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**Measuring Variability of a Moderate Snowpack Across a Forest Stand Boundary in the Sandia Mountains**

Adrian Marziliano

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Measuring variability of a moderate snowpack across a forest stand boundary in the Sandia Mountains

by

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COMMITTEE APPROVAL

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ABSTRACT

Mountain snowpacks provide much of the water resources for the southwestern United States. Due to limited freshwater supply and mounting climate stressors, accurate water budget forecasts have become increasingly important. Many regions, such as the lower-elevation mountains found in central New Mexico, lack valuable snow data that could improve these forecasts. The purpose of this research project is to measure and analyze the variability of a moderate snowpack in this region to better understand the representativeness of snow depth distribution and more accurately estimate snow water equivalence (SWE). A survey site with a 1,200 square meter plot in the eastern Sandia Mountains has been established to perform this analysis and to improve the collection of snowpack data in this region. Depth measurements across a forest stand boundary have been compared for the 2019 and 2020 winter seasons to evaluate annual snowpack distribution as well as interannual variability. One snow pit in both the open and forest areas provided density measurements for SWE estimates as well as temperature profiles for energy budget calculations. During 2019, snow depth reached a maximum of 148 cm (mean 83 cm). Maximum depth reached 125 cm (mean 57 cm) in 2020. Snow depth coefficients of variation ranged from 0.2 to 2.6 for both years although depth variability was noticeably higher in 2020. A transition period has been identified as occurring between the accumulation and melt period, whereby snow depth is recorded as increasing and decreasing in different locations across the plot and snowpack temperatures show some variability as they become more isothermal. One transect per 100 m² and about one depth point 20 per m² was required to achieve a representative depth measurement into the melt period during both seasons. A better understanding of snowpack distribution in these water-stressed regions will improve spring runoff forecasts and assist in more proactive water management decisions.
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1. **Introduction**

More than half of the freshwater supply in the western U.S. comes from snowmelt originating as mountain runoff (Li et al., 2017). About 160 million-acre feet (MAF) falls as snow on the mountain ranges of the West annually (Gergel et al., 2017). The Colorado River and its tributaries, which are predominantly snowmelt-dependent, supply water to some 40 million people (Bureau of Reclamation, 2012). Snowpack dynamics which drive mountain hydrology is currently in a state of transformation as winter precipitation is believed to be transitioning to rainfall as average temperatures continue to increase (McCabe et al, 2007; Ye et al, 2008; Cohen et al, 2015). By 2021, about half of snowmelt runoff is expected to decline (Li et al, 2017). This decline has already been realized in some of the West where there have been negative trends in snow water equivalent (SWE) since 1955, especially in states such as California (Mote et al., 2018). The lower elevation snowpacks, where there are greater fluctuations in winter temperatures, have tended to experience larger decreases in SWE. Regions where snowpack is expected to decline are also the places which depend on it the most, whether it’s for recreation, irrigation, or municipal supply (Bureau of Reclamation, 2012). The value of replacing the snowpack lost to future rain events is estimated to be as high as $4.7 trillion (Sturm et al., 2017). The economic losses associated with a decrease in superlative reflectance, or the effect that snow-covered areas have on planetary cooling which balances the global heat budget, are estimated at $575 billion (Euskirchen et al., 2013; Goseman et al., 1994; Warren, S.G., 1982). Gradual temperature increases will adversely affect snowpack volume and persistence due to earlier seasonal snowmelt periods, and the result will be a negative effect on streamflow (Musselman et al., 2017; Barnhart et al., 2016). This decrease in spring runoff availability, along with prolonged drought periods, will continue to stress forested areas in these Western US
mountain regions (Marlon et al., 2012). Such effects have already contributed to more forest fires in the western U.S., which have also increased in size and severity (Westerling et al., 2006; Miller et al., 2009). Since the availability of snowmelt runoff is partly dependent on the forested areas in the mountain ranges of these regions, the snowpack and energy budget will be drastically affected by the depletion of forest canopies (Burles & Boon, 2011, Bales et al., 2006). Thus, it is becoming increasingly important to obtain accurate estimates of water supplies stored in mountain snowpacks, both on a regional and local level.

The Southwest is a region in the U.S. characterized by complex topography with steep temperature gradients and variable wet-dry seasons. These factors make managing water supply difficult as trends of increasing temperatures and winter precipitation variability continue to stress an already scarce resource (Mote et al, 2018; Bales et al., 2006; Goodrich and Ellis, 2008). New Mexico is one such state in this region with limited water supplies that are heavily reliant on snowmelt. Roughly two-thirds of the water above Elephant Butte reservoir is generated from snowmelt (Li et al., 2017). As with the rest of the West, this supply is expected to further decline. The Valles Caldera, for example, has already seen a negative change in its mass snow balance due to large burned forest sections left from the Las Conchas fire in 2011 (Harpold et al., 2014). Since discharge from snowpack in this area relates directly to a large portion of ecological production and stream metabolism, negative effects on the riparian ecosystem are likely with the decline of annual snowpack accumulation (Shafer, B., 2013). As these adverse trends in snowpack accumulation and snowmelt processes continue, changes in mountain vegetation in an already semi-arid state are expected to follow (Harpold et al., 2014; Anderson, R.Y., 1961).

The eastern Sandia Mountains is another location in New Mexico where rising temperatures and precipitation variability will likely affect the local water supply and vegetation
distribution. Unlike the Valles Caldera, there is a lack of published snowpack research in this mountain area, making it difficult to estimate annual spring runoff and recharge. Groundwater reports published by Bernalillo county and the USGS mention snowpack as a main source of recharge for local groundwater sources in what Bernalillo county refers to as the East Mountain Area (EMA) of the Sandia and Manzano mountains (McGregor, D.L, 2008; Bartolino et al., 2011). Snow is mentioned in these reports alongside summer monsoons as a primary water source for groundwater recharge. However, no data regarding snowpack accumulation for the area is included. The USGS also published a separate report on precipitation and groundwater recharge for the eastern Sandia Mountains where monthly SWE values (January through April) were included for years 2001, 2004, 2005, and 2007; however, the data is sparse and there has been no evidence of continued analysis or data collection related to this work (McCoy & Blanchard, 2008). Sandoval county, the next county north of Bernalillo which shares a portion of the northmost end of Sandia Mountains, attributes some of its residents’ water supply to snowmelt from the Sandia Mountains but provides no other information on snowpack (Johnson & Campbell, 2008). The Cibola Ranger Districts of the US National Forest service published an assessment for a report of trends and risks to sustainability in the Cibola National Forest; however, there is no mention of snowpack as a water source nor any acknowledgement that a lack of snowmelt may increase fire risk (Kohrman, E., 2015). The mention of snow as a water source along with the lack of any in-depth snowpack analysis reveals a gap in information for this area of the state. A more comprehensive understanding of snowpack dynamics in this region is needed to provide better information to the county officials and forest managers mentioned above for more accurate water supply estimates. Ultimately, this will lead to more sustainable water management plans for all users in the EMA and the surrounding area.
Research completed in this paper provides an important step towards filling the information void for snowpack accumulation and snowmelt runoff in the eastern Sandia Mountains. In order to make advancements towards achieving accurate water estimates from snowmelt, a research site has been established whereby snow depth and density data may be collected and analyzed. Methods from a previous study of snow depth distribution have been adapted to form a single plot at this research site whereby depth transects can provide insight into snowpack accumulation as well as melt patterns (Lopez-Moreno, 2011). Since the plot scale ultimately differs from the scale where water management decisions will be made, proper analysis and understanding of snow distribution on this scale will be useful for future survey design rather than basin-wide water estimates. In other words, the measurements at the plot scale are to be used first to understand the process scale in order to better analyze larger scale snowpacks in this region in the future (Blöschl, G., 1999). Snow density and temperature are also useful to study snow processes in more detail to better understand the factors that contribute to the snowpacks’ energy budget and snowmelt timing (Jennings et al, 2018). A more complete understanding of these processes will illustrate how snowpack under canopy may be less sensitive to interannual variability and mid-winter melt, which is highly valuable to forest management strategies (Moloch, 2009). The data collected may also contribute to research on snowpacks in lower-elevation, lower-latitude mountain regions.

To begin establishing this research site, two years of snow depth measurements between an open and forested area have been compared and analyzed to determined spatial variability of snow depth distribution across the selected plot. The following two research questions have been proposed:
1. How many depth measurements are needed to obtain a representative observation of conditions in a 1,200m² area containing both forested and open sections?

2. How does SWE variability and distribution change across the forest stand boundary during the melt period?

In order to achieve the results needed to answer these questions, the following objectives were created:

A. Observe patterns of spatial and temporal snow depth distribution throughout the accumulation and melt phases.

B. Use statistical analysis to identify snow accumulation patterns and changes in depth during the melt period.

C. Record snow pit density and temperature observations to estimate energy fluxes and record when the snowpack becomes isothermal.

This research project provides answers to the research questions stated above in order to begin the process that will lead to more readily available snowpack information for the Sandia Mountains. Such information can be utilized to further progress snowpack research, which could ultimately lead to providing more accurate SWE estimates for such users as county water supply managers and the local forest service.

2. SITE DESCRIPTION

2.1 Site Area

The 10k research site is located on the eastern side of the Sandia Mountains. This eastward-tilted fault block is distinguished by a steep elevation gradient on its west side, which is made up of Precambrian crystalline rock while the crest and eastern slope are capped by
Paleozoic sedimentary rock (Kelley & Northrop, 1975). The Madera Limestone formation found here is responsible for transporting snowmelt runoff generated in the higher elevations of the Sandia Mountains, especially to water users in the Placitas area (Johnson & Campbell, 2008). This mountain range, along with the neighboring Manzano mountains, is part of the Arizona/New Mexico Mountains Ecoregion, which includes most of the mountain ranges in both states. This region is characterized by snowmelt and summer monsoons for the majority of its natural water supply (Sleeter et al., 2013).

The greatest amount of the snow precipitation occurs on the upper eastern slopes of the Sandia Mountains. Therefore, snowmelt runoff drains into the Western Estancia, Rio-Grande-Albuquerque, and Rio Grande-Santa Fe watersheds. As Figure 1 shows, the parts of these watersheds which receive runoff from the Sandia Mountains are located within Bernalillo, Sandoval, and Santa Fe Counties. (Bartolino et al., 2007; NRCS; Kelley & Northrop, 1975; Bailey, V., 1913). The three major streams on this eastern side are Las Huertas, San Pedro, and Tijeras. Snowmelt from the research site for this project runs off into Las Huertas Creek in the Rio-Grande-Santa Fe watershed, which likely ends up in Sandoval County (Bandeen, R.F., 2005; Kelly & Stewart, 1975). The Cibola National Forest and National Grasslands also cover a vast majority of land on both sides of the Sandia Mountains. Original habitants that lived in the Sandia mountains include the Genízario settlements of the Carnué Land Grand of 1973 (Gonzales & Lamadrid, 2019). This area is also considered to be the original homeland of the Tiwa Pueblos, which include the Sandia and Isleta Pueblos in this region (Dr. L. Tsinnajinnie, personal communication, Oct. 21, 2020).
Figure 1. The location map of the 10k research site in the Sandia Mountains, along with the Western Estancia, Rio Grande-Albuquerque, and Rio Grande-Santa Fe watershed boundaries. Overlayed polygons of the Bernalillo, Santa Fe, and Bernalillo counties are also included. The satellite image shows the proximity of the research site to Albuquerque and the University of New Mexico.

The large-scale weather systems, which account for most of the winter precipitation, transport moisture in from the sub-tropics of the Pacific Ocean. The low-pressure systems that bring snow to the Sandia Mountains tend to be located south of this mountain area. They carry warm air and moisture from the sub-tropics around Mexico and the counterclockwise air movement creates an upslope flow from the east. These air masses move in from the east and, as they rise up westward along the eastern slope, the orographic lift forces the moist air to cool, condense, and form snow precipitation. These weather systems are prone to a northward shift during La Niña years, characterized by cooler Pacific mean sea surface temperatures. During
these periods, less moisture is collected from the sub-tropics, resulting in less winter precipitation (K. Jones, personal communication, Sep. 2, 2020; Dr. D. Gutzler, personal communication, Sep. 2, 2020).

The 10k research site is about 20 kilometers northeast of the University of New Mexico in Albuquerque, New Mexico (Figure 1). The site can be reached from the 10k Trailhead parking lot (Figure 2). As the trailhead name implies, the site is located along the 10,000-ft. (3,048-m.) elevation line. The transect plot is roughly 250 meters north of the parking lot.

![Aerial drone image showing 10k research plot location, roughly 250m north of the 10k Trailhead parking lot. Tree 0 is marked. Open and forest area snow pit locations are also indicated. The decommissioned USGS weather station location is also highlighted, as well as the direction to the Sandia Crest.](image)
This elevation places the site at the beginning of the Canadian-Hudsonian Zone of the Sandia Mountains (Anderson, 1961; Bailey, 1913). The forested area at this site’s elevation, which is key to protecting water supply runoff, is dominated by spruce, fir and aspen trees, (Bailey, 1913; Bales et al., 2006).

A decommissioned, USGS-installed weather station is located roughly 300 meters south-southwest of the transect plot (Figure 2). Data collected from this site was part of a hydrological research project performed by the USGS for Bernalillo County, similar to that published in the USGS precipitation and groundwater recharge report for the Sandia Mountains previously mentioned (McCoy & Blanchard, 2008). Although the USGS stopped publishing data for the station in October 2018, before the research for this paper began, historical data was obtained to characterize the general weather conditions for the winter months. Graphs of this data can be found in Appendix A.

Figure 3. Image of decommissioned weather station (looking northeast). This station, along with another station by the Sandia Natural History Center in Cedar Crest, was used to collect data for a hydrological study by the USGS (McCoy & Blanchard, 2008).
Air temperature is available from December 4, 2013 to October 29, 2018; wind speed from January 12, 2018 to October 29, 2018; wind direction from October 15, 2015 to October 30, 2018; soil temperature from December 4, 2013 to October 30, 2018; and net radiation data from August 9, 2017 to October 29, 2017. The average wind direction from December to April falls around 230 degrees from north (i.e. the southwest direction). The average wind speed is about 2 m/s. Average air temperature is about -1.2°C from December to April with observations ranging from -14.1°C to 9°C for the period of record. During this period, soil temperatures ranged from -3.4°C to 12.4°C with a mean of -0.5°C, and net radiation fluxes ranged from -32 W/m^2 to 154 W/m^2, with a mean of about 32 W/m^2 (USGS, 2018).

The USGS took SWE measurements during a previous project in the Sandia Mountains between 2001 and 2008. As Figure 4 shows, there are some missing SWE values for three of the four years, leaving vital gaps in the representation of snowpack accumulation and melt for these seasons. The report stated that peak SWE was observed in March or April and that the snowpack was typically melted out be the end of April. (McCoy & Blanchard, 2008).

Table 3. Snow-survey data collected by the U.S. Geological Survey at site 1 near Sandia Crest, N. Mex.

<table>
<thead>
<tr>
<th>Month</th>
<th>2001</th>
<th>2004</th>
<th>2005</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>--</td>
<td>1.7</td>
<td>5</td>
<td>--</td>
</tr>
<tr>
<td>February</td>
<td>3.8</td>
<td>5.9</td>
<td>--</td>
<td>3.7</td>
</tr>
<tr>
<td>March</td>
<td>5.5</td>
<td>9.8</td>
<td>16</td>
<td>4.7</td>
</tr>
<tr>
<td>April</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>--</td>
</tr>
</tbody>
</table>

Figure 4. SWE measurements reported during snow surveys for a hydrological study run by the USGS and Bernalillo county (McCoy & Blanchard, 2008).
2.2 Research Plot

The research plot used for this project is aligned to capture variability in the east-west direction since winds are predominantly from the southwest. The plot has been designed with an open and under-canopy area to investigate any forest stand boundary effects that may play a role in the variability of snowpack distribution across these areas as suggested by Webb et al. (2019). The dimensions are 10 m by 120 m for a total area of 1,200 m². The open and forested areas are estimated at 350 m² and 850 m², respectively. The plot is located on a hill with an eastern aspect and a slope recorded at 18°. Thirteen 10-meter transects that run in a north-south direction were established. As seen in Image A of Figure 5, these transects are identified by their westward distance in meters from the southeastern corner of the plot, which is marked by a datum point, ‘Tree 0.' Another 120-meter transect bisects the 10-meter transections. The eastern edge of the forest stand occurs 35 meters uphill from the eastern boundary of the plot in the open area. Spacing between transects for the section of the plot located along this forest stand boundary was decreased from 10 meters to 5 meters to capture higher resolution data and observe variability that may be present in this area. The plot also comprises of two snow pits, one in the open area and one within the forest area. The open area snow pit is located on the northeastern end of the open area, between transects T 0 and T 10 (Figure 4, Image B). The forest area pit is located on the southern side of the forest area, between transects T 80 and T 100 (Figure 5, Image C). These pits are re-buried and marked with a PVC pipe each visit and then re-dug approximately 1-meter southward into undisturbed snow. Two snow pits were deemed sufficient for this plot size since the distribution of snow density is known to be less variable than snow depth (López-Moreno, 2012).
3. METHODS

3.1 Data Collection

Snowpack data were collected for both the 2019 and 2020 seasons. Snow survey observations were made at the 10k site on a weekly basis during the 2019 snow season. Snow depth, density, and stratigraphy observations began on February 8 and ended April 12.

Additional depth measurements were also taken April 25 and May 10 of that year. Observations continued for the 2020 season, starting on December 17, 2019 and lasting until April 28, 2020. December 17 was the only visit made during 2019. Site visits were then made on a bi-weekly
basis from January 14 until March 10, 2020, when the snowpack started to become isothermal. At this point, snow pit observations were recorded weekly while depth measurements continued on a bi-weekly basis. In April, depth measurements and snow pit observations were both recorded on a weekly basis to better capture the changes in snowpack distribution during the melt period. The open area snow pit melted two weeks prior to the final site visit, therefore, the open area snow pit observations ended April 14, 2020. The forest area snow pit was then observed for two more site visits on April 21 and April 28. Snow depth measurements and snow pit observations for both seasons have been published on the CUAHSI HydroShare platform (Marziliano, A, R. Webb, 2020).

Snow depth measurements along the 10-meter depth transects were recorded at 1-meter intervals while depth measurements for the bisecting plot were recorded at 3-meter intervals (Figure 5, Image A). Depth observations consisted of approximately 170 depth points each site visit. Snow depth measurements were taken using a 3-meter-long snow probe that measures with 1-centimeter precision (Figure 6, Image A).

Snow pit data observations were made in the open and forest area snow pits, and included density, temperature, snow grain size, and grain type. Density and temperature profiles were recorded at 10-cm vertical intervals along a smooth working face (Figure 6, Image E). Density was measured using a 1,000-cc wedge cutter and digital scale with a 1-gram resolution (Figure 6, Image C). The cutter weighs about 750 g, which was zeroed on the scale before measurements begin. The density measurements then can be recorded in kg/m$^3$, which can be directly translated to millimeters of SWE. Snow pit temperatures were measured using an analog thermometer with 0.5°C precision and +/- 1% accuracy (Figure 6, Image B). Stratigraphy observations identified
variable layers of snow crystal size and type within the snowpack using a crystal card and hand lens (Figure 6, Photo D).

**Figure 6.** Photos of field research equipment; Image A: author collecting depth measurements in the open area with a 300-meter depth probe sticking in the snow; Image B: hand lens sitting on top of crystal card stuck in a snow pit working face; Image C: wedge cutter measuring snow sample on digital scale and field notebook; Image D: stellar dendrite crystals on crystal card (view through hand lens); Image E: working face of forest area snow pit with fresh snow layer after April 13 storm in 2020; Image F: analog thermometer measuring 0°C at the 30 cm height (from ground) in a snow pit.

Manual hand wetness was also recorded during the snowmelt period, when the snowpack started to become isothermal. These observations began on March 29 in 2019 and February 13 in 2020. Hand wetness was recorded by following the liquid water content classification guide from the International Classification for Seasonal Snow on the Ground and using the code to designate the level of wetness (Figure 7) (Fierz et al., 2009). This information was collected to determine the ripening phase for snowpack energy budget calculations (further described below).
Figure 7. Liquid water content classification (Table 1.5) found in the International Classification for Seasonal Snow on the Ground and used for ‘hand wetness test’ to manually observe and record liquid water content. The codes and mean values of liquid water content (%) in the table, identified with red boxes, were used to determine the melt period for the ripening phase and used in the ripening phase energy budget calculations. For ‘soaked’ snowpacks, 15% was used in the calculation (Fierz et al, 2009).

3.2 Data Analysis

Field data were analyzed using scripts in MATLAB. Snow depth histograms were plotted for each site visit (Appendix B). It was determined that snow depth follows a normal distribution pattern for parametric analysis such as mean depth and the coefficient of variation (COV) to be calculated for each transect. Mean snow depth and COV plots were produced to compare site visits and identify patterns of variability in depth distribution. The change in mean depth was also calculated to study the temporal variability of snow depth distribution. Depth measurements were averaged for the open and forest areas, then multiplied by mean density of the corresponding snow pits to estimate SWE for both areas.
GIS surfaces were created by interpolating snow depth values between known depth measurement points along the plot. Spline interpolation was chosen to create the depth surfaces as it minimizes overall surface curvature, that is, it does not add additional variation in depth, and it preserves the original data points (López-Moreno & Nogués-Bravo, 2006).

Further snow depth analysis utilized MATLAB scripts to randomly select transects and depth point measurements, calculate the means for these selections, and then to relate the representativeness of the mean of each selection to the mean of the total plot for each site visit. The results were compared to Lopez-Moreno’s study of depth measurement representativeness, where 5 depth points were required to achieve a maximum depth measurement error of 10% (Lopez-Moreno et al., 2011). The script utilized the 13 transects T0 through T120 (Image A, Figure 5). The 120-meter-long, bisecting transect was left out of this analysis as it was comprised of a difficult length, spacing, and direction. The depth points of this longer transect were still used to calculate the total mean depth for the entire plot. The MATLAB analysis repeated the random selection procedure 1,000 times for each amount of transects selected before comparing the mean depth of each selection to the total mean depth of all thirteen transects. The absolute difference between the mean depth of the selection and the total mean depth was represented as a percentage and referred to as the absolute residual. The random depth point selection process was operated similarly to the transect selection script, however the random selection procedure ranged from one depth point to 143 depth points. The random depth point selection repeated itself 1,000 times before comparing the resulting mean of selections to the total mean and calculating the absolute residual. The results were used to determine the number of transects and number depth points that were under 10% for a representative measurement.
Snowpack net energy fluxes were also calculated for both years using depth, density, and temperature measurements. This method is described by Jennings et al. as analyzing the residual of the snowpack energy balance (2018). Snowpack wetness observations and change in SWE values between site visits were also included in the calculation. The equation used to calculate cold content and net energy fluxes was adapted from the net energy budget found in the Snow and Snow Hydrology chapter of Physical Hydrology (Dingman, 2015). The adapted equation breaks down the snowpack net energy budget as follows:

\[
Net\ Energy = U_{CC} + U_{Out} + U_{Ret}.
\] (1)

The \(U_{CC}\) term is the cold content, or the amount of energy per unit area (MJ/m\(^2\)) that is required to raise the remaining snowpack’s temperature to the melting point. The cold content of the snowpack was calculated using the following equation:

\[
U_{CC} = -2.012 \frac{MJ}{kg} \times 1000 \frac{kg}{m^3} \times \Delta SWE \times (T_s - T_{mp}),
\] (2)

where \(\Delta SWE\) is the difference in SWE (mm) divided by 100 to convert centimeters to meters for unit homogeneity, \(T_s\) is the mean temperature of the snowpack (°C), and \(T_{mp}\) is the melting point of snow (0°C). The first two terms are constants and represent the heat capacity of ice (2.012 MJ/kg) and the density of water (1,000 kg/m\(^3\)). There is a negative sign because the cold content is considered an energy budget deficit when added to the other two positive energy fluxes, \(U_{Out}\) and \(U_{Ret}\) (Dingman, 2015). The snowmelt output energy term, \(U_{out}\), represents the energy (MJ/m\(^2\)) that melted snow which left the snowpack as meltwater. This was found by multiplying the difference in SWE by the density of water and the heat fusion of ice (0.334 MJ/kg). The energy to melt out the snowpack the is represented by the following equation:
The retained snowmelt energy term, $U_{Ret.}$, is the amount of energy which melted snow that was still retained in the snowpack as meltwater. This is estimated by using the liquid water content values found in Figure 6. The liquid water content for each snow pit was an average of the degree of wetness observed during each visit. These liquid water content values, represented as a decimal, are then multiplied by the density of water and the heat fusion of ice. This calculation is summarized as follows:

$$U_{Ret} = LWC \times 1,000 \frac{kg}{m^3} \times 0.334 \frac{MJ}{kg}$$  \hspace{1cm} (4)$$

All three of the above energy fluxes makeup the snowpack’s net energy flux and are represented in units of MJ/m$^2$.

4. **RESULTS**

4.1 **Snow Depth Measurements**

The maximum snow depth was recorded on March 8 (148 cm) during the 2019 season and February 25 (125 cm) during the 2020 season. The deepest snow was measured between transects T30 and T35, along the forest stand boundary, from February to the beginning of March for both 2019 and 2020 seasons. Starting in mid-March during both seasons, the deepest snow depths were recorded at transect T60, about 30 meters into the forest stand in both seasons. Figure 8 shows interpolated snow depths represented as GIS surfaces for the plot, which provide a visual representation of snow depth distribution described. The deeper snow is shown by the darker blue areas and shallower snow in red. Depth surfaces in April show that deeper snow persists longer at transect T60 as the melt period progresses during both seasons. Another result
illustrated with these surfaces is that there are larger areas of deeper snow in the 2019 season. This corresponds with higher snow depth levels seen for 2019 in Figure 9. The larger variation of colors between transects T 30 to T 60, seen mostly in February of 2019 and through most of 2020, suggests there may be higher variability in depth at this forest stand boundary. The open area was recored as melted out on April 26, 2019 and April 28, 2020. The area around transect T 80 seems to also begin to melt out around the same time, however, more of this section was melted out during the 2020 visit. Finally, the visit during May 10, 2019 recorded new snowfall during a late season snow storm, with depths ranging from 4-18 cm. This leads one to assume the snowpack had melted out at the plot sometime before this date.

Histograms of snow depth measurements for both seasons show a normal distribution for the accumulation phase, with the majority of the depth measurements falling relatively symmetrical around mean depth for each visit until snowmelt begins (Appendix B). During the melt period in 2019 and 2020, there are more depth points with no snow in the open area than during the accumulation phase, resulting in right-skewed distribution towards larger amounts of 0 values. Mean snow depth in both the open and forest area remain similar until April for both seasons. Then the mean depth decreases in both areas, but consistently faster in the open area.

The mean snow depths for the open and forest areas during the 2019 season were 85 cm and 80 cm, respectively. In 2020, mean snow depths for the open and forest areas was 57 cm and 58 cm, respectively. The mean depth for the entire plot was 83 cm in 2019 and 57 cm in 2020. Figure 9 shows some variability during the accumulation period in 2019. Maximum snow depth was reached earlier in the open area than the forest area in 2019 before decreasing for a short period. It was after this point that the maximum depth for the entire plot was reached. The values for 2020 show a more even and gradual increase in snow depth during the accumulation period,
as seen in the graph. The spikes in mean depth for both the open and forest area in April 2020 was due to a late season snowstorm that occurred April 13, 2020, one day before the site visit.

![Snow depth surfaces created from spline interpolation on GIS software. Snow depth is indicated by color, with deeper snow in the blue spectrum and shallower snow in the red spectrum. Depth transects are labelled on the left and depth point measurements are marked as black dots. The deepest snow for both 2019 and 2020 seasons can be seen around transects T30, T35, and T60. The open area from transects T 0 to T 30 as well as the area between transects T 80 and T 100 (circled in red for 2019) melt out the earliest. Tree 0 (transect T 0) still has a small patch of snow at the northern side of its base (see red circles) as it protects this snow from solar radiation.](image)

**Figure 8.** Snow depth surfaces created from spline interpolation on GIS software. Snow depth is indicated by color, with deeper snow in the blue spectrum and shallower snow in the red spectrum. Depth transects are labelled on the left and depth point measurements are marked as black dots. The deepest snow for both 2019 and 2020 seasons can be seen around transects T30, T35, and T60. The open area from transects T 0 to T 30 as well as the area between transects T 80 and T 100 (circled in red for 2019) melt out the earliest. Tree 0 (transect T 0) still has a small patch of snow at the northern side of its base (see red circles) as it protects this snow from solar radiation.
As stated above, changes in mean snow depth showed some variability in 2019. The February 15 site visit shown in Figure 10 recorded a small decrease in depth across the entire plot. This was followed by two weeks of increasing snow depths, except for a few transects along the forest stand boundary on February 28. Then in March, there was a period where some transects increased in snow depth while others decreased. The mean depth changes are fairly small during this time, staying within a range of about 15 cm. This lasted until March 29, 2019, when there began a clear trend towards decreasing snow across the transect as the melt period began.

Figure 9. Mean snow depth for the open and forest areas shows deeper mean snow occurred in 2019 compared to 2020. There also appeared to be more variability in overall mean depth changes in 2019 during the accumulation period. The large spike in April 2020 was due to a late-season snowstorm that occurred a day before the collection date.

On April 5, snow depth still appears to be consistently decreasing, but with smaller negative changes across the plot. The graphs for 2020 show a consistent accumulation period. From the end of February to the beginning of March, there is a short period of transition similar to the one seen in 2019 (Figure 10). Like 2019, change in mean snow depth occurs within smaller 15-cm intervals. The difference in 2020 is that this period appears shorter before a clear and more sudden trend of decreasing mean snow depth begins. Snow accumulates again only during the late season storm mentioned above before continuing to melt out.
Figure 10. Change in mean snow depth (cm) for the transects T 0 through T 120. Blue outlined graphs with up arrows refer to collection dates where there are more transects with positive depth changes. Red-outlined graphs with a down arrows refer to overall negative mean depth changes. Orange-outlined graphs with a tilde are in between positive and negative and mean depth change is not large enough (within 15 cm) to be considered completely positive of negative. When there was some doubt in classifying a site visit, mean depth changes for the open area, forest area, and entire plot were also used to determine how the collection date should be identified.

The coefficient of variation (COV) of snow depth for both seasons stayed below 0.4 during the accumulation period until the beginning of April. Then for two weeks, snow depth variability increased but stayed within a range of about 0.2 to 0.6. After mid-April, well into the melt period, variability greatly increased across the plot as the COV jumped to as much as 1.1 in 2019 and 2.3 in 2020 (Figure 11). There was some indication that a larger amount of variability occurred consistently around the forest stand boundary (transects T 30 through T 60) during the accumulation phase, however, it is hard to determine if this variability can be entirely attributed
to the location of the forest boundary. Any such pattern was then immediately overshadowed by an increase in variability across the entire plot during the melt period for both years.

![Graph showing snow depth coefficients of variation](image)

**Figure 11.** Snow depth coefficients of variation plotted against distances along transects. Each colored line relates to a site visit where depth measurements were recorded. The darker blue refers to the beginning of the season and the lighter green refers to the melt period at the end.

Snow water equivalent calculations reveal that peak SWE comes early in the spring season at the research plot (Figure 12). Mean peak SWE for the entire plot in 2019 was observed as 338 mm and occurred on March 21. Peak SWE for the forest area (315 mm) occurred one week before, on March 16, 2019. The range for 2019 was 189 mm to 362 mm in the open area and 219 mm to 315 mm in the forest area. In 2020, mean peak SWE for the entire plot was observed at 254 mm on February 25. The open and forest areas reached their peak SWE on the same date. The range for 2020 was 108 mm to 275 mm in the open area and 97 mm to 232 mm in the forest area. The graphs in Figure 12 show SWE in 2019 and 2020 increasing to higher in the open area during the accumulation phase in, and then a steeper decline in this area once peak SWE has been reached. The SWE values for forest area in both years show a more drawn out melt period.
Figure 12. Snow water equivalent (SWE) for 2019 and 2020 seasons. Peak SWE occurred on March 21 in 2019 (338 mm) and February 25 in 2020 (254 mm). The open area experienced higher SWE values while the forest area had a more prolonged melt period in both seasons.

4.2 Snow Pit Temperature and Density

Temperature observations in the open and forest snow pits revealed the coldest single temperature in the snowpack during a site visit to be -13°C in both 2019 and 2020 seasons. The coldest mean temperature for a site visit was -5.3°C in the open area in 2019, occurring on February 8, and -7.6°C in the open area in 2020, occurring on December 17, 2019. The coldest mean temperatures for forest area were -4.3°C in 2019 and -4.8°C in 2020. Figure 13 shows the temperature profiles in relation to snow pit depth for each site visit during the 2019 and 2020 seasons. These colder temperature readings all occurred towards the surface of the snowpack during both seasons. According to observations, the snowpack began its transition towards isothermal temperatures during the first week of March in both seasons. This period of isothermal temperature profile variation around -2°C and -1°C values lasted until March 21, 2019 and March 24, 2020. After this, snowpack temperatures remained isothermal around 0°C, with the exception of a site visit on April 14, 2020, one day after the late season storm mentioned above. The -1°C values in late March and April for 2019 are believed to be due to user calibration error.
Figure 13. Snow pit temperature profiles for the 2019 (left) and 2020 (right) seasons. Profiles are divided into three categories reflecting phases of progress from the accumulation phase (row A) towards the melt phase when the snowpack becomes isothermal at 0°C (row C). The phase displayed in row B is thought to be a transition period where the snowpack has become almost isothermal, but there are still some instances of variability and the entire snowpack has not completely reach 0°C.

Snow pit observations reached maximum density in the open area and in the forest area on March 29 in 2019. In 2020, maximum density for the open area occurred on March 31 and the maximum for the forest area occurred on April 21, 2020. Density observations range from 182 to 481 kg/m³ in the open area and 165 to 465 kg/m³ in the forest area in 2019. In 2020, observations ranged from 156 to 460 kg/m³ in the open area and 147 to 462 kg/m³ in the forest area. Mean density was 335 kg/m³ in the open area and 334 kg/m³ in the forest area in 2019, and 305 kg/m³ in the open area and 326 kg/m³ in the forest area in 2020. Density profiles also revealed patterns of transition similar to the temperature measurements mentioned above, where the snow was
becoming denser in periods of transitions marked by apparent thresholds. During the accumulation period, from February 8 until February 22 in 2019, density stayed below 350 kg/m³. This was the same for the period between December 17 and January 28 in 2020. Between February 28 and March 16 in 2019, density values increased but stayed below 400 kg/m³ for three site visits. This was the same for the three site visits in 2020 between February 13 and March 10. Then, on March 20, 2019 and March 17, 2020, snow density began to increase to its maximum values as the snowpack transitioned into the melt period.

4.3 Snowpack Energy Budget

Snow pit cold content and energy budget calculations are shown in the above figures. The cold content peak of about 2.7 MJ/m² is recorded at the first site visit in 2019, on February 8. After this, the cold content value drops in mid-February as the snowpack almost reaches isothermal temperatures during a short mid-season warming event. Another cold content peak is recorded on Feb 22, 2019 at 1.8 MJ/m² in the forest area and 1.3 MJ/m² in the open area.

![Figure 14. Cold content estimates plotted for the open and forest area for 2019 and 2020.](image)

Peak cold content for the 2020 season is 2.6 MJ/m² for both the open and forest areas and is observed on February 25, 2020. Between February 25 to March 10, there appears to be a large
drop in cold content, similar to that in 2019. During this same period, the snowpack experiences the largest energy flux for the season, which is calculated at 1.8 MJ/m² in the open area and 0.6 MJ/m² in the forest area.

The cold content calculations for 2019 and 2020 seasons show the open and forest areas to change at roughly the same rate. The cold content also appears to decrease at a very similar rate in both the open and forest areas when there is a large, sudden drop, such as what happened towards the end of February in both seasons. Also similar in both seasons, the forest area appears to consistently have a larger cold content value than the open area until the melt period begins in April.

Net energy flux calculations in Figure 15 show a large drop in mid-February during the 2019 season, driven entirely by a recovery in cold content after an early and short period of melt the previous site visit. Changes in net energy are then mostly positive, with an exception in mid-March where the open and forest area experience negative changes again. After this, net energy changes are positive as the melt period begins. The open area appears to experience a larger variation of change in net energy for both seasons. This variability is more apparent in the open area in 2020 until the end of March, where the energy fluxes start to follow a similar pattern. The final drop in the net energy flux in 2020 is most likely due to the late-season storm mentioned previously.
Figure 15. Net energy flux estimates plotted for the open and forest areas for 2019 and 2020 seasons.

4.4 Random Depth Point and Transect Selection

Transect and depth selection provided the resulting graphs in Figures 16 and 17, where absolute residual on the y-axis has been plotted against the number of observations. Randomly selected depth points revealed that 47 depth measurements were sufficient to stay within the 10% absolute residual in 2019 while 62 depth measurements were needed to stay within this limit during the 2020 season. As Figure 16 shows, very few depth points (3) were necessary for a representative measurement in 2019 during the accumulation period in February and March. It was not until April, when the open area began to melt, that more depth points were needed. The 2020 season was more variable with regards to depth distribution (Figure 11) and consistently required more depth points to stay within the 10% limit. While three depth measurements were enough for February and March in the 2019 season, a minimum of six depth points were required in February in the 2020 season. This number increase to 10 by March 24, 2020. By the beginning of April, nine depth points were required in 2019 and 13 were required in 2020.
The results for transects randomly selected for each site visit during both seasons reveal that more transects are needed as the melt season progresses (Figure 17). During the beginning of the accumulation period in February, one transect appears sufficient to stay within the 10% residual limit in both 2019 and 2020 seasons. For 2019, one transect was sufficient to achieve an accurate measurement until the beginning of April. In 2020, two transects are needed to stay within 10% by the second week of March and six transects were required by the beginning of April. As the snow begins to completely melt out at the end of April, 11 and 12 transects are required for the 2019 and 2020 seasons, respectively. The plot line for May 10, 2019, a day when

\[ \text{Figure 16. Random depth point selection for 2019 and 2020. Percentage error is plotted against the number of depth measurements chosen. Values of depth measurement numbers and percentage errors are displayed in the boxes to show peak errors around the 10\% limit.} \]
fresh snow had fallen on an already melted out plot, shows how the number of transects needed goes down to three when new snow starts to accumulate again.

**Figure 17.** Random transect selection for the 2019 and 2020 seasons. Percentage error is plotted against the number of transects chosen. Values of transect numbers and percentage errors are displayed in the boxes to show peak errors around the 10% limit.

### 5. Discussion

Snow depth analysis for the 2019 and 2020 seasons revealed snow depth was greater in 2019. This can be seen in both the mean snow depth in Figure 9 as well as SWE in Figure 12. Peak SWE occurred on March 21 for the entire plot in 2019 and on February 25 in 2020. The March date for peak SWE in 2019 is similar to the timing of peak SWE found by the USGS.
study as well as other research results in New Mexico (McCoy & Blanchard, 2008; Harpold et al., 2014; Molotch et al., 2009). The additional snow which fell in 2019 appears to have come in March right before peak SWE. The accumulation period in 2020 seems more consistent and gradual while there is some variability during accumulation in 2019 (Figure 9). Snow depth variability then appears to be greater during the 2020 melt period (Figure 11). Even with these differences, however, similarities in spatial accumulation patterns were identified for both years in similar sections of the plot. For example, the most snow accumulated at the beginning of the forest stand boundary. This could be due to the distribution of vegetation at this area, the aspect of the tree line in relation to the average wind direction and angle of the sun during the winter period, the change in slope between the open and forest areas, or a combination of these and other factors. Fassnacht et al. (2018) suggests that such spatial patterns are temporally consistent, especially in the open area where there are fewer physical features to affect variability. Deeper snow also occurred 30 meters into the forest stand for both seasons. As the melt period began, the deeper snow depths at the beginning of the forest boundary decreased while the deeper areas further into the forest stand took longer to melt. During the melt period, the open area completely melted out at the end of April in both 2019 and 2020. The next area that began to melt out the fastest was 50 to 60 meters into the forest stand, next to the forest area snow pit. This appears to be due to a large opening in the forest canopy at this spot, which can be seen between Transects T 80 and T 100 in Figure 5. This could allow for less protection from shortwave solar radiation in this area. Since the May 10, 2019 visit recorded all new snow during a late snowstorm, it is believed that the rest of the snow tends to melt out sometime between the last week of April and first week of May during both seasons.
Cold content and net energy flux calculations also illustrated the role of the forest stand in protecting the under-canopy snowpack from shortwave radiation during the melt period. The larger variability of net energy fluxes seen for the open area in Figure 15 illustrates how the forest stand insulates the snowpack from energy fluctuations. This can also be seen in cold content graphs in Figure 14 where the forest area cold content is generally larger than the open area until large decreases occur, signifying the possible melt periods. As well, SWE is shown as decreasing at a slower rate in the forest area in Figure 12. This important feature of the forest stand regulates snowmelt and the timing of runoff in the spring (Musselman et al., 2008). These findings support the assumption that if there were no forested areas, the rate of snowmelt in Sandia mountains would look a lot more like the blue open area line in the graphs. Melt periods that warm the snowpack and reduce cold content at a faster rate, as seen in mid-February in 2019 as well as early March in 2020 in Figure 14, do not appear to show any insulating effect from the forest stand. More analysis of these processes could help in understanding the ideal balance of forest density and snowpack persistence, which could guide forest fire mitigation practices run by the forest service.

A period of transition in mid-March, between the accumulation and melt phases, was first discovered by studying the shift of maximum snow depth from the forest stand boundary edge to transect T 60, 30 meters into the forest stand. This period was further defined as mean change in snow depth varies between smaller positive and negative values across the plot (Figure 10). The coefficient of variation in depth ranges from 0.4 to 0.6, more variable than the COV range of 0.2 and 0.4 found during the accumulation phase. Snow density also increases from a maximum of 350 kg/m² to 400 kg/m². Temperature profiles appear to become relatively isothermal, but still have not reached 0°C as the snowpack fluctuates with diurnal temperature variability at this time.
This is likely the reason why temperatures are still negative closer to the surface, seen clearly in section B of Figure 13. This transition period appears longer and more pronounced during 2019. Although there is evidence of this period occurring in 2020, a more rapid trend towards decreasing mean snow depths across the plot is found during this season. The longer transition period in 2019 could explain how SWE increased to higher levels when compared to 2020. More robust data on precipitation and weather conditions for both years would be needed to provide a better answer for this suggestion. The shorter transition period in 2020 could also explain the higher overall variability that’s seen in that year when comparing the coefficients of variation in Figure 11. The temperatures recorded on February 15, 2019 stand out as the entire profile almost entirely becomes isothermal at 0°C.

A better understanding of this transition period would be helpful in determining the variability of snow during different periods for appropriate survey designs. It may also provide more insight to determine what phase the snowpack is experiencing at a given time during the winter season, which could help recognize early melt periods to adjust estimates for water supply budgets. According to Jennings et al., shallower snowpacks at lower elevations are more prone to rapid changes in net energy from surface energy fluxes (2018). Although this type of early melt event was only captured once in February of 2019 and was very brief, it points out a potential vulnerability the snowpack at this site could have in the future as rapid temperature fluctuations are expected to continue (Li et al., 2017; Sturm et al., 2017). Periods of warming temperature fluctuations can start an early transition period, causing the snowpack to become isothermal early on and ready to melt out. This is best illustrated in Figures 10 and 14 during mid-February in 2019. More in depth analysis of this transition phase with more continuous data of snow depth, snowpack temperature, and energy fluxes could provide a better determination if such a
transition period exists each year as well as how much it may vary. A more defined period of transition could assist in revealing which lower elevation snowpacks are more prone to winter droughts and earlier melt periods. This analysis could also potentially highlight which regions are most in danger of completely losing annual snowpack accumulation.

The higher variability mentioned for the 2020 season was also apparent in the random snow depth and transect selection analysis. Although 47 depth points were sufficient for a representative measurement in 2019, at least 62 points were needed in 2020. When randomly selecting 10-meter transects during the accumulation and transition periods, results showed that one transect would achieve an accurate measurement in 2019 while up to six transects were needed in February 2020 to provide enough accuracy to stay within the 10% absolute residual limits. As the melt season progresses into mid-April, almost all of the transects are needed to maintain an accurate measurement. This is most likely due to the fact that the open area has melted out by this point. These results suggest that location and spacing between depth points is highly important (Fassnacht et al., 2018). By comparing results from both methods of analysis, it appears that two transects spaced at least 5 meters apart and consisting of 10 depth points would suffice at gathering a representative measurement during the accumulation and transition periods in either year. When compared to the plot area, the required measurements would amount to one transect per 600 m² and one depth point per 120 m². During the melt period, however, the requirement increases in April to 12 transects and 62 depth points, or 1 transect per 100 m² and about 1 depth point per 20 m². This increase is most likely due to the higher variability that occurred when the open area and areas under larger gaps in the forest canopy began to melt out. More analysis would be required to determine how to better design an effective snow depth survey that results in representative measurements within the error limit. Greater spacing
between depth points, or increasing the plot size, may provide more acceptable results. Another potential more for accuracy may be to use a different depth point layout, such as the ‘plus’ shape of 21 points which produced a more accurate mean in Fassnacht et al. (2018). A higher resolution of depth data may also be required to achieve a better assessment of the transect design at this plot.

5.1 Users of Sandia Snow Data

Although there is currently a lack of published snowpack-related research for the Sandia Mountains, there are many different user groups that could benefit from such data being readily available. The Cibola National Forest Mountain Ranger Districts can utilize information related to the spatial variability of snow accumulation to better manage optimal forest thinning techniques. Such a technique could make use of snow survey design suggestions from this research to achieve a forest density that minimizes the risk of forest fires. Research previously performed by the USGS for Bernalillo County could be progressed in order to provide county hydrologists and water managers with more accurate groundwater supply forecasts. With more consistent annual snowpack data from the upper Sandia elevations, local well water users and water suppliers would be able of more accurately estimate recharge estimates and supply budgets. Recreational services, such as the Sandia Peak Tramway & Ski Area, located at the same elevation and less than 2 kilometers south of the research site, could greatly benefit from snow accumulation data. Finally, the snowpack research community could also benefit from data at such a unique site as the Sandia Mountains. Although research is well-established in the United States and Canada, few snow sites are located so far south. Collecting more data in a moderate, lower elevation snowpack found in the Sandia Mountains will contribute to a wider variety of snowpack and related snow processes available to researchers across the discipline.
5.2 Future Research

Understanding snowpack dynamics at the plot scale is the first step in establishing a long-term research site to better understand the processes occurring during the accumulation and melt periods. Eventually, this understanding can be applied to broader-scale analysis to determine how these processes affect the timing and magnitude of spring runoff and how this affects the supply of water in this region. Future research can utilize the characterization of this site, as well as snow depth distribution and snow survey design results to continue measuring snowpack at scales more useful to managers dependent on this information listed above.

Snow temperature profiles have been useful in determining the patterns in the transition to isothermal snowpacks as well as the calculation of the cold content and net energy fluxes. As these values were only recorded at two snow pit locations, it would be useful to collect a more robust dataset of snowpack temperatures. This could be done by creating temperature posts to be installed at the site with temperature sensor-loggers (e.g. ibuttons) to gather continuous data for the entire winter season. Multiple posts could be installed across the plot, similar to the locations of the depth transects, to analyze patterns that occur across forest stand boundary. Such information could provide a greater understanding of the melt period and how the forest stand intercepts and transmits surface energy in relation to snowpack temperatures. Since these shallower snowpacks at lower elevations are considered to be more susceptible to early melt cycles from fluctuations in surface energy, such data would be valuable to the research community as well as future efforts in predicting snowmelt patterns in this region (Jennings et al., 2018; Musselman et al., 2008).
As shown in the energy flux calculations for this project, the liquid water content is important when understanding snowmelt processes. Liquid water content for this project was recorded using a subjective method of using one’s hand to determine amounts of meltwater remaining in the snowpack. During the 2020 season site visits, data was collected to test a more comprehensive method for determining liquid water content. Snow calorimetry was utilized along with measurements from an A2 Photonics WISE sensor to develop an equation for in-situ field measurements of liquid water content in a snowpack. As this was the first year collecting data for this project, work is expected to continue at this and other sites. Once fully developed, this method would provide much more accurate measurements of liquid water content. Such a method would also allow for more accurate measurements to obtained with such applications as aerial SWE observations using radar. This work is another example of how continued work on the 10k research site can benefit the greater snow research community.

5.3 Repurposing the Weather Station

As mentioned before, the weather station located very close to the 10k plot was installed by the USGS for a previous hydrologic study, but decommissioned before this research project began. Data such as air temperature, soil temperature, and net radiation would have been very useful to compare with data collected across the plot. Net radiation values could have been compared to the ones calculated from the snow pit data to determine the accuracy of such a method of estimation. The continuous data this weather station could have provided would have allowed for a greater understanding in the diurnal fluctuations that occur at this elevation, something that would be impossible to achieve with site visits. At the time of writing, there are efforts to restart and repurpose the use of this weather station to begin gathering data at this site again. The plan is to continue gathering similar weather observation parameters that were
collected before along with added instrumentation for snow observations. It is believed that continuous data collection in conjunction with data from this weather station would allow for greater progress in snowpack analysis that will eventually lead to forecasting water supply availability for the forest area and residents of the East Mountain Area. This weather station data would also have multiple other applications and be useful to many other users, including for recreation, weather forecasts, aviation, rescue operations, and general awareness of weather patterns at this elevation and in this climate.

6. **Conclusion**

The research performed at the 10k site was the first step in establishing a baseline for future snowpack analysis to be completed. The proposed research questions were answered in order to develop a useful guide for future snow surveys in this area as well as to begin a general understanding of the natural processes that occur in the snowpack at this lower elevation site. Although a number of 62 depth points was determined to be sufficient in accurately measuring snow depth throughout each snow season, the spatial variability during the melt period increased the number of transects required to 12 out of the 13 analyzed. This indicates that greater spacing between depth points would assist in achieving a representative measurement. Energy budget results highlight the importance of the canopy cover in protecting snow persistence in the forest area. A transition period has been identified that could provide further insight when these shallower, low elevation snowpacks could be most vulnerable to early season melt occurrences. The results of this project set up for future research to progress the work that is needed to achieve the analysis methods and data collection that will ultimately lead to better information for water resource management decisions to made.
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8. APPENDICES

APPENDIX A. USGS WEATHER STATION DATA

Figure. USGS Data for decommissioned weather station; A: wind speed, B: wind direction ranges from 140˚W-270˚W, C: air temperature, D: soil temperatures were coldest during 2018 when there was very little snowpack accumulation, E: net solar and long wave radiation peaks at about 200 W/m² in the winter (provisional data) (US Geological Survey, 2018).
APPENDIX B. SNOW DEPTH HISTOGRAMS

Figure. Histograms of depth measurement frequency for the 2019 and 2020 seasons.