INVESTIGATIONS TOWARD UNDERSTANDING THE SPATIAL REPRESENTATIVENESS OF SNOTEL MEASUREMENTS OF SNOW WATER EQUIVALENCE

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ABSTRACT

The spatial distribution of snow water equivalence (SWE) is important for accurately predicting water availability, particularly in semi-arid, high elevation regions typical of the Western United States where as much as 75% of stream flow originates as snowmelt. The Natural Resource Conservation Service (NRCS), formerly the Soil Conservation Service, provides much of the data currently available for operational snow hydrology in the Western United States through its Snow Telemetry (SNOTEL) and snow course network. While this network provides a valuable index to seasonal runoff, little is known about how well these stations represent the local snow distribution. This is of utmost importance as snow hydrologists look for data sources for ground truth of remote sensing applications and move towards physically based snowmelt models. Intensive field campaigns in the Colorado Rockies and the Sierra Nevada have been conducted to address these issues on the scales of 30m x 30m and 1km^2. Both grid sizes are commonly used in Digital Elevation Models (DEM) and satellite remote sensing. Our results indicate that the measured SNOTEL sites tend to over represent SWE in their local areas.

INTRODUCTION

In response to the drought of 1934, the Soil Conservation Services (SCS), now renamed the Natural Resource Conservation Service (NRCS) implemented a network of manual snow courses throughout the mountainous Western United States. These snow courses were typically measured monthly and provided a valuable aid in stream flow forecasting through correlations between snow water equivalence (SWE) and runoff. Many of these snow courses are still measured today. To provide more timely information on snowpack conditions, the SCS began installing a network of automated snow telemetry sites called SNOTEL, for the measurement of SWE, precipitation, temperature, and sometimes other parameters. SWE is measured using an anti-freeze filled snow pillow with pressure calibrated to SWE. The locations of these sites were typically co-located with existing snow courses that had demonstrated high correlation to runoff. Additionally practical limitations for site selection are: safe summer and winter access, gentle local slope and typical location within a small clearing (Soil Conservation Service 1982). This network was designed primarily to serve as an index to aid in water supply forecasting, and for this purpose does an excellent job. Additionally the network provides the only near real time information on SWE in the mountainous Western U.S. As such it has frequently been used, and will continue to be used for many other research purposes including, but not limited to ground truth for remote sensing applications and SWE input for physically based snow distribution and snow melt models. For these and other uses it is necessary to understand how well SNOTEL sites represent a spatial area around them. It is the goal of the research presented here to address this issue. Intensive field snow surveys were conducted at SNOTEL sites on the scales of 30m x 30m and 1km^2 and results compared with SNOTEL output for the dates of each survey.

STUDY SITES

Nine SNOTEL sites were selected for intensive field measurements. These sites were selected to represent a broad range of snow, terrain, and vegetative conditions as well as logistical concerns and collaborations. Eight sites were selected in Colorado in the Park Range and Eastern San Juans. The Colorado sites from North to South are: Tower, Rabbit Ears, Slumgullion Pass, Upper Rio Grande, Middle Creek, Wolf Creek, Upper San Juan, and Lily Pond (Figure 1). A single Sierra Nevada site at Independence Lake northwest of Truckee, CA was selected for more frequent visits to study the temporal variability of SNOTEL representativeness (Figure 2).

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Paper presented at the Western Snow Conference 2002

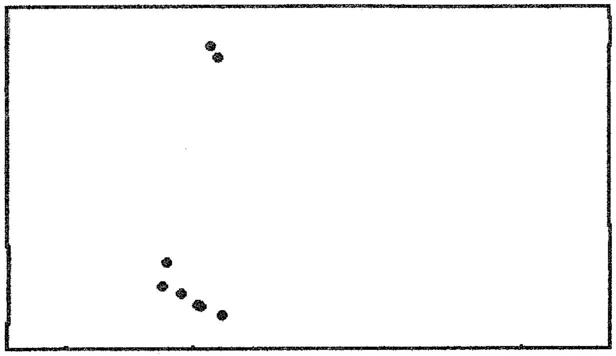

Figure 1. Outline of Colorado with study sites identified with black dots. Sites from North to South are Tower, Rabbit Ears, Slumgullion Pass, Upper Rio Grande, Middle Creek, Wolf Creek, Upper San Juan, and Lily Pond. Note that Wolf Creek and Upper San Juan plot on top of each other at this scale.

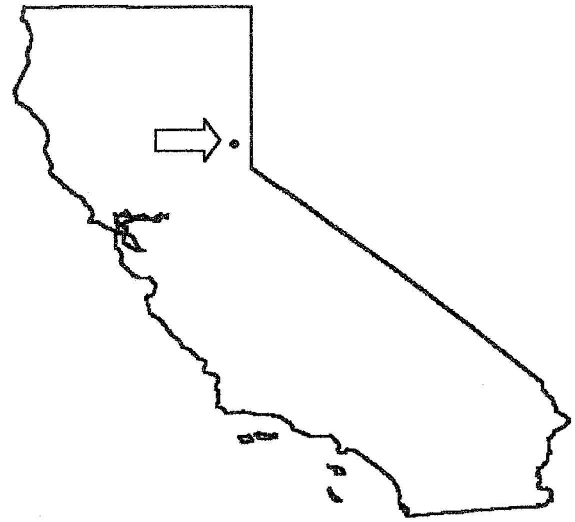

Figure 2. Outline of California with Independence Lake site indicated by black dot and arrow.

FIELD METHODS

Snow surveys were conducted at each site between one and six visits per site over a two-winter period. The goal of each survey was to determine a representative spatially averaged SWE on both the 30m x 30m and $1km^2$ scales. It must be emphasized that the sampling strategy described below was not intended to address spatial variability or predict snow distribution within these two scales. Additionally sampling was limited by available personnel and funding and thus the following strategy was designed for each site to be completed by two people in one day. Snow depth was measured at a greater frequency then snow density since snow density has been shown to be less variable then snow depth, and snow density is far more labor intensive to measure (Logan 1973, Elder et. al. 1991).

Field Measurements $1km^2$ Area

Four five hundred meter long transects were measured radiating out from the snow pillow in cardinal directions. Along each of these transects snow depth was measured every 25 meters by inserting a carbon fiber probe to the ground and recording snow depth to the nearest centimeter. At every one hundred meter interval Federal Snow Sampler (FSS) measurements were taken in triplicate for snow density and locations logged with a global positioning system. While previous literature has shown a tendency for the FSS to over-sample by approximately ten percent, it is the authors' belief that FSS accuracy is more variable and highly dependent on snow conditions (Work et. al. 1965, Peterson 1975, Farnes et. al. 1983). In order to test this belief and to more accurately represent the density in the area, a calibration snow pit was excavated within five meters of the snow pillow in an area with similar terrain features and snow depth as the pillow. The snow pit was excavated to ground, and density was measured every 10cm using a 1000cc stainless steal cutter. Duplicate density transects were measured when possible, and the average of the two profiles used. Adjacent to the snow pit face three to five FSS measurements were taken. A correction factor was calculated to adjust the Federal density measurement to the snow pit measurement, and this calibration coefficient was applied to each spatially distributed FSS measurement. In most cases a total of 80 depths and 20 densities were measured in the $1km^2$ area, but in a few cases travel safety and logistical problems prevented access to all points.

Field Measurements 30m x 30m Area

The 30m x 30m field measurements consisted of four transects of 15m each, in cardinal directions from the snow pillow. Depth was measured every meter, excluding the locations that are located directly on the snow pillow. The snow pit was assumed to represent the snow density over this entire area. Typically 52 depths and one density were measured over this area.

RESULTS

Federal Snow Sampler vs. Snow Pit Comparison

Results from the co-located Federal samples and snow pit measurements indicate an overall very strong relationship, with the tendency for the FSS to slightly over sample SWE (Figure 3). These results are in agreement, but with lesser over sampling then the literature (Work et. al. 1965, Peterson 1975, Farnes et. al. 1983). A closer look at individual measurements reveals a high degree of variability in the percent difference between Federal measurements and snow pit measurements (Figure 4). It appears that Federal sampling efficiency varies not only with location, but also with snow pack conditions during sampling, with the greatest error occurring under the very rotten and low snow conditions present in Colorado during the spring of 2002. The Independence Lake site in the Sierra Nevada tends to over sample as predicted, while Colorado sites are less predictable and more variable.

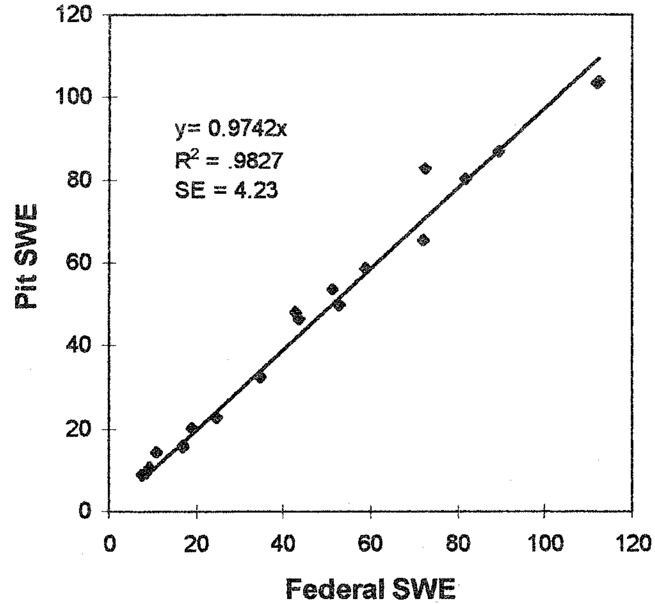

Figure 3. Linear regression of snow pit SWE vs. Federal Snow Sampler SWE

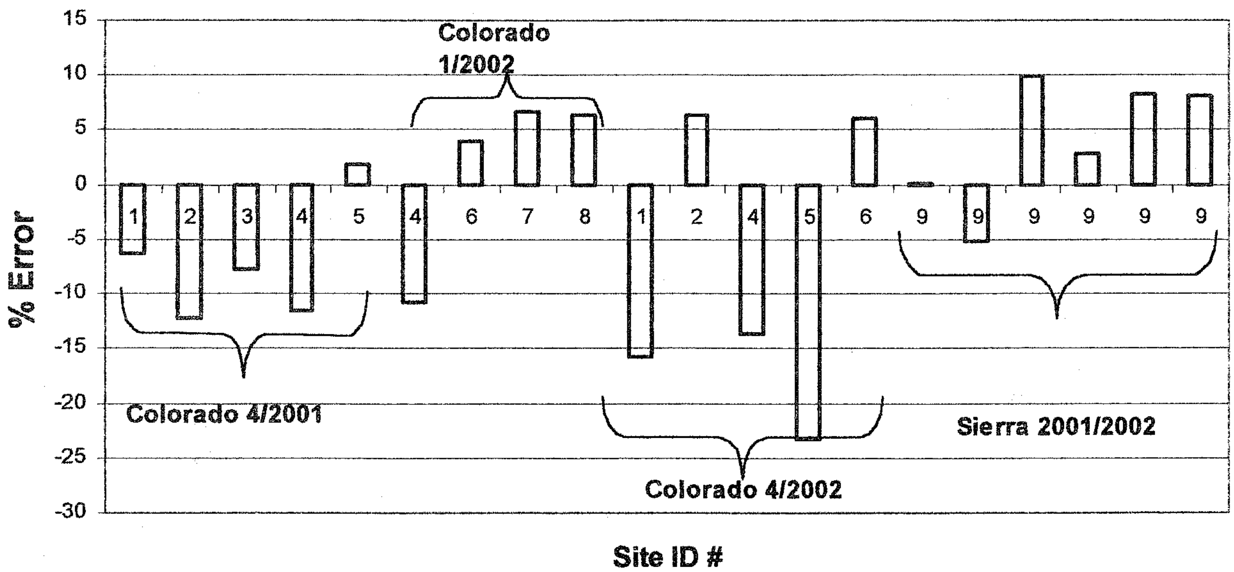

Figure 4. Percent Error of Federal Snow Sampler density measurements as compared with co-located snow pits. A positive percent error indicates over sampling by the Federal Snow Sampler. Sampling times are grouped by date, except in the Sierra where sample order is 4/2001, 12/2001, 1/2002, 2/2002, 3/2002, and 4/2002. Site ID's 1 to 9 refer to the following sites in order: Lily Pond, Upper San Juan, Upper Rio Grande, Slumgullion Pass, Middle Creek, Wolf Creek, Rabbit Ears, Tower, and Independence Lake.

Point SWE vs. SNOTEL SWE

The four closest snow depth measurements to the pillow were used in combination with the snow pit to evaluate the accuracy with which the SNOTEL stations reported SWE at the snow pillow (Figure 5). Generally these snow depths were measured two meters from the center of the pillow in each cardinal coordinate. A very strong relationship exists, similar to that shown in previous literature (Schaefer and Shafer 1982). This paper will not analyze these data in detail, as it was impossible to measure the actual snow on the pillow without disturbing the SNOTEL measurement, and this type of analysis has been evaluated in the past (Smith and Boyne 1981, Schaefer and Shafer 1982).

30m x 30m SWE vs. SNOTEL SWE

The relationship between SNOTEL reported SWE and field measurements on the 30m x 30m scale was very strong, however the SNOTEL measurements had a tendency to significantly over sample the area (Figure 6). A paired t-test revealed significant difference at $p = 0.01$. Of the twenty-one available measurements on this scale four under sampled between 12 and 100%. Six field measurements had percent differences below 5%. The remaining eleven measurements over sampled between 5 and 65%(Figure 7 and 8.)

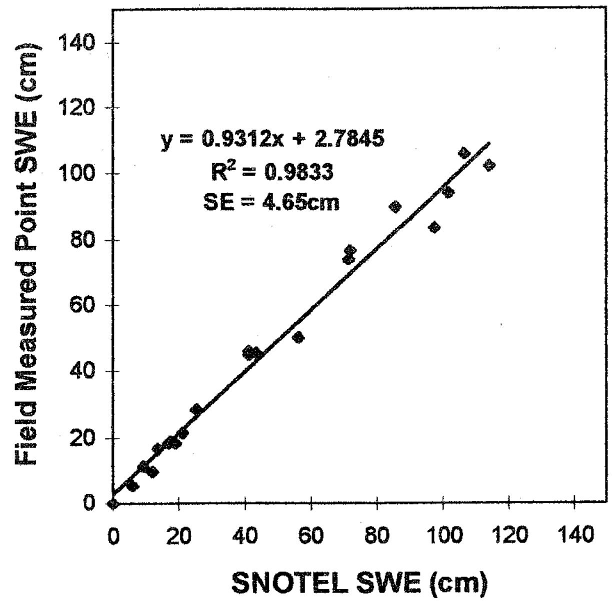

Figure 5. Linear relationship between field measured point SWE determined from four local depths and a snow pit for density as compared with SNOTEL output.

1km^2 SWE vs. SNOTEL SWE

The relationship between SNOTEL reported SWE and spatially averaged SWE on the 1km^2 scale was strong, but with considerably more variability and a greater degree of over sampling then on the 30m x 30m scale (Figure 9). A paired t-test revealed significant difference at $p = 0.01$. On the 1km^2 scale three measurement dates had percent difference below five percent, while six site visits under sampled between six and 100% and 13 visits over sampled between six and 150%(Figure 7 and 8).

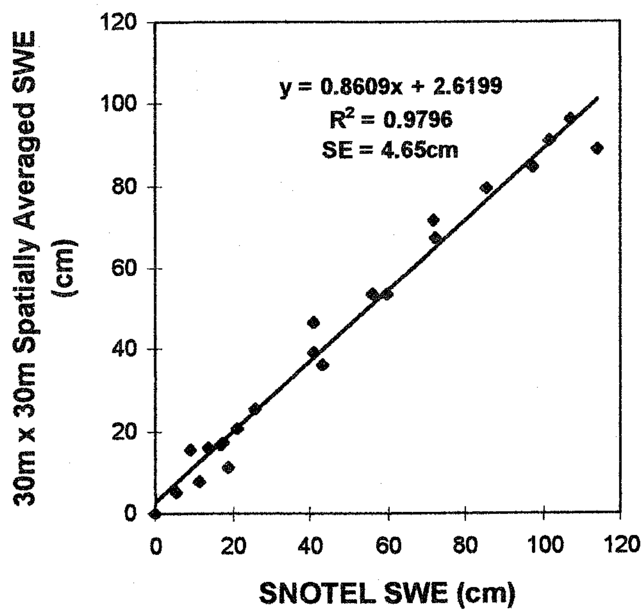

Figure 6. Linear relationship between spatially averaged field measurements of SWE on a 30m x 30m scale and reported SNOTEL SWE.

Temporal Variability of SNOTEL Representativeness

Snow surveys were conducted on a monthly bases at the Independence Lake SNOTEL in the Sierra Nevada from December 2001 to April of 2002 to evaluate if and how the spatial representativeness changed throughout a season (Figure 8). These data indicate a continuous increase in the percent of over sampling throughout the season. Additional data to support this trend exists at two sites that were measured in January of 2002 and again in April of 2002. These sites are Slumgullion Pass (site #4) and Wolf Creek (site #6). While Slumgullion Pass changes from considerable over sampling in January to high over sampling in April, the Wolf Creek Site goes from moderate under sampling in January to moderate over sampling in April (Figure 7). With only two years of record it is difficult to address year-to-year variability in SNOTEL representativeness. The seasons of 2000/2001 and 2001/2002 were very different especially in Southern Colorado, where 2000/2001 conditions were near average and 2001/2002 was drastically below average. With these limitations in mind, it does appear with very few exceptions that sites that over sampled one year tended to over sample the next and vice versa when April 2001 and April 2002 measurements are compared (Figure 7 and 8).

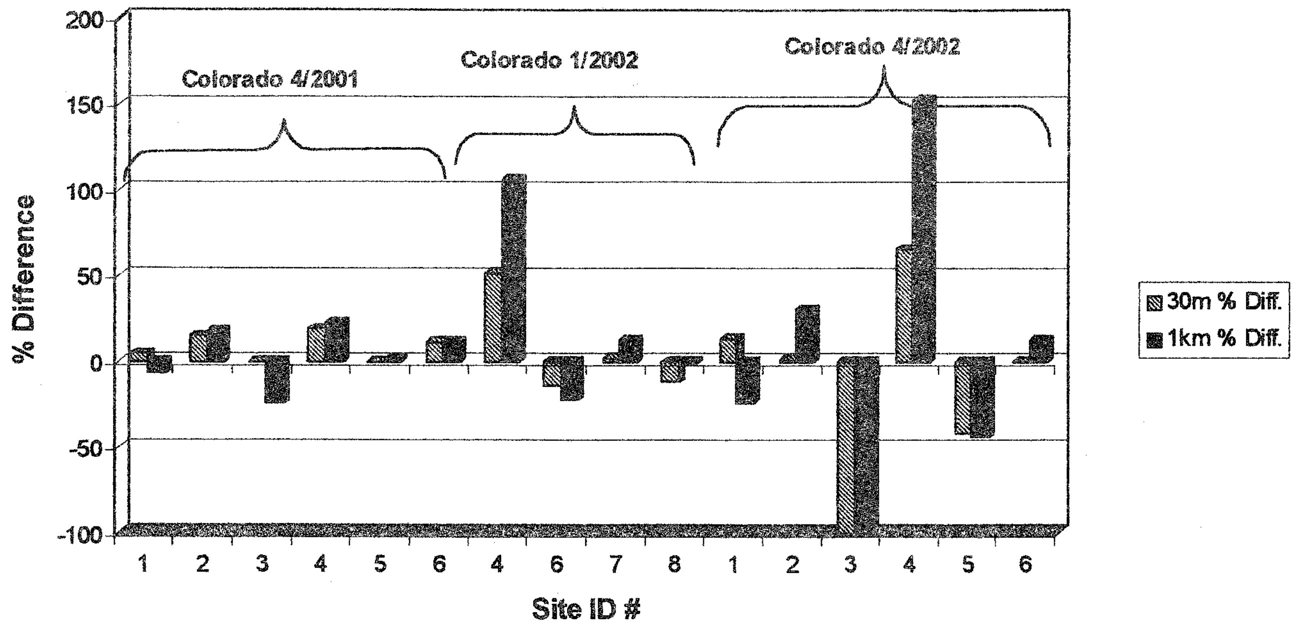

Figure 7. Percent difference of spatially averaged SWE measurements on 30m x 30m and 1km^2 scales vs. reported SNOTEL SWE at Colorado Sites. Sampling times are grouped. Site ID's 1 to 8 refer to the following sites in order: Lily Pond, Upper San Juan, Upper Rio Grande, Slumgullion Pass, Middle Creek, Wolf Creek, Rabbit Ears, and Tower. The 100% under sampling at the Upper Rio Grande site in April 2002 must be interpreted carefully and requires further explanation. When field measurements were made the pillow was snow free, and correctly recorded 0 cm SWE. Very little snow still existed on both the 30m x 30m and 1km^2 scales, resulting in spatially distributed averages of less then 0.5 cm SWE on both scales.

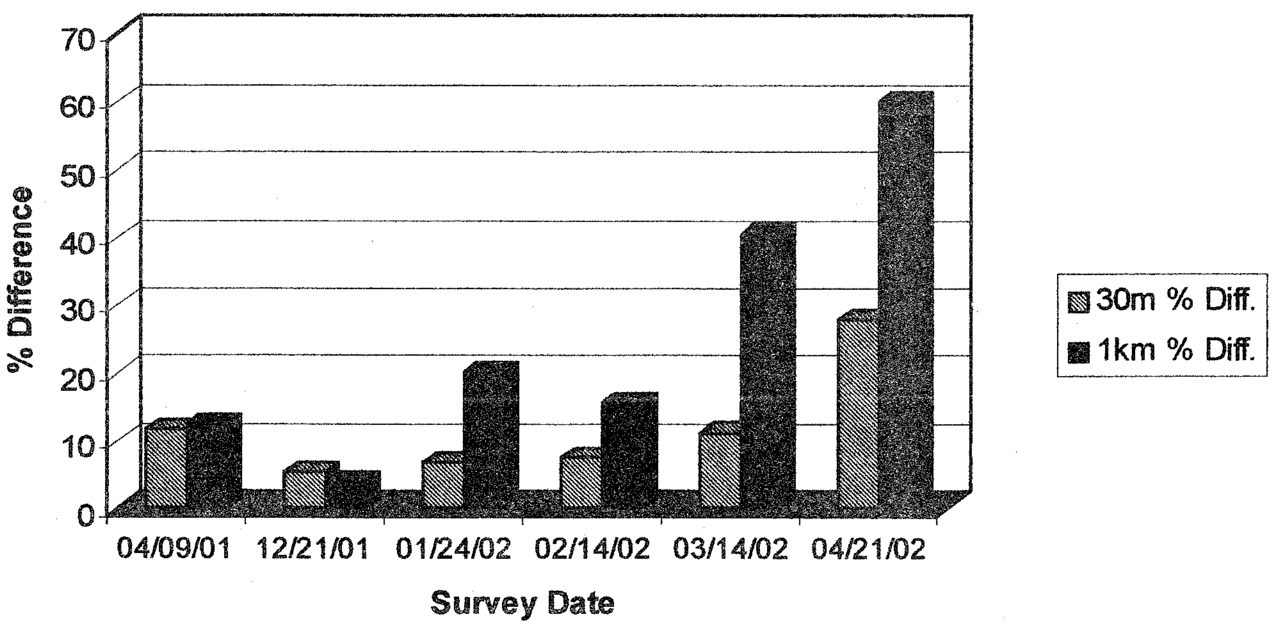

Figure 8. Temporal variability of SNOTEL representativeness at Independence Lake CA for April 2001 through April 2002. The percent difference of spatially averaged SWE measurements on 30m x 30m and 1km^2 scales is plotted vs. reported SNOTEL SWE.

DISCUSSION

SNOTEL representativeness seems to be controlled by a number of factors. The range and variability of SWE in the local area of the SNOTEL site have an influence on representativeness. Sites that tended to do a better job representing their local areas generally had a smaller range and less variability in SWE and vice versa (Figures 10 and 11). It appears that the tendency for a SNOTEL site to over or sometimes under estimate the SWE in its local area is very dependent on the specifics of the exact site locations terrain and vegetative characteristics relative to the surrounding area. With the majority of sites studied having a tendency to over sample their local area it is likely that the site selection criteria outlined in the introduction of this paper leads to sites that have a tendency to either collect more snow and or have less snow losses then their surrounding areas. In addition to site selection criteria, the effort to co-locate SNOTEL sites with historic snow courses may lead to an additional sampling bias. Little documentation exists on precisely how these snow courses were located. It is likely these sites were selected to have a relatively long snow covered season in order to provide a long seasonal record, and therefore tending to hold more snow then the surrounding area.

There is a tendency for over estimates of SWE to increase as the snow season continues. There is not enough evidence here to address how sites that under collect change throughout the season. Taking a closer look at the Independence Lake data, (Figure 8) the percent difference is very low for the December 2001 measurement, and quite high for the April 2002 measurement. It is the authors' opinions that the precipitation is relatively uniform over the sampling area, and this drives the early season distribution. As the season progresses local scale variability of energy inputs and redistribution by wind and possibly avalanche takes over and causes increased range in the SWE distribution (Figures 12 and 13). By the April sampling at Independence Lake the greatest SWE measurements in the $1km^2$ area were adjacent to the snow pillow.

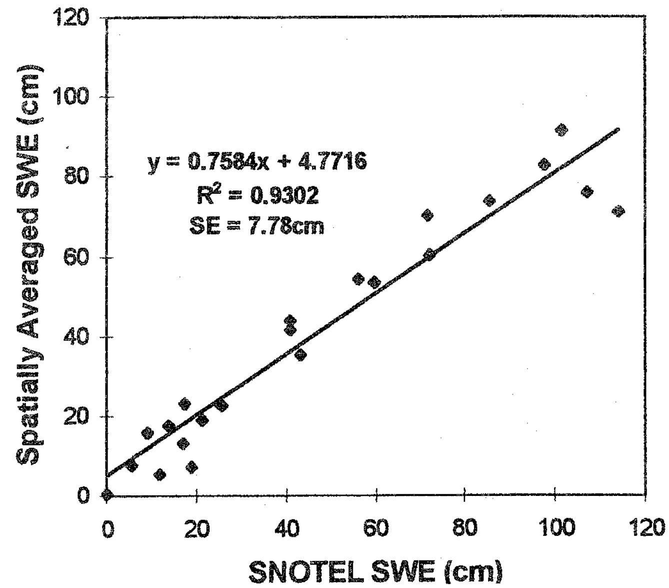

Figure 9. Linear relationship between spatially averaged SWE on a $1km^2$ scale and reported SNOTEL SWE.

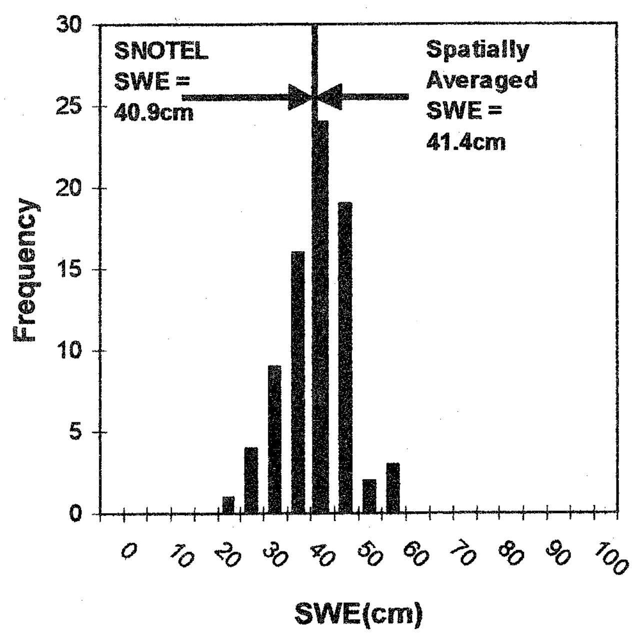

Figure 10. $1km^2$ SWE distribution at Tower site 1/14/2002

CONCLUSIONS

While measurements of SWE and snow density from the FSS correlate very well to the more precise method of snow pits, caution needs to be used when correcting such measurements under highly variable snow conditions. The SNOTEL sites in this study are reasonably representative of the 30m x 30m area surrounding them, with a tendency to over sample. They are less representative of the $1km^2$ area surrounding them and tend to over sample to a greater extent on this scale. While most sites in this study represented the 30m x 30m area within ~ 25% and the $1km^2$ area within 50%, a few instances had far greater differences. Using SNOTEL data in any distributed fashion must be done with caution and with specific knowledge of the individual sites as well as terrain and vegetative features of the area.

FUTURE WORK

Efforts are in progress to cross validate the field measurement techniques used for this project. In March of 2002 the 1km^2 cross pattern was sampled on the same area and a day later then the NASA Cold Lands Processes Field Experiment (CLPX). The CLPX sampling method was very intensive with 500 snow depths and 16 snow pits per 1km^2 area (Cline et. al. 2001). The CLPX data set will be considered truth and will be used to test the accuracy of the method used here. Data presented in this paper will be used to ask the question: Can we predict if a site is likely to over or under sample it's local area? Several sites will be evaluated using a geographic information system classification. Information on slope, aspect, elevation, forest coverage, and radiation will be tested for a relationship to SWE. The single grid cell including the SNOTEL site will be compared to the surrounding 1km^2 for sites that under and over estimated this scale to determine if a relationship can be established between under and over sampling and any or several of these features.

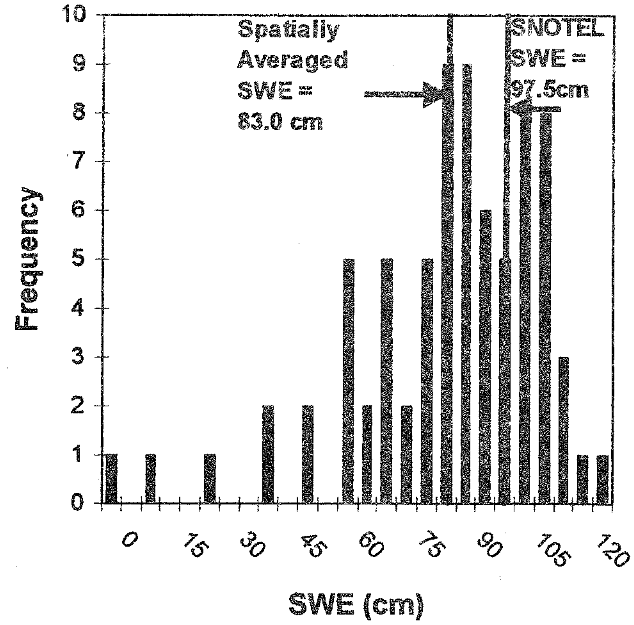

Figure 11. 1km^2 SWE distribution for Upper San Juan site 4/23/01

ACKNOWLEDGEMENTS

Research Support was provided by the Environmental Protection Agency STAR Fellowship, the Sustainability of semi-Arid Hydrology and Riparian Areas Science and Technology Center, the Desert Research Institute Division of Hydrologic Sciences, and the University of California Berkeley Sagehen Creek Field Station. Special thanks goes out to Don Cline, Kelly Elder and Mark Williams, who provided invaluable expertise in the design and implementation of this project, and for the many people who assisted with fieldwork, especially Adam Hobson, Gregg Lamorey, and Andy Rossi, and Gayle Dana who assisted with this manuscript.

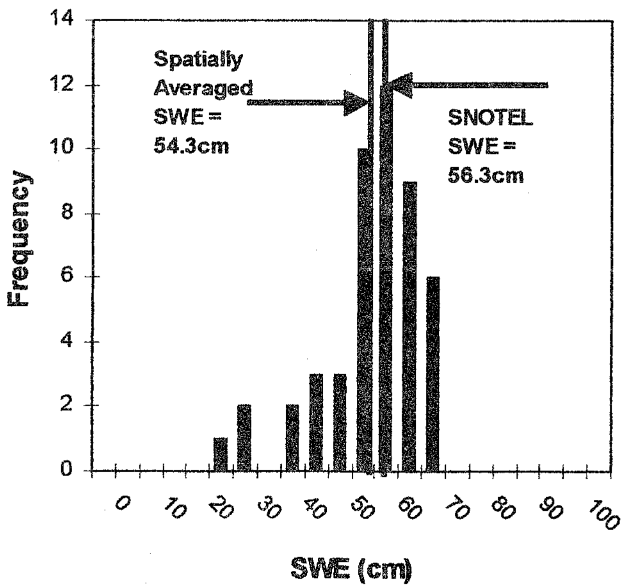

Figure 12. 1km^2 SWE distribution for Independence Lake 12/21/01

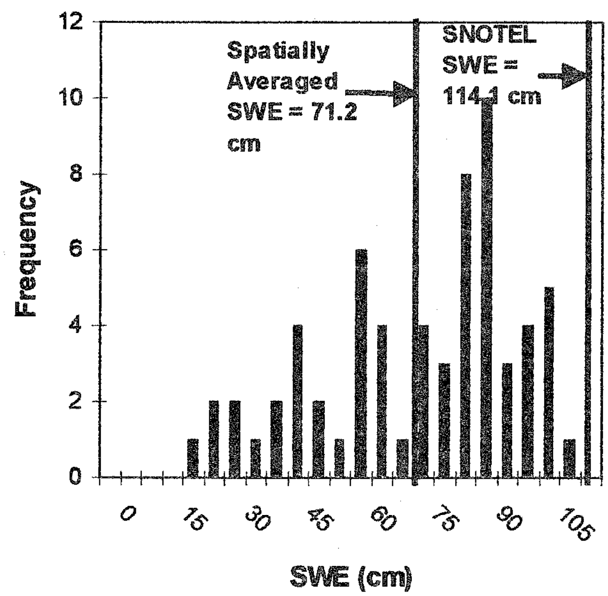

Figure 13. 1km^2 SWE distribution for Independence Lake 4/21/02

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