# IMPROVED ESTIMATES OF SNOW WATER EQUIVALENT AT NRCS AERIAL MARKERS USING NEW STATISTICAL METHODOLOGY

Jon Lea[1], Matthew Sturm[2], and Jolyne Lea[3]


## ABSTRACT

Natural Resources Conservation Service (NRCS) Aerial Markers snow depth data have been measured since the late 1940s and are located in remote areas of the West. These stations would typically take hours or days of ground travel to visit, so are measured by aircraft over-flights to get a monthly depth reading. This depth reading and an estimate of the snowpack density are used to estimate snow water equivalent (SWE) for use in water supply forecasting. The NRCS historically has used an empirical method described in the agency National Engineering Handbook (Davis, R. T., et al.) to calculate densities. Using Bayesian analysis technique, Sturm et al. developed densification parameters from worldwide snow pack data. With these parameters, the accuracy of the estimates of density can be improved using only the snow depth, day of the year, and climate class of the snowpack. These parameters were applied to a subset of data from February 1, 2012, NRCS Cooperative snow surveys where measurements of SWE and depth were measured. The density of the snow pack using the observed data was compared to the modeled density. Differences between the modeled and the measured densities were about 1%. With additional refinement, this method can be applied to depth readings throughout the NRCS Aerial Marker network to calculate SWE values in a consistent and repeatable fashion. (Keywords: NRCS, aerial markers, Bayesian analysis, bulk density, climate (snow) class, snow water equivalent, SWE)


## INTRODUCTION

Thousands of snow depth measurements have been taken by the Natural Resources Conservation Service (NRCS) and other agencies responsible for monitoring snowpack for water supply needs, at Aerial marker (AM) and similar stations throughout North America (Sturm, et al. 2010). The NRCS has measured snow using aerial markers since the 1940s. These small groups of snow depth measuring sites are the most remote or hazardous and difficult to access of all the stations in the mountainous West. Many of these would take days of hazardous driving, skiing or helicopter access to reach them for a ground survey. Aerial markers are usually measured by a fly-by reading from a fixed wing airplane or helicopter.

The type or style of aerial marker varies. The NRCS AMs are typically constructed of a steel pipe mounted vertically in the ground, with long cross arms located on 2 foot centers and a shorter cross arm on the 1 foot mark between them. Often times a diagonal connects the larger cross arms, with the mid-point being at the one foot location (Figure 1). Typically, the longer cross arms are 1x6 materials, 18-24 inches long. The height of the markers differs considerably depending on the snow depth at that location. As the pilot flies the aircraft, the observer, reads and records the number of the cross arms that are visible above the snow, as well as an estimate of the distance from the lowest cross arm to the snow surface. Pictures are taken if possible. This data is sent back to the NRCS State office for a depth determination and an estimate of snow water equivalent (SWE). The snow depth is related to the SWE by the bulk density (or in many cases referred to simply as the density of the snowpack). The densities are functions of time of year, snow depth, wind, temperature, elevation, solar radiation, and rainfall. Empirical methods accounting for the above conditions have been used by the NRCS to convert snow depth to SWE since the AM were first installed. The process is somewhat labor intensive and requires a good knowledge of existing conditions, thus there is some interpretation of the empirical relationships. While both snow depth and SWE measurements are required for snow characterization for different purposes, they are not interchangeable. To take advantage of their relationship, a reliable method of determining SWE from a depth measurement is required. Historically, the NRCS has relied on nearby snow course and SNOTEL measurements of depth and SWE to determine the density to be applied on depth measurements at aerial markers even though they may be geographically distant from the measured site.

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[1] Jon Lea, USDA NRCS Snow Surveys, Portland, Oregon. 97232, jon.lea@or.usda.gov

[2] Matthew Sturm, US Army, CRREL, Fairbanks, Alaska, Matthew.Sturm@usace.army.mil

[3] Jolyne Lea, USDA NRCS Snow Surveys, NWCC Portland, Oregon 97232, jolyne.lea@por.usda.gov

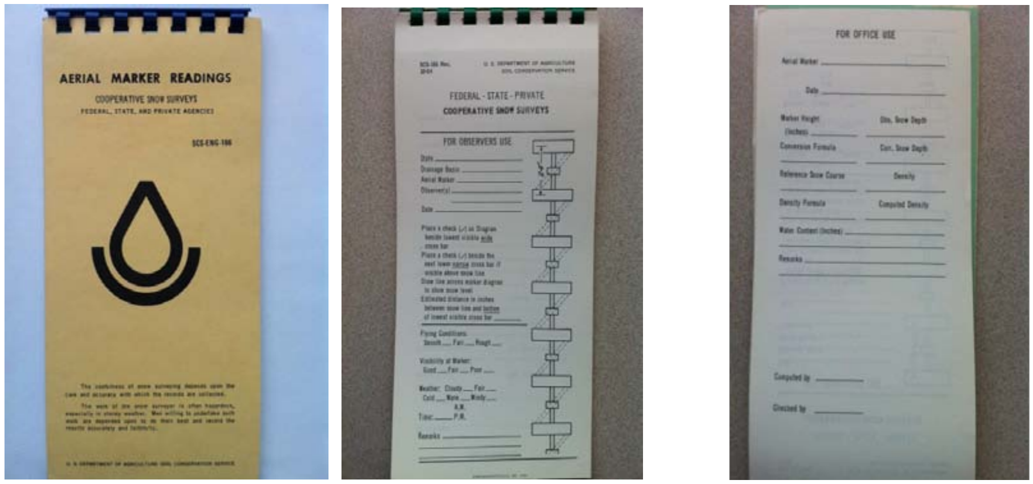

Figure 1. NRCS Aerial Marker records.

The NRCS National Engineering Handbook (Davis et al., 1970) has been used to determine the SWE using qualitative rules for adjusting local mean snow density up or down depending on snowpack conditions. In addition to the NRCS AM network, measurements of depth for other application also need to be converted into SWE. There is also a current emphasis within the NRCS to automate remote AM locations with snow depth sensors, to provide daily reading. This near real time daily depth data will require an automated procedure to convert this data to SWE.

In a recent paper, (Sturm et al., 2010), a statistical method was proposed for objectively determining the density of the snowpack at any given time or location. This method lends itself to automated processing snow depth into SWE. As a foundation, snow depth ($h_s$) is related to SWE by the local bulk density ($\rho_b$), and $\rho_w$ is the density of water (1 g/cm$^3$).

$$SWE\ (cm) = h_s\ \frac{\rho_b}{\rho_w} \qquad [1][\text{Sturm, et al., 2010}]$$

The basic idea behind the proposed method is to estimated the value in the above equation of the local bulk density ($\rho_b$) so that SWE can be computed. While the range of snow depth can be highly variable, the range of densities of the snowpack is relatively small. For example data from 5,323 stations in Alaska had bulk densities ranging 0.12 and 0.42 for 95% for all values. Typically, in snow course measurements, the bulk density term is reduced to the density of the snowpack, a unit-less value. Because the snow depth is a more dynamic parameter and is available at the AM stations, the modestly varying of density can be estimated well enough to provide a good estimate of SWE. Moreover, all of the different ways of measuring density and SWE in the field have inherent errors due to errors in instrumentation (snow tubes, scales and methods) that are hard to quantify, and make statistically estimated values look promising.

## METHODS

In Sturm et al. (2010), Bayesian statistical methods were used to develop non-linear ANCOVA models of bulk densities for multiple worldwide snow survey networks. Rather than looking at a single density for all snowpacks, the modeling effort was begun by separating a subset worldwide snowpack data into 5 different snow classes, each representing different geographical areas, climate regimes, depth and other parameters. These classes are maritime, alpine, prairie, taiga and tundra as defined earlier by Sturm et al. in 1995. These classes exhibit some variation in bulk density, but by working within a class, allowances for some generalities could be to be applied, and therefore narrow the range of density in comparison to depth for purposes of estimation of SWE.

The results of the analysis of the various snow classes are shown in Table 1, using all data for the snow season. The different snow classes have a distinct range of bulk density due to the depth and snow climate in each location. An average value for the snow class results are shown in the Table 1 below. $k_1$ and $k_2$ show the range of densification due to aging of the snowpack.

Table 1. The snow class range of values for the test dataset using the 5 snow classes and densification ($k_1$ and $k_2$) of the snow by time of year. $P_0$ is the initial density of new snowfall and $P_{max}$ is the maximum density of the snowpack. Bulk Density for the training data set (model) and (test) dataset are included.

| Snow Class | $P_{max}$ | $P_0$ | $k_1$ | $k_2$ | $BDensity_{model}$ | $BDensity_{test}$ |
|---|---|---|---|---|---|---|
| Alpine | 0.5975 | 0.2237 | 0.0012 | 0.0038 | 0.312 | 0.274 |
| Maritime | 0.5979 | 0.2578 | 0.0010 | 0.0038 | 0.335 | 0.292 |
| Prairie | 0.5940 | 0.2332 | 0.0016 | 0.0031 | 0.343 | 0.279 |
| Tundra | 0.3630 | 0.2425 | 0.0029 | 0.0049 | 0.284 | 0.260 |
| Taiga | 0.2170 | 0.2170 | 0.0000 | 0.0000 | 0.217 | 0.214 |

Sturm et al. states in his methods: The simplest (but still accepted) method to estimate density is to use the work-wide seasonal value of which was found to be 0.312 g/cm$^3$ to convert depth to SWE using Equation 1. A refinement of this approach however, is to first classify the sites being modeled and then use the mean densities for each individual class (Table 1). The most accurate approach, however, is to directly include the effect of snow depth ($h_s$) from Equation 1, the effect of snow aging (older snow is generally deeper and denser than younger snow) through the use of the day of the year (DOY), and to indirectly include the effects of climate (temperature, wind) through the use of snow classes. This is done by using the parameters in Table 1 in the following Equation:

$$\rho_{hi,DOY_i} = (\rho\max - \rho 0)(1 - \exp(-k1 \cdot hi - k2 \cdot DOYi)) + \rho 0 \qquad \text{Equation [2]}$$

$k_1$ and $k_2$ are densification parameters for depth and DOY respectively, $\rho_{max}$, $\rho_0$, $k_1$, and $k_2$ vary with snow class (Table 1), and *i* indicates the *ith* observation. Because the winter season in the Northern Hemisphere spans two calendar years, DOY runs from -92(October 1st) to +181 (June 30th), with no zero value. In this system, February 1st comes out as DOY=32, while November 15th is DOY= -47.

## RESULTS

Using Equation 2 and the values from Table 1, the accuracy of resulting modeled density can be compared to calculations of density from measurements of depth and SWE readings at Snow Courses in the NRCS and cooperator data collection networks. Manually measured stations with both snow depth and SWE were selected from the February 1, 2012 snow survey and used to compare estimated to observed densities. The stations were all in the Alpine snow class, thus making the analysis simpler. These results are shown in Table 2. It can be seen that the errors of the estimate are small, hence this same procedure for calculating densities could be applied to the depth data collected at AM sites to compute estimates of SWE in a repeatable and accurate fashion. Additionally the modeled densities were considerably more accurate than the fixed density estimates.

## CONCLUSIONS

The snowpack across the world is a vital resource that is changing both seasonally and from long climatic trends. Snow is an invaluable water resource that provides abundant clean water for populations across the globe. Snow depth measurements will continue to be a big part of the snow measurement system. Satellites, airborne and ground based snow depth sensor systems, and aerial markers will continue to be a quick, viable and expanding way to measure the snowpack. To take advantage of the many snow depth readings, the process presented provides an easy, repeatable method for determining SWE from snow depth readings.

Equation 2 can be used for the conversion of snow depth to SWE, with the selection of the parameters which represent the station location snow class. These parameters, which account for, the aging and densification of the snowpack based on the depth of the snowpack, ($h_s$) and the day of the year (DOY), can provide an accurate estimate of SWE. In the small sample of sites selected from the February 1, 2012 snow survey from the NRCS and Cooperators networks, the difference between the observed densities between the snow courses and the model densities from Equation 2, are smaller than the differences between the observed and the simply using the average density of the Alpine snow classification (.312). This supports the concept that the densities modeled using Equation 2, represent a better estimate than just using a one general density. In this example the modeled densities were under estimating the observed densities by 1%. This is a small test set of date points, but with further review

Table 2. Summary of density analysis based on data collected for the February 1, 2012 Snow Survey for NRCS and Cooperator Snow Courses

| State / Prov. | Snow Course Station | Actual Date (2012) | Feb 1 Depth (cm) | Feb 1 SWE (cm) | Measured Density | Average Density (Alpine) | Model Density | Average (Alpine) Difference | Model Error |
|---|---|---|---|---|---|---|---|---|---|
| **AK** | Anchor Hillside | 1-Feb | 119 | 31 | 0.264 | 0.312 | 0.285 | -0.048 | -0.021 |
| **AK** | Coldfoot | 1-Feb | 69 | 15 | 0.219 | 0.312 | 0.272 | -0.093 | -0.053 |
| **BC** | Waleach Lake | 2-Feb | 157 | 48 | 0.303 | 0.312 | 0.291 | -0.009 | 0.012 |
| **BC** | Glacier | 28-Jan | 201 | 64 | 0.320 | 0.312 | 0.293 | 0.008 | 0.027 |
| **BC** | Farron | 2-Feb | 71 | 15 | 0.211 | 0.312 | 0.277 | -0.101 | -0.066 |
| **BC** | Vaseux Creek | 1-Feb | 33 | 9 | 0.269 | 0.312 | 0.272 | -0.043 | -0.003 |
| **CA** | Adin Mountain | 30-Jan | 15 | 6 | 0.400 | 0.312 | 0.268 | 0.088 | 0.132 |
| **CA** | Cedar Pass | 1-Feb | 28 | 9 | 0.327 | 0.312 | 0.271 | 0.015 | 0.056 |
| **CA** | Fordyce Lake | 25-Jan | 56 | 12 | 0.223 | 0.312 | 0.262 | -0.089 | -0.039 |
| **CO** | Berthoud Pass | 27-Jan | 81 | 15 | 0.184 | 0.312 | 0.272 | -0.128 | -0.088 |
| **CO** | Bear River | 30-Jan | 71 | 15 | 0.214 | 0.312 | 0.276 | -0.098 | -0.062 |
| **CO** | Crested Butte | 27-Jan | 79 | 13 | 0.165 | 0.312 | 0.272 | -0.147 | -0.107 |
| **ID** | Benton Meadow | 1-Feb | 124 | 37 | 0.298 | 0.312 | 0.285 | -0.014 | 0.013 |
| **ID** | Ketchum RS | 31-Jan | 61 | 13 | 0.208 | 0.312 | 0.275 | -0.104 | -0.067 |
| **NV** | Lamoille #1 | 27-Jan | 30 | 7 | 0.225 | 0.312 | 0.262 | -0.087 | -0.037 |
| **NV** | Lamoille #5 | 27-Jan | 114 | 26 | 0.231 | 0.312 | 0.275 | -0.081 | -0.044 |
| **OR** | Camas Creek | 31-Jan | 30 | 9 | 0.292 | 0.312 | 0.271 | -0.020 | 0.021 |
| **OR** | Eldorado Pass | 30-Jan | 15 | 5 | 0.300 | 0.312 | 0.26 | -0.012 | 0.040 |
| **OR** | Dooley Mountain | 30-Jan | 53 | 12 | 0.229 | 0.312 | 0.272 | -0.083 | -0.043 |
| **OR** | High Prairie | 27-Jan | 226 | 74 | 0.326 | 0.312 | 0.3 | 0.014 | 0.026 |
| **OR** | Mt Hood | 31-Jan | 259 | 102 | 0.392 | 0.312 | 0.305 | 0.080 | 0.087 |
| **UT** | Brighton Cabin | 25-Jan | 122 | 25 | 0.206 | 0.312 | 0.275 | -0.106 | -0.069 |
| **WA** | Alpine Meadows | 26-Jan | 178 | 50 | 0.283 | 0.312 | 0.286 | -0.029 | -0.003 |
| **WA** | Bumping Lake (New) | 31-Jan | 122 | 35 | 0.290 | 0.312 | 0.284 | -0.022 | 0.006 |
| **WA** | Chewalah #2 | 30-Jan | 112 | 30 | 0.268 | 0.312 | 0.28 | -0.044 | -0.012 |
| **WA** | Cox Valley | 31-Jan | 175 | 58 | 0.330 | 0.312 | 0.292 | 0.018 | 0.038 |
| | *Average error difference:* | | | | | | | ***-0.044*** | ***-0.010*** |

of the local observations, and care in selecting the snow class, this procedure can be used to calculate SWE from snow depth in consistent and repeatable fashion across a much wider network, such as the Aerial Markers. With a developing interest in the collection of daily transmitted snow depth data, this procedure could be utilized to compute SWE as a part of an automated process.

## REFERENCES


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