre-feet of water and has 75 miles of shoreline (California State Parks, 2012). During a normal run-off from the Sierra Nevada, 2.7 million acre-feet of water flows into the lake. Folsom lake can only hold 1,010,000 acre-feet, so 1.7 million acre-feet are released for flood control each year (California State Parks, 2012).

Figure 5-Folsom Lake and Dam taken Sept 2, 2012, by the author

Methods

Several steps were taken in the analysis of the data:

1. Data Collection
2. Software Tool
3. Data Preparation
4. Data Analysis Methodology
5. Data Calculations

1. Data Collection

The data used for the analysis included Landsat images of the Sierra Nevada from Feb 1985 to April 2011 and water storage data for Folsom Lake from 1985-2011. The images were obtained using the USGS Global Visualization Viewer. The exact dates used for this analysis are listed in Table 1. The remote sensing scenes were Landsat 4-5 TM images. Landsat TM has a resolution of 30 meters, which is considered suitable for mapping snow in drainage basins, according to Hall, Riggs, & Salomonson (1995). Images were downloaded if they had cloud cover less than 10%, but images with cloud cover as high as 20% were downloaded if they were the only images available. Path 43 row 33 was used, as it covered the American River Basin in one image. Each image came with remote sensing bands 1-7. All the images used are from the Feb-April time frame, as April 1 is generally considered the date of the heaviest snowpack (Mote et al., 2005).

The annual snowfall records for Donner Summit for 1985-2011 were obtained from the Central Sierra Snow Laboratory web page. The data for the Folsom Dam storage capacity were downloaded from the California Department of Water Resources, California Data Exchange Center. The data collected were for the years 1985-2011. The station identifier was FOL and the monthly data were for reservoir storage capacity in acre feet. The highest monthly storage for each year was used as the peak storage for that year.

Table 1-Dates of Landsat images

Date of Landsat image
2/23/85
3/1/87
3/19/88
3/22/89
3/9/90
4/13/91
3/1/93
3/20/94
3/7/95
4/26/96
3/12/97
3/15/98
3/18/99
3/4/00
3/7/01
2/6/02
3/29/03
3/15/04
4/6/06
3/8/07
4/11/08
3/29/09
4/17/10
4/4/11

2. Software Tool

The main software package used for remote sensing analysis was IDRISI32. IDRISI is one of the software packages used for the analysis and display of geospatial raster data. The software has an analysis package which allows the user different options to analyze imagery. This program uses remote sensing analysis and spatial modeling to create new data. IDRISI is a GIS analysis package for basic and advanced spatial analysis, including tools for surface and statistical analysis, decision support, and change and time series analysis.

3. Data Preparation

Before the data were analyzed, a number of steps were needed to prepare the data. The data were downloaded from the USGS Landsat site and then imported into IDRISI and converted to GeoTIFF format. To make sure all images covered the exact same area, each image was windowed to the same coordinates.

4. Data Analysis Methodology

The analysis used the methodology proposed by Dozier (1989) to map snow cover by using remote sensing of Landsat TM bands 2 and 5. This method is called the Normalized Difference Snow Index (NDSI). NDSI uses two spectral bands to differentiate between snow-free and snow-covered areas. It uses a spectral band in the visible part of the spectrum, TM band 2, and a band in the near infrared, TM band 5.

$$\mathrm{NDSI} = \frac{\mathrm{TM\ Band\ 2} - \mathrm{TM\ Band\ 5}}{\mathrm{TM\ Band\ 2} + \mathrm{TM\ Band\ 5}}$$

NDSI values greater than equal to 0.4 have been found to represent snow cover well (Hall et al., 1995). The next step was to apply this threshold to get NDSI values for each year. An additional threshold was needed to separate snow and water as water can also be mapped when the NDSI value is >= 0.4. In TM band 4 the reflectance of water is <11%. Snow will be mapped when TM band 4 >11% and NDSI <= 0.4. A water mask was created using band 4 and the previously calculated NDSI. The output was the final NDSI value for each image.

5. Data Calculations

To calculate snow acres, the input was the final NDSI value and the output was calculated in acres. All the data for Folsom Lake peak storage and NDSI snow acres were loaded into an Excel spreadsheet by year. Then an analysis was conducted using bar graphs and scatterplots.

Discussion and Results

The analysis first calculated a NDSI value for each year. Then a snow threshold was applied for every year. A water mask was created to mask out water bodies before the final snow acres were calculated. The calculated NDSI was used to get the final snow acres for each year.

The snow acres for each year are shown in Figure 6.

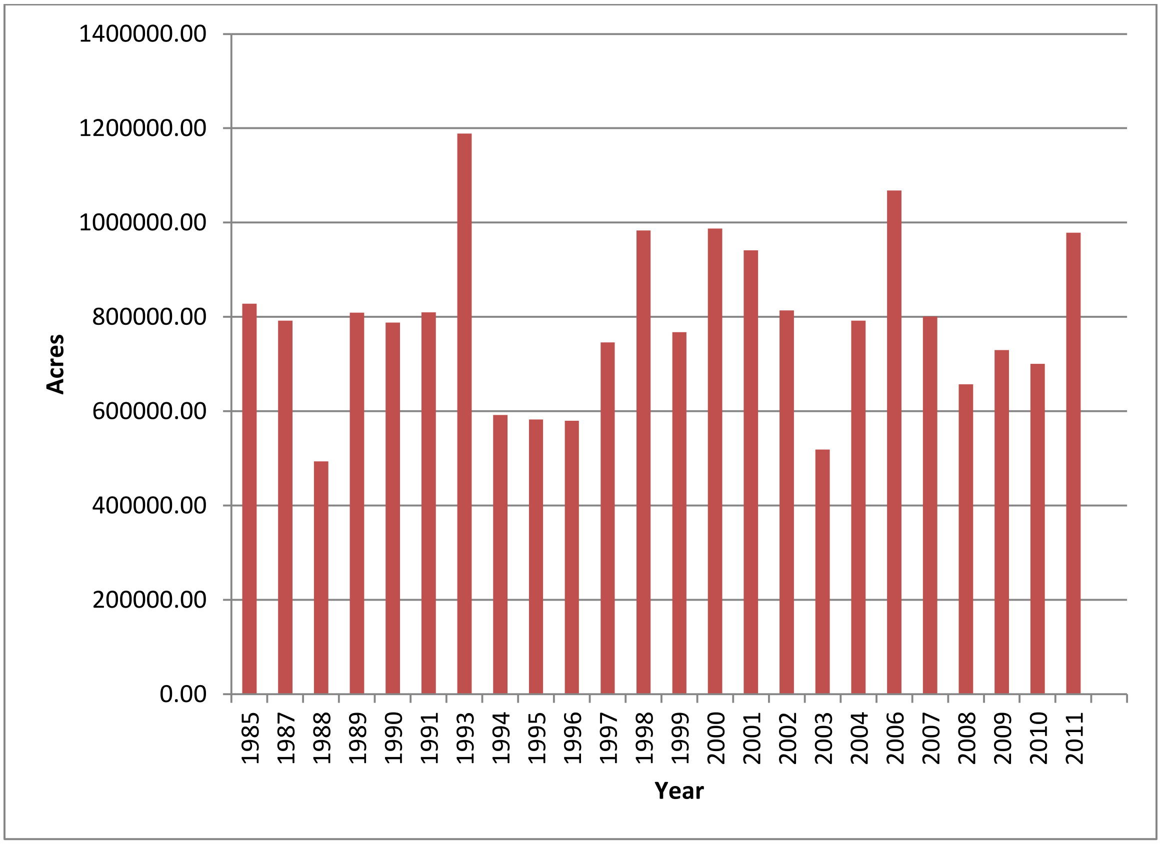

Figure 6- NDSI snow acres by year for 1985-2011

Peak storage at Folsom Lake and NDSI snow acres are shown in the graph in Figure 7. Most years show a positive correlation between peak storage and snow acres. There are a few years, such as 1990, 1995, 1996, 1999, 2003 and 2009, where the correlation is not as strong as in the other years.

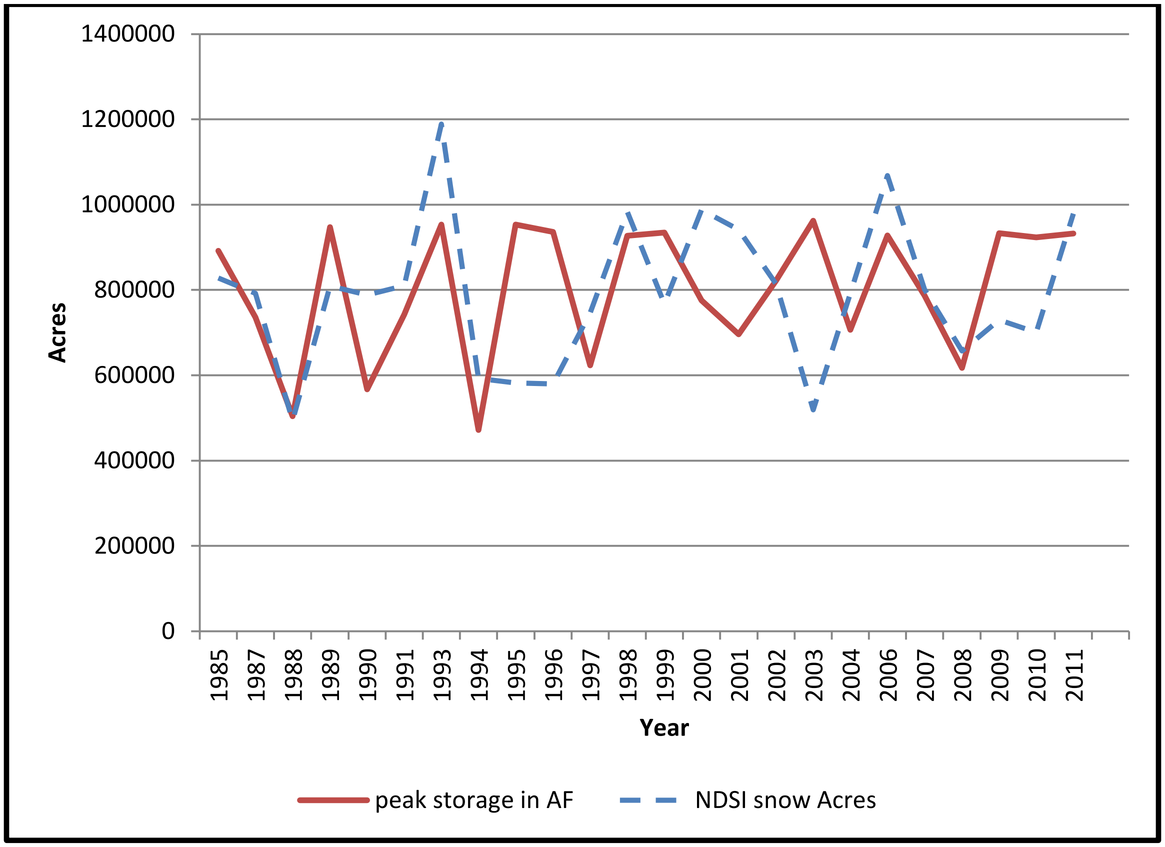

Figure 7- snow acres vs. Folsom Lake peak storage for 1985-2011

There was a positive correlation between snow acres and peak storage in Folsom Lake, as shown in Figure 8.

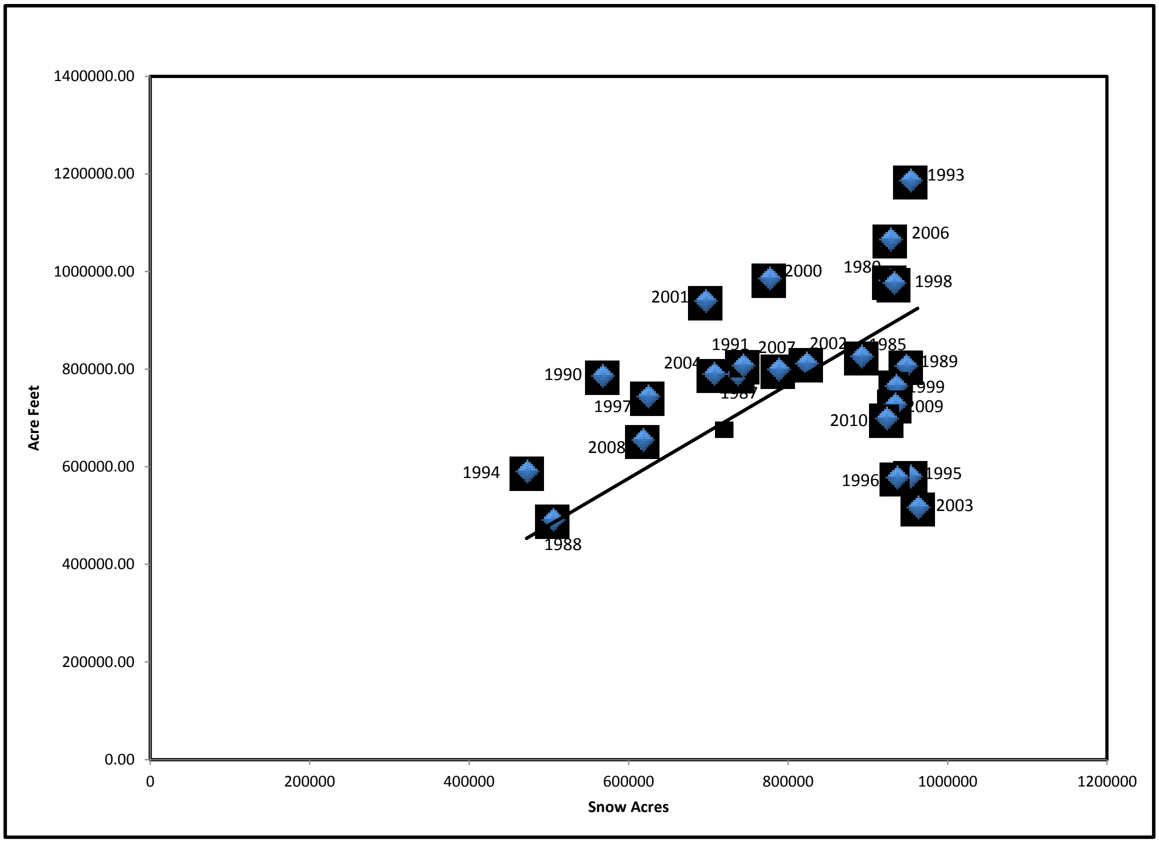

Figure 8-Scatterplot of snow acres vs. peak storage in Folsom Lake

The actual values for peak storage at Folsom Lake and the NDSI snow acres are listed in Table 2. The exact month and year used for the peak storage is listed in Table 3.

Table 2 - Peak storage at Folsom Lake and Snow acres listed by year

Year	peak storage in AF	NDSI snow Acres
1985	891700	828110.00
1987	736000	791824.00
1988	504300	493465.00
1989	947500	809072.00
1990	566800	788376.00
1991	742608	809754.00
1993	953000	1188716.00
1994	471949	592299.00
1995	953056	582279.00
1996	936300	580036.00
1997	623400	746082.00
1998	926916	983629.00
1999	934800	767703.00
2000	775700	987533.00
2001	695800	941372.00
2002	822211	813868.00
2003	962364	518851.00
2004	706553	792062.00
2006	927571	1067872.00
2007	787214	801228.00
2008	617057	657264.00
2009	933141	729831.00
2010	923096	700830.00
2011	932156	978627.00

Table 3 - Peak storage at Folsom Lake by month and year

Date	peak storage in AF (acre feet)
Apr-85	891700
May-87	736000
Apr-88	504300
Apr-89	947500
May-90	566800
May-91	742608
May-93	953000
May-94	471949
Jun-95	953056
May-96	936300
May-97	623400
Jul-98	926916
Jun-99	934800
May-00	775700
May-01	695800
May-02	822211
May-03	962364
Mar-04	706553
May-06	927571
May-07	787214
May-08	617057
May-09	933141
Jun-10	923096
Jul-11	932156

The annual snowfall totals for the 1985-2011 for Donner Summit and the monthly snowfall for the month of each Landsat image acquired for the study are shown in Figure 9.

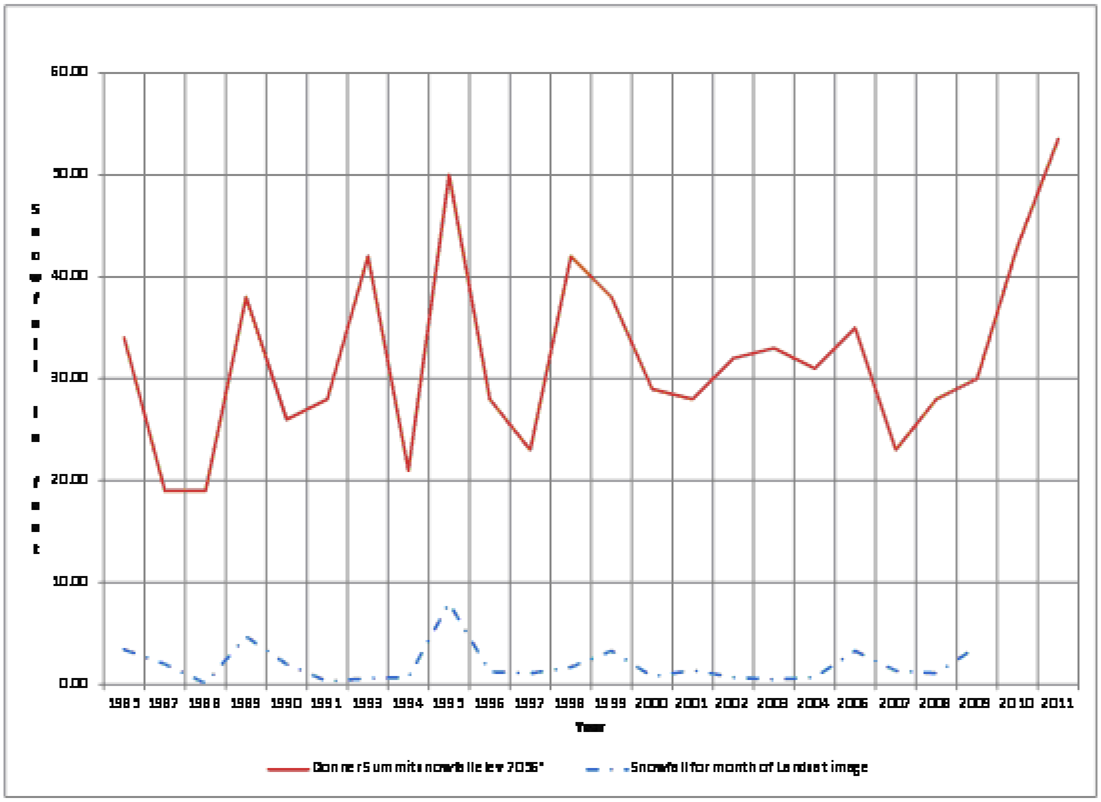

Figure 9-Yearly snowfall at Donner Summit and monthly snowfall at Truckee ranger station

Generally, there is a positive correlation between snow acres and peak storage in Folsom Lake, but there are some exceptions. The snow acres and peak storage do not match every year as the Bureau of Reclamation has seven reasons for releasing water from Folsom Lake. Every year these reasons and their priorities can change causing the release of water to fluctuate by year. The seven main reasons for releasing water from Folsom Lake are flood control, delta water quality or delta salinity, hydroelectricity, domestic use (drinking water), wildlife (salmon and steelhead trout spawning), recreation, and agriculture.

Another possible reason why not all the years show a positive correlation between snow acres and peak storage is the low snow depth on the ground when the image was acquired. In 1990, the image was acquired on March 9. In February there was a snowfall total of 85 inches, and in March there was 25 inches of snow. For this year, there was a dip in the peak storage in Folsom Lake while the amount of snow acres calculated was similar to the previous year. Since the total snowfall for the year was below average at only 26 feet, it appears that the Landsat image was acquired when there was a high volume of snow on the ground.

In 1995, the image was captured on March 7 and although the monthly total for March was 97 inches the total for February was only 13 inches. Because the date was close to February, there could have been less snow on the ground as a lot of the snow in March could have fallen near the end of the month. The total snowfall for 1995 was 50 feet, which would account for higher peak storage at Folsom Lake.

The image for 1996 was captured on April 26, and the total snowfall for April was only 15 inches. Even though the total snowfall for the year was only 28 feet, the previous year, 1995, was a very wet year so there were still high water levels. By looking at the reservoir records it can be seen that it usually takes two dry years before the reservoir will begin to register drought categories according to state definitions.

The 1999, the image was acquired on March 18. The snowfall totals for March were 40 inches but the storms delivering this snow could have occurred later in the month, causing less show to be on the ground on March 18. Above average snowfall occurred in 1998 so there could have been holdover high water levels in Folsom Lake.

In 2003 and 2009 the images were captured on March 29. In 2003, the total snowfall for March was only 6 inches, so it is possible that the snow on the ground was sparse. In 2009, the monthly snowfall for March was 45 inches, but it could have fallen early in the month.

The snowpack is changing in response to changes in its environment. There can be various factors that can influence snowpack changes over time, such as forest canopy changes and land use changes (Mote et al., 2005).

Conclusion

The results showed that it is possible to use this data to get information on snow hydrology but not necessarily in a straight forward way. The interpretation involves human elements as the water released from Folsom Lake depends on many factors that change monthly.

Climate change has had an impact on the runoff timing for the American River at Folsom. According to the California Department of Water Resources (2007), water runoff was 47% in 1985 and was down to 44.5% by 2004. As temperatures increase there is more rain, less snow and an earlier snow melt. Even though more ground area is covered by snow, the depth of the snow has decreased. Springtime snowpack has declined by approximately 10% over the last 50 years (Mote et al., 2005). Declines in the April snowpack have been shown to exist for the Pacific Northwest (Mote et al., 2005). Spring snowpack is one of the more important predictors of streamflow. Most sites used for snowpack measurements reach their peak snowpack near April 1. November to March is the usual snow accumulation season in California.

Estimates of warming trends for the future in the western US are in the range of 2-5 degrees C over the next century (Mote et al., 2005). The losses in snowpack that have been observed will likely continue and this will have critical consequences in an area that already has water use issues (Mote et al., 2005).

A further extension of this study would be to examine the snowfall records of each day of the months involved from the Landsat images for each year. This would give a more detailed analysis of exactly when there were snow storms and when there were periods of no new snow.

In summary, it is important to take note that this study is a snapshot in time of a particular set of days. Results are based on specific days of each year rather than averages for multiple images. Climatic factors play a role in the outcome of the results. Remotely sensed data can be helpful in giving a quick estimate that could be helpful to people who need to manage the water supply.

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