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Gin Flat Snow Water Equivalent Estimation from Field Methods

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Abstract

Snow surveying is an engineering ground inventory procedure that collects snow water equivalent (SWE) measurements, depths of snow, and snow densities. The ability to successfully acquire these measurements accurately allows for an estimate in the amount of water available. We used methods of snow probing, snow coring, and the use of snow pits to find the SWE and density at different locations in Gin Flat, which is located in Yosemite National Park. The results we calculated were different at each site. The SWE values calculated at the snow course were 53 cm using the probing method and 37 cm using the coring method. The SWE values calculated at the snow pillow were 36 cm by probing and 34 cm by coring. There were three groups that split up to take probing measurements of different parts on Gin Flat; these areas will be referred to as Gin Flat I, Gin Flat II, and Gin Flat III. These groups found that the SWE in each area was 39 cm in Gin Flat I, 16 cm in Gin Flat II, and 32 cm in Gin Flat III. Our snow survey measurements were compared to values from the California Data Exchange Center (CDEC) to determine the accuracy and efficiency of snow probing and snow coring. Also, we looked to see if snow courses or snow pillows provided an accurate spatial distribution of SWE. Snow coring was found to be more efficient and accurate compared to snow probing. Furthermore, snow pillows were found to be more accurate in estimated point SWE measurements and provided comparable spatial distribution measurements.

Introduction

In countries with mountainous terrain, snowmelt runoff is a major resource that provides a significant portion of the water used for agriculture, hydroelectric energy generation, recreation, and municipal/industrial water supplies [Johnson and Schaefer, 2002]. In these regions, it is crucial to understand the amount available water and the amount of potential water that is stored in reservoirs; this is because less than one percent of the Earth's water is available for use from non-polluted groundwater, lakes and rivers. Since most of the water on Earth is found in the ocean and unusable in its natural form, freshwater sources must be taken seriously and meaningfully applied.

Globally, it has been estimated that 90% of all the water vapor transported across the midlatitudes is transported within narrow, intense bands of moist air, called atmospheric rivers (ARs) [Dettinger, 2011]. Once the water vapor is transported across the Pacific Ocean within the ARs, it precipitates in the Western regions of the United States. Precipitation that occurs in these regions is much higher in mountains because of the orographic effect. Orographic precipitation is generated by a forced upward movement of air upon encountering a physiographic upland [Dettinger et al., 2004]. The higher altitude catchments receive more precipitation resulting in a snowpack, which is a giant reservoir in the mountains that stores and accumulates the precipitation that falls [Abramovich, 2007]. In the Western United States, a snowpack can provide about 50-80% of the region's water supply; for example, snow contributes up to 67% of the annual precipitation in the Sierra Nevada. Understanding the fundamental processes in these regions allows for a better understanding of water availability or effects of climate change [Meromy et al., 2012]. Climate change increases the rate of snowpack melt leading to the risk of floods becoming more frequent or extreme [Dettinger, 2011]. The snowpack melts faster, which makes forecasting water supply more difficult. It is important to forecast and quantify the amount of water that is stored in snowpacks, which is best exemplified by the notion that it helps Californian farmers determine which crops to grow in each season [Abramovich, 2007].

Snow surveying dates back to the early 1900s when Dr. James E. Church conducted the first documented snow survey on the Androscoggin River; his purpose was to satisfy and quantify necessary information on water resource management through the snowmelt towards Lake Tahoe [Church, 1933]. Through Dr. Church's work, knowledge of snow melt associated with different aspects of hydrology led to quantifiable results of SWE and better resource management data methods. Its principles and applications worldwide changed over time, however, measuring snow remains a significant challenge [Rasmussen et al., 2012]. Snow surveying is the geographical review of areas with different environments. For example, the degrees of forest canopy, changes in wind velocity, or differences in sky conditions influence the amounts of snowmelt.

Today, there are more advanced methods of measuring snowmelt, like remote sensing processes via airborne and space-borne means. Data collection of snow through an aircraft senses naturally occurring gamma radiation to estimate SWE and has the advantage of being able to measure ice and standing water, which would not be possible through ground measurements. This method also allows researchers to collect a large amount of data at a faster rate. Space-borne methods are performed via satellite imaging which is used to measure spectral bands. The advantage of this method is that a simple calculation can frequently determine snow measurements over a large area. Unfortunately, airborne and space-borne measurements may be inaccurate at times because of issues with snow imaging through cloud cover interference and vegetation occlusion based on the angle of approach. Since no method of snow data collection is perfect, ground, airborne and space-borne collection methods are still in use today. It is important to expand knowledge in snow surveying because it increases the accuracy of estimating our current water resource, since accuracy may currently be the only limitation in the field.

The objectives of this research were to estimate the spatial SWE through the measurement from snow coring and snow pits and to collect snow depth measurements through snow probing. This is accomplished through density measurements with a snow core, probing rods and snow core samples on a snow pillow and within multiple points on a snow course. The goal of this paper is to answer the following 5 questions: (i) are snow pillows an accurate point measurement for SWE? (ii) are snow pillows a good representative of snow course SWE measurements? (iii) do snow pillow/snow courses provide an accurate measure of the spatial distribution of SWE? (iv) does density vary spatially throughout the study area at Gin Flat? and (v) which method (probing v. coring) is the most accurate and most efficient means of collecting accurate data on SWE?

Methods and Procedures

The study was conducted on February 24, 2013 in Yosemite National Park in the Sierra Nevada of California at Gin Flat. Gin Flat is located at an elevation of 2165 m (latitude 37.7655 and Longitude -119.7746), and is the location of a California Department of Water Resources snow course (1930-present) and snow pillow (1980-present), and long-term research sites for the United States Geological Survey, Scripps Institute of Oceanography, Desert Research Institute, and University of California, Merced (Figure 1). Snow water equivalent was measured at the snow pillow, snow course, Gin Flat I, Gin Flat II, and Gin Flat III using a Federal Snow Sampler (FSS). We determined the density of the areas using a snow pit. Snow pillow data for February 24, 2013 was downloaded from the California Data Exchange Center (CDEC) (http://cdec.water.ca.gov/) and used for comparison for the in-situ measurements.

The snow pillow is located on flat terrain with 0-2% canopy cover with rocks (erratic) and small knolls on the outlying terrain. Snow depth measurements were made around the border of the snow pillow with a 3 m probe with 1 cm graduations (Figure 2). We took one snow depth measurement on each side of the snow pillow and two additional measurements 3 m to the left and right of the first snow depth measurement. The average of the three snow depths was considered the mean snow depth for that side of the snow pillow. Overall, there were 12 measurements taken to obtain the averaged snow depth that was representative of the depth at the snow pillow. A snow pit was dug to the ground 15 m from the snow pillow to obtain the mean snow density (kg m-3). Snow samples were measured every 10 cm along the face of the snow pit with an aluminum 1000 cm3 snow density cutter, and each snow sample was weighed on a scale with an accuracy of 0.1 g. The following equation was used to determine SWE from the probing method:

$$SWE = \frac{1}{\varrho_{H20}} \int_{0}^{h} \varrho_s dh$$

where ρ is the mean density of snow and h is the snow depth.

In addition to the probing method, SWE was measured on each of the four sides of the snow pillow using the FSS. The FSS is an aluminum tube; each section is 1 m in length with 2.54 cm graduations. The FSS and snow core was weighed, and SWE was determined by taking the difference between the FSS and snow core and the empty FSS. The average of the four measurements was the mean SWE at the snow pillow using the FSS.

The snow course is located in a meadow and the terrain that was considered flat and open, with a canopy cover of 0-2%. Highway 120, which was covered with snow, ran through the measurement transect near the first sample point, and had no influence on the measurements (Figure 1). The start and end of the snow course was designated by four large trees marked with an orange placards, from which a transect of 10 points were created, making an “X”. The first measurement was taken 36.6 m from the first tree, and the remaining 9 points were measured every 30.5 m. There were 6 measurement points along the first transect, and 4 points along the second. Using the probing method, an additional 2 measurements were taken at each point, 3 m behind and 3 m in front. The mean of the 3 measurements was considered the snow depth for that point. A snow pit was dug adjacent to the transect and the average density was measured. Using Equation 1, SWE was calculated at each point and the mean SWE was determined for the 10 sample points at the snow course. In addition to snow probing, the FSS was used to measure SWE at each point along the transect. The mean SWE for the snow course from the FSS was the average of the 10 sample points.

Gin Flat I was located adjacent to the snow pillow with the transect consisting of 10 sample points, spaced 45.7 m apart, along a bearing of 360 degrees, and located in the Tuolumne River basin (Figure 1). The terrain was considered rolling with north and east aspects, with canopy densities ranging from 0-2%. Using the probing method, 10 snow depths were measured, and 2 additional measurements were taken at each point, 3 m behind and 3 m in front. The mean of the 3 measurements were considered the snow depth for that point. A snow pit was dug at point 7,320 m from point 1 and the average density was measured. Using Equation 1, SWE was calculated at each point, and the mean SWE was calculated for Gin Flat I by averaging the 10 sample points.

Gin Flat II is located adjacent to the snow pillow and snow course, with variable terrain consisting of rocks (erratics), and a canopy cover of 40-60%, and an ephemeral creek (Figure 1). Using the probing method, 10 snow depths were measured every 17.5 m along a bearing of 240 degrees, and an additional 2 measurements were taken at each point, 3 m to the left and 3 m to the right. Similar to Gin Flat I, the mean of the 3 measurements was considered the snow depth for that point. A snow pit was dug adjacent to the transect, and the average density was measured. Again, using Equation 1, SWE was calculated for each point, and the mean SWE was calculated for Gin Flat II by averaging the 10 sample points.

Gin Flat III is located southeast and adjacent to the snow pillow, with variable terrain consisting of rocks (erratics), and a canopy cover of 25-60% (Figure 1). Using the probing method, 10 snow depths were measured along a bearing of 135 degrees every 30.5 m, and an additional 2 measurements were taken at each point, 3 m to the left and 3 m to the right, much like Gin Flat II. The mean of the 3 measurements was considered the snow depth for that point. A snow pit was dug adjacent to the transect, and the average density was measured. Finally, using Equation 1, SWE was calculated at each point, and the mean SWE was calculated for Gin Flat III by averaging the 10 recorded points.

Results

The measured snow water equivalent at the snow course from probing was 53 cm. The SWE at the same location using the coring method was 37 cm (Table 1). The SWE from the California Cooperative (CC) Snow Survey on March 1 was 41 cm. The SWE at the snow pillow site from probing was measured to be 36 cm, while the SWE from coring was 34 cm. The measured SWE at the snow pillow as reported on the California Data Exchange Center (CDEC) was 33 cm. The measured SWE from probing for Gin Flat I was 39 cm, Gin flat II had a SWE of 16 cm, and Gin Flat III had a SWE of 32 cm.

The mean density was 413 kg m-3; this was measured using a snow pit at the snow course. Using the snow core, the average density was 356 kg m-3 (Table 2). The CC Snow Survey on March 1 measured an average density of 370 kg m-3. The mean density measured for the snow pillow by means of a snow pit, was 386 kg m-3. Using the snow depth and SWE at the snow pillow, CDEC had a density measurement of 353 kg m-3 for February 25th. At Gin Flat I, II and III the average density was 372, 466, and 380 kg m-3, respectively.

Figure 4 plots the 4 points of probing versus coring at the snow pillow and the 10 points for the snow course. Both graphs reveal that snow probing has the tendency to record larger snow depth measurements than coring for the same area. The top graph of figure 4, probing versus coring at the snow pillow, shows all points to the right of a 1:1 line. The lower graph shows that the same relationship can be seen with the 10 points at the snow course. Also, the regression line for the data points at the snow course is not equal to 1, confirming a bias towards probing. This reveals that there is a bias towards larger recorded probing values at the snow course and snow pillow.

Figure 5 summarizes the distribution of SWE measurements of the 4 snow sampling sites at Gin Flat. The values recorded for probing at the snow course varied from the max of 74 cm to a minimum value of 20 cm with the median around 62 cm. The 25th percentile was above the average value of SWE at the snow pillow (black dashed line). The values recorded from coring at the snow course varied from 50 cm to 9 cm, with a median of 41 cm. The 25th to the 75th percentile were within range of the average SWE at the snow pillow. Gin Flat I ranged from 50 to 29 cm, with a median of about 40 cm. It should be noted that the data for Gin Flat I was similar in value. Gin Flat II ranged from 37 to 3 cm, with a median of 17 cm; and all the data for Gin Flat II was below the average value of SWE. Gin Flat III ranged from 60 to 12 cm, with a median of 29 cm.

Discussion

The snow course probing method recorded a much larger amount of SWE than coring (Table 1). This was partially due to the group conducting the survey pushing the probe past the snow ice level, deep into the soft soil. It can also be noted that Gin Flat II had a smaller amount of SWE using the probing method (see Table 1 and Figure 5). Table 1 shows the SWE equal to 16 cm, which is much smaller than the other values from probing. Also, Figure 5 shows the majority of the data is much lower than the average SWE recorded from probing at the snow pillow. These results can be explained from understanding environmental factors. The location where the field methods were conducted for Gin Flat II had variable and erratic terrain, as well as a canopy cover of 40-60%. Mountainous terrain shadows play an important role in determining the amount of direct solar radiation reaching a given point [G.M. Gray and D.H. Male, 1981]. The trees surrounding the snow course absorbs, scatters, and reflects the direct beam solar radiation and emits long-wave radiation [G.M. Gray and D.H. Male, 1981]. The amount of direct beam radiation received by the snow surface was reduced by the shading of the trunks and canopy. Canopy interception was a large contributor to snow distribution patterns [G.M. Gray and D.H. Male, 1981]. Depending on the amount of wind in the area, forests have the capacity to accumulate snow. The intercepted snow ultimately finds its way to the ground with some losses by evaporation [Church, 1933].

The values recorded using the coring method resulted in values similar to one another (Table 1). The CC Snow Survey value for the snow course was higher than the values for the snow pillow. In this study, comparing the SWE values of the snow course and pillow suggests that snow course measurements generally favor higher SWE values.

Conclusion

Snow pillows are an accurate point measurement for SWE. The average value of SWE recorded using the coring method around the snow pillow was 34 cm. The CDEC value of SWE for the same snow pillow was 33 cm, an error of 3%. Comparing the average probing values of 36 cm to CDEC, the error was 9%. These values are not far off from each other leading to the conclusion that the snow pillows are accurate for the point measurement of SWE. However, its been pointed out that snow pillows can exhibit large errors from snow bridging, when the snow pillow is partially or fully supported by the surrounding snow [Johnson and Schaefer, 2002]. Johnson and Schaefer discuss other ways snow pillow accuracy can deviate in their research paper but, even though their research reveals the inconsistency of snow pillows, the data collected by our peers does not reveal large errors [Johnson and Schaefer, 2002].

Snow pillows are representative of snow course SWE measurements. Table 1 shows a large difference in the SWE for probing, however, there were errors made in the field methods for the snow course and environmental factors that affected results. Comparing the coring values at both sites reveals that they are similar values of 34 cm at the snow pillow and 37 cm at the snow course (Table 1). These comparable values are result of the 0-2% canopy cover at the snow course, which simulated the same environment at the snow pillow. Therefore, snow pillows are representative of snow course SWE measurements if the sites surveyed are similar in environment.

Snow pillows do not provide an accurate measure of the spatial distribution of SWE. Snow pillows do however provide an accurate point measurement. The snow pillow only records data for a given point at Gin Flat. In reality, the other areas are receiving different amounts of snow. Most notably, the recorded SWE for Gin Flat II was much less than Gin Flat I and III, even though they were following the same probing methods (Table 1). The things that factor into the spatially distributed SWE were the terrain, canopy cover, and aspect.

On the other hand, snow courses provide a more accurate measure of the spatial distribution of SWE than snow pillows. Snow courses take into account a larger area than the snow pillow (Figure 1). Physically, the larger area should provide a more accurate measure of the spatial distribution of SWE than the point measurement of the snow pillow.

Furthermore, density varies spatially throughout the surveyed areas of Gin Flat. Table 2 displays the densities for each of the surveyed areas. Most notably, the snow pits for the snow course and Gin Flat II recorded higher densities than the other areas. Ignoring the errors made for the snow course, the high density recorded from Gin Flat II could be the result of the hydrologic cycles, discussed in the discussion section. The radiation from the vegetation and canopy resulted in a higher density because the snow absorbs more energy, leading to snowmelt. This is also confirmed in the very low average SWE from table 1. It must be noted that the groups conducting the surveys were not professionals, as it was the first or second time using the equipment. However, the results from table 2 show that the density varies spatially throughout Gin Flat.

The results from the study show that snow coring is the most accurate and efficient method of SWE measurement. In terms of accuracy, Table 1 shows similar results for coring at the snow course to the CC Snow Survey conducted four days later. Also from table 1, values of coring at the snow pillow compared with CDEC values for the same day are almost the same, with only a 3 % error. Comparing these to the widely distributed values, it appears coring is less prone to error. Table 2 also shows similar values to both CDEC and the CC Snow Survey results. Looking at Figure 4, there is bias towards snow probing versus snow coring. If the values were one to one, there would be no bias, however, the regression line of the plotted points show otherwise. The probing method generally records larger amounts of SWE, leading to more possibilities of error. Finally, Figure 5 reveals how spatially distributed the values are for both probing and coring. Gin Flat I obtained values close to the average found at the snow pillow, whereas Gin Flat II and probing at the snow course had values lower and higher than the average, respectively. Even though the 25th to 75th percentiles were in the range of the average SWE, it still recorded a much lower minimum value. This could have resulted from hydrological processes stated in the results section. In terms of efficiency, the probing method takes three times as many points and the SWE must be calculated from the average density found by a snow pit, whereas the SWE is found with simple calculation from a single measurement using the coring method. Overall, interpreting the results leads to the conclusion that the coring method for SWE measurement is more accurate and efficient because it takes less points and calculating the SWE is simpler. However, with proper training, the probing groups could record more accurate data.

Further research is needed to determine a more accurate way to estimate SWE because water resources management in the western USA will become progressively difficult to manage due to the ever-changing climate conditions [Meromy et al., 2012]. Water availability affects everything from farmers to the environment. Knowing how much water is stored in the mountains is of utmost importance because it is necessary for life.

Acknowledgements

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SWE, cm

	Probing	Coring	CDEC	CC Snow Survey*
Snow Course	53	37	-	41
Snow Pillow	36	34	33	-
Gin Flat I	39	-	-	-
Gin Flat II	16	-	-	-
Gin Flat III	32	-	-	-

*March 1

Table 1. Snow water equivalent of 5 snow sampling locations at Gin Flat.

Density, kg m-3

	Snow pit	Snow core	CDEC	CC Snow Survey
Snow Course	413	356	-	370
Snow Pillow	386	-	353	-
Gin Flat I	372	-	-	-
Gin Flat II	466	-	-	-
Gin Flat III	380	-	-	-

Table 2. Density measurements at the 5 snow sampling sites at Gin Flat

Figure 1. Gin Flat is located in Yosemite National Park in the Sierra Nevada within the Merced River watershed. Five sites at Gin Flat were used to sample snow depth and measure SWE: Gin Flat Met station, Gin Flat snow course, Gin Flat I, II, and III. Gin Flat I, II, and III areas are located at respective black points. The snow sampling points at the snow course are denoted by the yellow circles and the snow pillow is located at the large red circle.

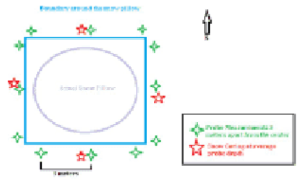

Figure 2. Snow Pillow Diagram. One probe measurement was taken at the center of each side of the pillow (green star). Then, two other probe measurements were taken three meters to each side of the center probe measurement (green star). The average of these three probe depths was the mean recorded as the mean probe depth for that side of the pillow. This was done for each of the remaining sides of the snow pillow. Next, the snow depth was taken using the snow corer around the average recorded probe depth (red stars). This was also done for each of the four sides.

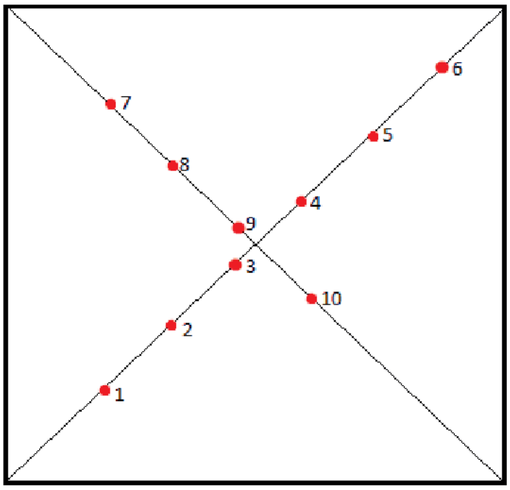

Figure 3. Map layout of the snow course the groups used. The group started at the marked tree (point 1) and proceeded along the transect until point 6. Then, the group started a new transect (point 7) and proceeded perpendicular until point 10.

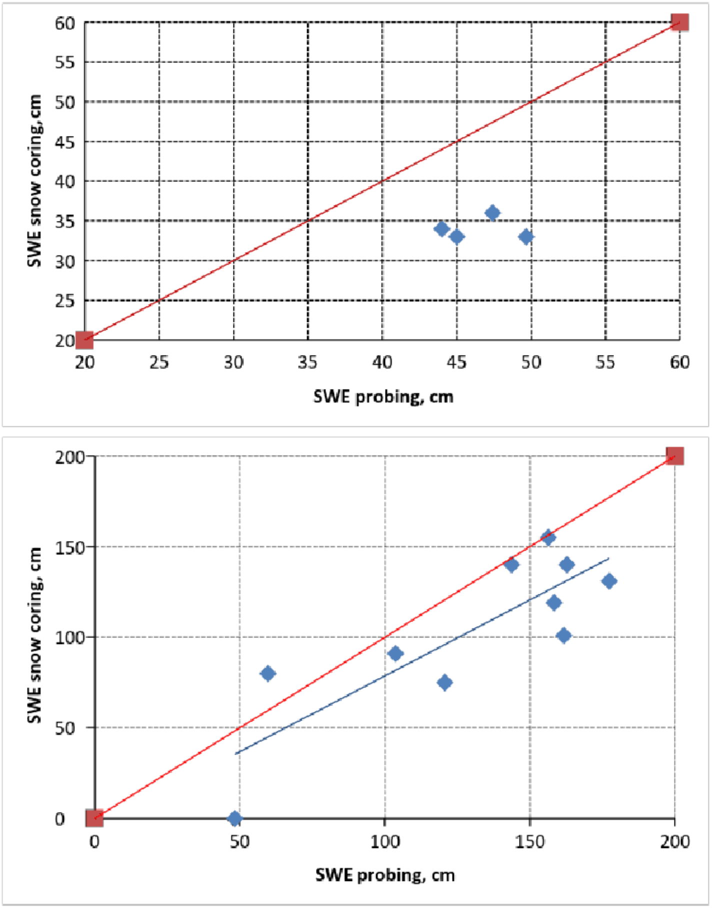

Figure 4. Probing versus snow coring for the 4 points at the Gin Flat snow pillow (top) and 10 points along the Gin Flat snow course (bottom). The red line is a 1:1 line indicating a bias in the sampling methods, while the blue line is the regression line.

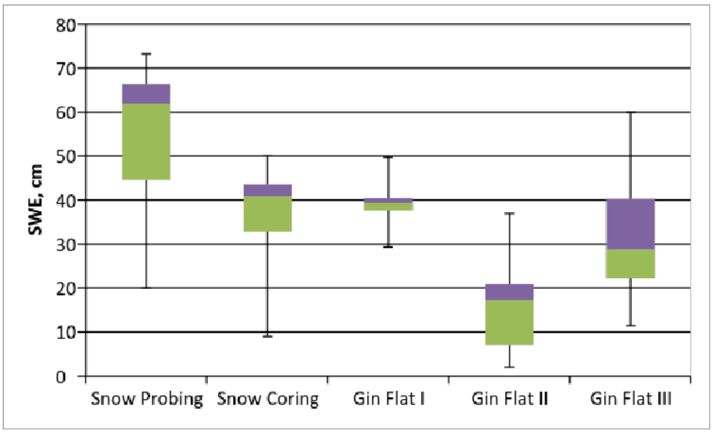

Figure 5. Distributions of measured SWE at the 4 snow sampling sites at Gin Flat. The vertical lines represent the range of measure values, the rectangular boxes represent the 25^{th} and 75^{th} percentiles and thus the middle half of the SWE distributions, represent the median of the spatial distribution. Where the purple and green boxes meet is the median of the spatial distribution. The horizontal dashed line (black) is the average SWE by snow probing on each of the 4 sides of the snow pillow.

Jordan Vida

Jordan Vida is a 4th year Environmental Engineering (ENVE) student at the University of California, Merced, and is expecting to graduate on May 17, 2014. His interest in ENVE arose from the Science Channel from seeing all the environmentally friendly inventions. He got the chance to visit UC Merced during the end of his junior year of high school and quickly fell in love with the campus. Once accepted to UC Merced, he became involved with the school by working for the Dining Commons and joining the clubs: Pilipino American Alliance and Dance Coalition. He got the chance of an internship during the summer of 2013 with Sierra Nevada Research Institute (SNRI), where he fabricated and installed remote sensors in the American River Basin. This project's objective was to better understand the snowpack in the Sierra Nevada remotely. By October 2013, he was offered a student research position for SNRI, where he calculated values for a water balance for meadows being researched. During December 2013, he founded and became the inaugural president of Pilipino Americans in Science and Engineering, a club catering to the academic and professional advancement of its members. After graduating, he would like to get involved with water resource management because it is a big problem in the world today, especially in California.