SNOW DEPTH VARIATIONS FROM STORM TRAJECTORY AND MOUNTAIN TOPOGRAPHY IN THE TUOLUMNE RIVER BASIN, CALIFORNIA

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ABSTRACT

The Western United States relies heavily on water from snowmelt to sustain water demand through summer months. Understanding the snow water equivalent (SWE), the product of depth and density, of a snowpack is crucial for budgeting water appropriately. The varied topography of mountainous regions makes measuring snowpack depth difficult. It has recently been demonstrated by the Airborne Snow Observatory (ASO; NASA-JPL) that differential mapping of snow depth with an airborne scanning lidar is an efficient and accurate way to monitor snow depth at the watershed scale. Snow depth time series from ASO in the Tuolumne Basin, CA show that snow does not accumulate evenly. Factors such as the trajectory of a storm, snow accumulation rates, and aspect/elevation can affect snow deposition patterns. Here, we use ASO measured snow depth on April 2014, April 2015, and March 2017 and two acquisitions before and after a precipitation event (April 8, 2015) to assess variation in snow depth across the basin. Results show that the most snow is present on northerly aspects and at elevations from 10,000 - 12,000 feet. Potential for future research includes looking at a different storm event and more basins as LiDAR generated snow depths become available. (KEYWORDS: Tuolumne River Basin, LiDAR, snow depth, Airborne Snow Observatory, remote sensing)

INTRODUCTION

Communities throughout the Western United States rely heavily on water from snowmelt to replenish both surface and groundwater sources, and more than 70% of water resources in many regions of the Western US can come from snowmelt. Having access to more accurate snowpack data is the first step toward better water management practices. The Airborne Snow Observatory (NASA-JPL) has developed a method for calculating snow water equivalent (SWE) at the watershed scale using scanning LiDAR to differentially map snow depth and a physically based snow energy balance model to estimate snow density (*Painter et al.*, 2016). These methods provide the most accurate spatially extensive SWE calculations to date and are being utilized to study spatial/temporal snow processes and are the standard against which snow models can be compared to determine their accuracy.

The scanning LiDAR used by the ASO measures snow depth across the Tuolumne River Basin (Figure 1) every 3 meters with a mean error of < 8cm (*Painter et al.*, 2016). The most important factor when calculating SWE over complex terrain is snow depth. Due to snow metamorphism processes, estimating snow density can be done with more certainty than snow depth, which varies more across the landscape, particularly in mountain watersheds due to many factors including elevation and aspect. Because of these frequent changes in snow depth, it is difficult to accurately interpolate data collected at single points (measurement stations) over a large area.

To further demonstrate the high variability in snowpack depth, here we present ASO data from the Tuolumne River Basin, assessing snow depth by aspect and elevation respectively. Snow depth data from ASO are analyzed from flights made as close to April 1st as possible from the 2014, 2015 and 2017 snow years, which are low, extremely low, and high snow years respectively. In addition to comparing these extreme snow accumulation years, we also look at snow deposition patterns by looking at snow depth before and after a snow event, which occurred on April 8, 2015.

METHODS

Study Site

The Tuolumne Basin is located in the Sierra Nevada Mountains in California. Here we assess snow depth

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in the upper watershed above Hetch Hetchy reservoir. The Tuolumne River Basin was selected because of the availability of LiDAR-measured snow depth data; it is an ASO test basin, and there have been over 50 flights since 2013.

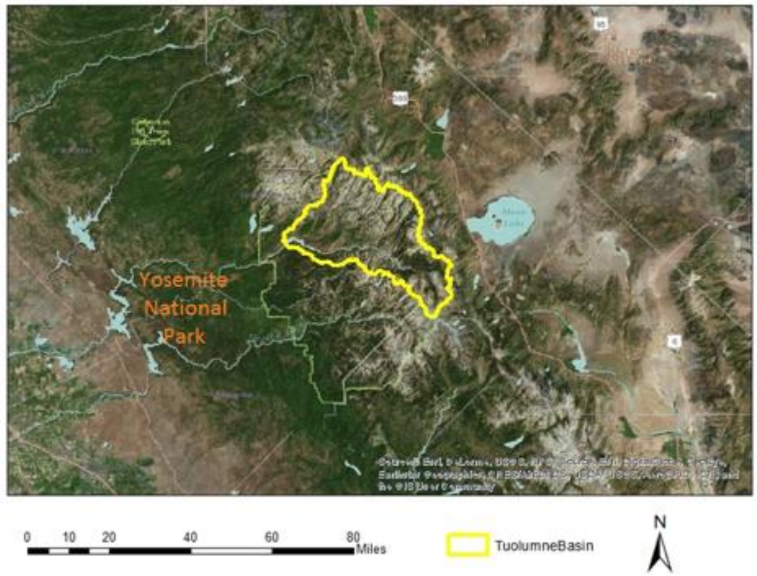

Figure 1. Overview of the Tuolumne River Basin above Hetch Hetchy, located in the Northeast side of Yosemite National Park.

<u>Snow Depth Analysis</u>

Snow depth data from ASO for 2014, 2015 and 2017, was selected as close to April 1st as possible, and then trimmed to the Tuolumne River Basin boundary. Ideally the measurements would be from the same day each year, but the data are only available on days when the ASO made a flight. The flight dates were as follows: April 1, 2014, April 3, 2015 and March 3, 2017. The snow depth data used for the April 8, 2015 storm was calculated by subtracting the April 3, 2015 depth from the April 9, 2015 deptha (Figure 2). A 3-meter Digital Elevation Model of the basin was used to create masks for elevation in 2000 foot increments and 8 different directions for aspect. Snow depth by elevation band was found for each date by extracting the trimmed files by the 4 elevation masks individually. The same process was used to extract each date by aspect (using 8 masks). Histograms were generated for each new map and the mean snow depth recorded. Images were created by draping snow layers over a a 3-meter DEM of the basin.

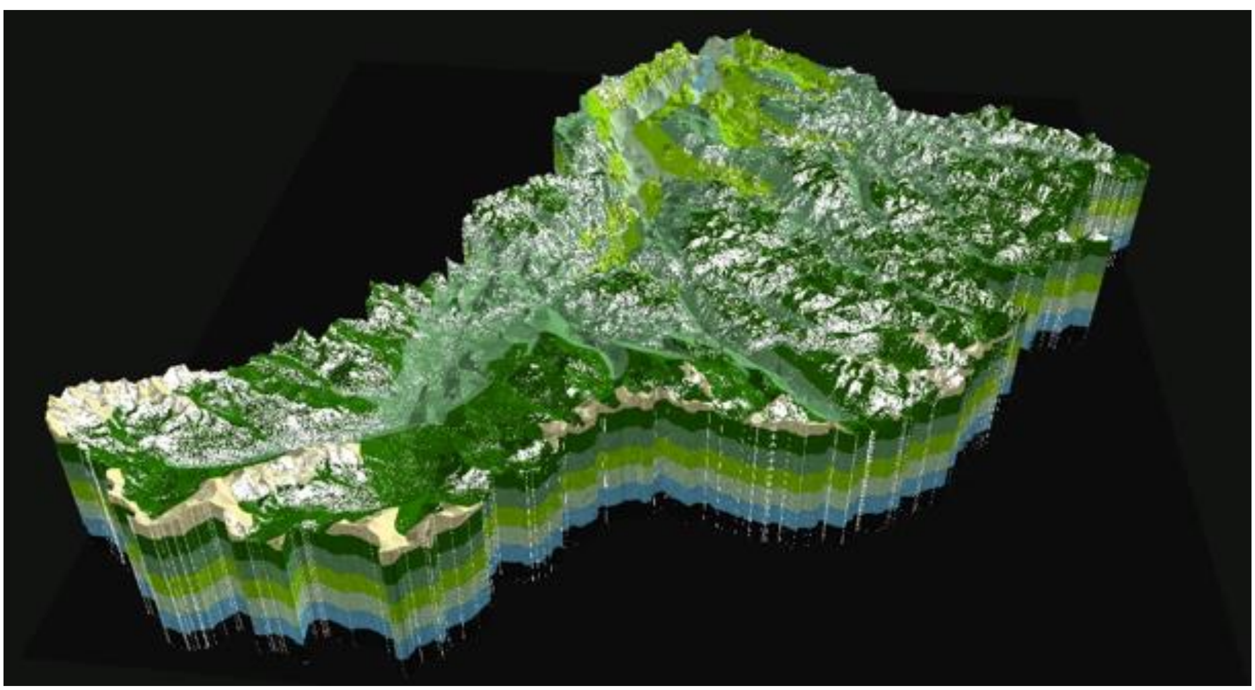

Figure 2. A 3-d cross section of Tuolumne River Basin; highlighting snow on eastern/northeastern aspects from the April 8, 2015 storm. Mean snow deposition for these aspects was 0.9 feet.

RESULTS AND DISCUSSION

Elevation

Snow depth by elevation remains relatively consistent in high and low snow years. The deepest snow is consistently found, not at the highest elevations, but rather between 10,000 – 12,000 feet. The next highest snow elevation band is 8,000 -10,000 feet and then 12,000 – 14,000 feet. The lowest snow depths are at the lower elevation band, between 6,000 – 8,000 feet. There are two notable inconsistences with this trend:

1) In the 2017 (extreme high) snow year 12,000 -14,000 feet has the lowest mean snow depth for that year measuring about one inch less than the 6,000 – 8,000 feet elevation band.

2) In the 2015 (extreme low) snow year 12,000 – 14,000 feet had the second highest mean snow depth with half a foot more snow on average than 8,000 – 10,000 feet.

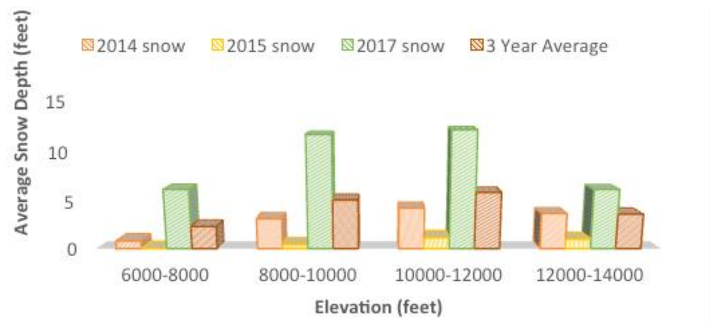

Figure 3. Year to year comparison of mean snow depth by elevation band. The largest mean (12.1 feet) was measured in 2017 from 10,000 – 12,000 feet.

Aspect

Snow deposition by aspect shows both similarities and differences across the three selected years, which represent extremes in total snow accumulation. All three years show a different aspect reporting the highest mean depth: in 2014 the most snow was on northwesterly aspects, in 2015 it was northerly aspects, and in 2017 it was easterly aspects. Despite the differences in aspect, all three years follow a similar pattern of higher amounts on northern and eastern aspects and lower on southern and western aspects.

This difference can be observed in Figure 4, which exhibits a similar pattern for each year. This pattern is most visible when looking at the 2017 snow year when the snow was deepest and thus the pattern is most pronounced.

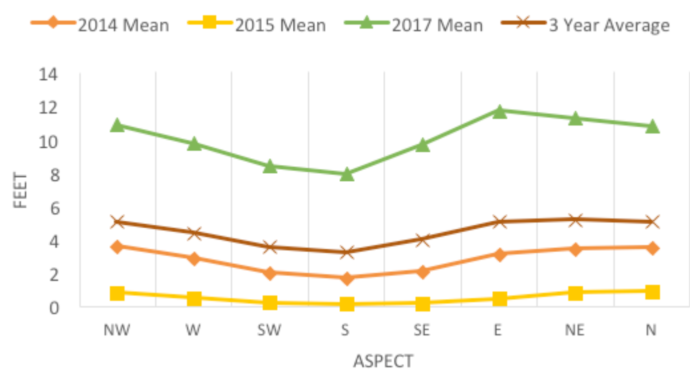

Figure 4. Mean snow depth by aspect. Each year had the greatest depth on a different aspect: 2014 it was northwest, 2015 north, and 2017 east.

Single Storm Snow Deposition

Twenty-four-hour ensemble back trajectories generated from the online version of the HYSPLIT model

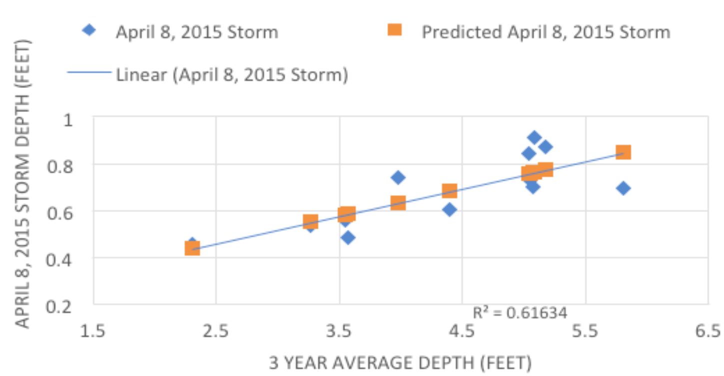

Figure 5. The relationship between predicted, using average measured snow depth, and measured new snow deposition from the April 8 storm (R^2 of 0.62).

(http://www.arl.noaa.gov/HYSPLIT.php) show that the April 8th, 2015 storm approached the Tuolumne Basin the southwest. This is not an uncommon trajectory precipitation events come from the Pacific Ocean and cross California from west to east. Because this is a typical trajectory for a storm in this area, the deposition of snow from the storm should reflect the snowpack distribution. Predicted storm deposition amounts can be calculated using a three-year average of the aspect and elevation data. Predictions generated using the three-year composite can predict the elevation distribution of the storm with an adjusted R^2 of 0.51. The distribution by aspect can be predicted with an adjusted R^2 of 0.56. A storm prediction based on three-year composites of both aspect and elevation can predict the April 8, 2015 with an R^2 of 0.62.

SUMMARY

Snow depth is highly variable across large areas, especially those with extreme terrain. In the Tuolumne River Basin these variations are fairly consistent from year to year with slight variations depending on high relative to low snow years. The most variability found when looking at snow distribution by elevation is from 6,000 – 8,000 feet to 10,000 – 12,000 feet. A mean difference of 3.5 feet is observed between these two elevation bands. The most variability for snow depth by aspect exists when looking at southern aspects relative to northeastern aspect. The mean difference of these two aspects is 1.9 feet. This is not unexpected given the difference in exposure to solar radiation between the two opposing aspects. Our case study of single storm snow deposition indicates that storms that approach the basin with a common westerly or southwesterly trajectory may deposit snow in a predictable fashion. Based on the analyses conducted in this study, storms with a typical trajectory can be expected to favor eastern and north-eastern aspects and elevations between 8,000 – 12,000 feet in the Tuolumne Basin. Future research will include looking at other factors that impact snow depth and snow water equivalent. These factors include snow redistribution by wind, sublimation, snow compaction and densification, snow above and below tree line, and melt rates based on elevation or aspect.

REFERENCES

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