

APPLICATION OF A WIRELESS SENSOR NETWORK FOR DISTRIBUTED SNOW WATER EQUIVALENCE ESTIMATION

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ABSTRACT:

Snow accumulated in mountainous areas is the source of water supply for much of the western United States. Estimates of the expected amounts of annual discharge in rivers are based on snow water equivalence (SWE) measurements and regression models that have climate stability as an underlying assumption. This is likely to be untrue as climate changes. This suggests that assessments of water availability change from statistical models to physically-based models. However, the current data collection network for SWE provides sparse areal coverage. Inexpensive wireless sensor networks and simple estimation techniques could be used to extend the areal coverage of snow data to improve spatial resolution.

We report results of deployment of a prototype wireless sensor network, Snowcloud, at the Sagehen Creek, CA experimental field station. The network reported snow depth and temperature from January—May, 2010. A simple estimate of SWE at each node was based on the assumption of stability of the ratio SWE/SD and predicted SWE with reasonable accuracy (average difference of +1.0 cm (0.4 in), standard deviation = 3.0 cm (1.2 in)). Regression analysis indicated significant associations ($P < .05$) between SWE and % canopy closure to the north, weekly total incoming solar radiation and monthly average temperature. These results indicate that wireless sensor networks measuring SD can be used to extend information from snow measurement sites accurately to give estimates of water availability in snowpack. (KEYWORDS: wireless network, snow water equivalent, snow sensor, snow, snow depth, areal estimation)

INTRODUCTION

Snowpack in the mountainous portions of the western United States provides water for irrigation, municipal water supply, recreational flows, aquatic life and ecosystems. The current approach used to forecast annual flow volume in the Truckee and Carson Rivers in Nevada is based on regression modeling using total annual flow observed at critical points on rivers and measurements of snow water equivalence (SWE) at one or more meteorological stations or snow courses (www.wcc.nrcs.usda.gov/snowcourse/, last accessed July, 2011) made at the presumed end of the seasonal snow accumulation cycle (~April 1 of each year). Regressions use the Natural Resources Conservation Service's Snow Telemetry (SNOTEL) network and require a minimum of five years of observations and assume stationarity in underlying climatic trends. If this condition is not met the regression models, however robust in development, lose validity. Current regression models operate relatively well when snow accumulations are within the long term mean (Elder et al., 1991; Rice et al., 2010). However, when annual accumulations deviate from the data set used to develop models, forecasts are less likely to be accurate (Rice et al., 2010). Given trends of earlier melt and release and increases in the annual average elevation of the transition zone between rain and snow (Lundquist et al., 2003) the precision and accuracy of predictions based on regression are likely to decrease.

As an alternative, annual total discharge estimates can be based on simulations that represent physical processes that rely on data collected at high spatial resolution. Information needed includes meteorological data useful for energy balance and snow pack characteristics such as snow depth, areal coverage and snow water equivalence.

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SD and SWE accumulation and ablation trends are related to latitude, elevation, azimuth, slope, canopy cover, wind, temperature and solar radiation. Erikson et al (2005) noted that the relationships between SD, SWE, topography, canopy cover, and to a lesser extent wind are constant. Jost et al. (2007) reported that elevation, azimuth and canopy cover accounted for 80—90 % of the variability of snow accumulation in a forested watershed, with azimuth having the greatest influence during the accumulation phase. Consequently, spatial and temporal trends in snow accumulation are similar in areas with similar topography, canopy cover and wind patterns. This suggests that if SD can be measured accurately within an area surrounding a meteorological station, SWE measurements at a point could be extended to surrounding areas with a high degree of confidence.

Molotoch et al. (2005) and Elder et al. (1991, 1998) reported that snow density varied much less than snow depth. Both found that characterizing the environmental determinants of SWE variation was difficult because spatial variability in snow density is inherently less than that found in snow depth. They also found that snow density did not correlate well with factors such as temperature, solar radiation and wind, especially when the snowpack has a uniform temperature approaching 0°C (32°F). At this temperature snow density is conservative compared to snow depth. Jonas et al (2009) found that snow density did not correlate well with topography, though density increased with increasing snow depth and with duration on the ground.

The total volume of water held in snow (Q_{total}) in an area can be estimated as:

$$Q_{total} = \sum_1^n d_i \times \frac{\rho_{s i}}{\rho_w} (SCA_i) \quad (\text{eq. 1})$$

in which d_i = snow depth at point i , $\rho_{s i}$ = density of snow at point i , ρ_w = density of water, and SCA_i = snow covered area represented by point i . For application in large areas, this equation assumes that d_i and SCA_i can be represented with averages or single measurements. If either quantity varies significantly in space this implies spatially intensive measurements to avoid bias in estimates. Snow courses are one approach to increasing measurement intensity, with the objective of producing representative values of SWE and SD. However, these have logistical and administrative costs that limit measurement frequency. SNOTEL sites provide continuous weather records and are located in open areas, usually as permanent installations. Wireless sensor networks coupled with permanent installations for snow sensing could greatly increase spatial resolution of areal and point measurements of SWE simply by increasing the number of SD measurement points and extrapolating snow density from one or more index sites.

This study assessed utility of inexpensive, portable networks to measure snow depth and estimate snow water equivalence in open areas and within canopy—meadow interfaces typical of the Sierra Nevada. It was a feasibility study to evaluate a method of extrapolating SWE observations to an area beyond a single snow pillow.

Methods and materials

The Snowcloud system, developed at the University of Vermont, consisted of six independent nodes in a wireless network. Each node transmitted snow depth and temperature data to a base station using radio frequency (RF) signals. The system was deployed adjacent to a meteorological station on a 0.77 ha site within Sagehen Creek Experimental Field Station north of Truckee, CA from January—May, 2010 (Figure 1). Six sensors were connected to a base station via TinyOS multihop (also known as mesh) communication. The multi-hop communication structure extended the potential range of the Snowcloud network and allowed data collection and transmission in the event of partial network failure. Each node communicated with an omni-directional antenna with a range of 50—100 meters (164—328 ft). The support structure for each node was modular aluminum tubing with a base plate anchored to the soil. The nodes in Sagehen Creek were 2.7 m (9 ft) tall, with an effective vertical sensing distance of 2.1 m (7 ft).

A 12V, 12ah lead acid battery recharged by a 12 W solar panel with a -40°C (-40°F) operational rating provided power. The sensor module was a Crossbow TeloB (Crossbow Technology Inc. www.xbow.com, last accessed 7/2011), with a TinyOS operating system, 1 Mb of internal flash storage to retain data in case of transmission or antenna failure and a Max Sonar® – WR1™ (MB7060) sonar emitter/receiver to sense snow depth (www.maxbotix.com, last accessed 7/2011). The MB7060 required little power (requiring a minimum of 3.5 V) and had a vertical range of 0.25—7.65 m (0.83—25.1ft), with 1 cm (0.4 in) resolution. Post-processing of sonar voltage readings (e.g. voltage-to-distance conversion and temperature compensation) was performed off-site. This

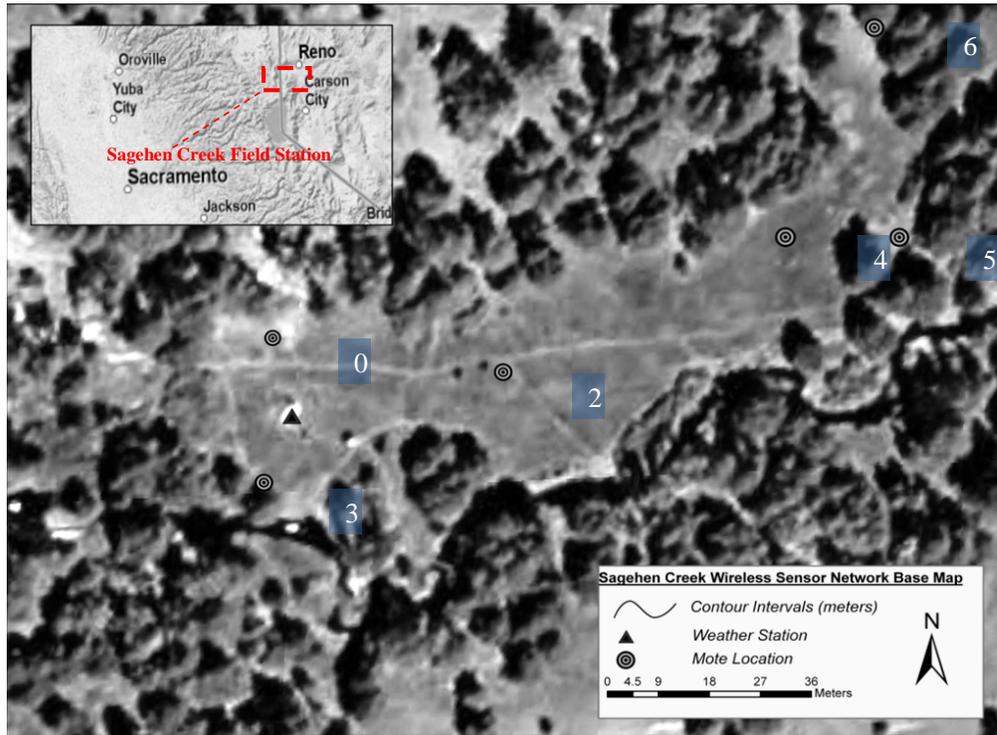


Figure 1: The field area and location of nodes within the Sagehen Creek Experimental Field Station.

“homebrew” SD measurement solution provided significant cost reduction compared to off-the-shelf SD sensor systems, especially in this multi-node sensor network.

Sonar signals were corrected for temperature effects on sound transmission (eq. 2, from Ryan, et al., 2008):

$$SD = D_{gs} - \left[\frac{V}{\left(\frac{V \times 331.3 \sqrt{1 + \frac{\bar{T}}{278.15}}}{m_i x + b} \right)} \right] \left(331.3 \sqrt{1 + \frac{\bar{T}}{278.15}} \right) \quad \text{eq. 2}$$

in which SD= snow depth (ft), D_{gs} = distance from ground surface to sonar emitter (ft), V= voltage output, T= average temperature (°C) at sample time and $m_i x + b$ = linear calibration equation for node i. The distance from the ground surface to the sonar emitter (D_{gs}) was measured with an avalanche probe with centimeter gradations after deployment.

Sensing and communication regimes for each network node were custom programmed. Each node took hourly sonar and temperature readings throughout the deployment period. The network maintained communication throughout, with only ~3 days of down time at a single node.

Field Site: The Sagehen Creek Field Station near Truckee, California is a snow-dominated hydrologic watershed with a meteorological station similar to those in the SNOTEL network, equipped with a snow pillow that collected weather and SWE information at ten minute intervals (Figure 1). The nodes were deployed inside and around a 0.77 ha (1.90 ac) meadow near the meteorological station and reported SD within tree canopies and areas with mixed canopy—meadow cover. A meteorological station with a 30.5 m (100 ft) tower measured wind speed (m/s), wind direction, air temperature (°C), relative humidity (%), barometric pressure (millibars), shortwave radiation (kilowatts) and incoming shortwave radiation (mega joules) at 10 minute intervals, with an instrument cluster at 7.6 m (25 ft).

Manual SWE and SD Measurement: A Mount Rose snow sampler (Rickly Hydrological Supply Inc, www.rickly.com, last accessed 7/2011) was used to measure SD and SWE to verify predictions of SWE at each Snowcloud node. SWE and SD sampling took place weekly from January 18—April 26, 2010 ending when the site was ~85% free of snow cover.

Canopy closure: Canopy closure is the percent of tree canopy that overlies the soil surface, expressed as a percent and ranging from 0—100%. A convex spherical densitometer (Model A, www.terratech.net, last accessed 7/2011) was used to measure canopy closure at each Snowcloud node using the dot method described by Korhonen et al. (2006). The densitometer, placed on a tripod 1.4 m (4.5 ft) above the soil surface, characterized canopy closure in a 60° radius relative to the user’s eye, based on a grid of 96 elements superimposed on a hemispherical surface observed from each cardinal direction. Each grid cell was assigned a value of 1 (representing canopy observed) or 0 (no canopy observed). Values for each cardinal direction were summed and a percentage of canopy closure calculated based on a total of 96 observation cells. Percentages from each cardinal direction were then averaged to characterize total canopy closure at each Snowcloud node (Figure 2).

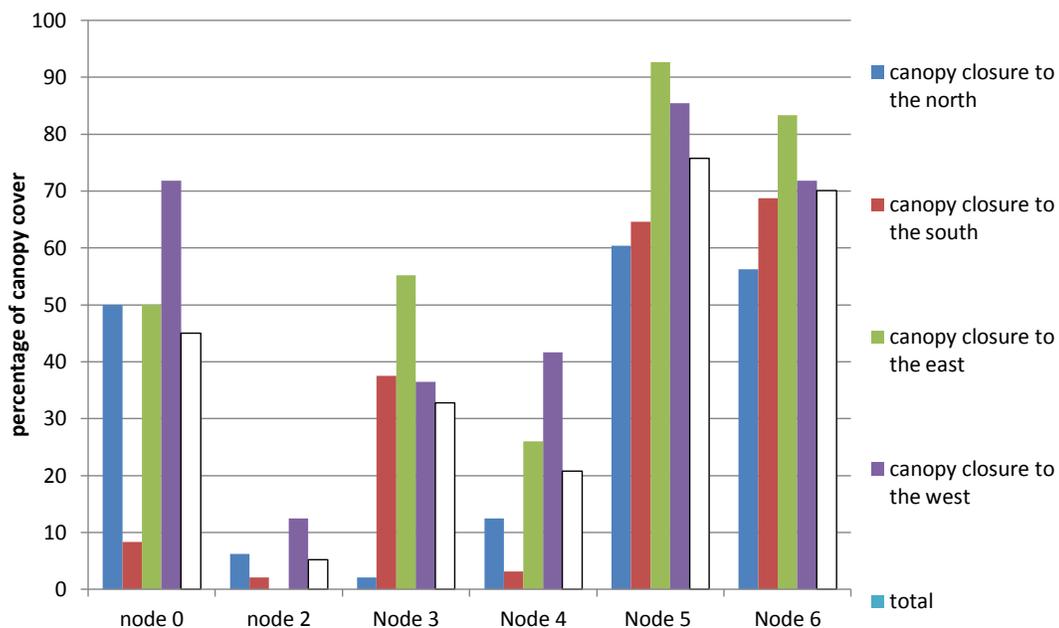


Figure 2: Canopy closure at each node in the Snowcloud network.

Data analysis: The study applied a SWE estimation method based on the assumption that while SD and SWE varied significantly across the site, the ratio of SWE/SD was approximately constant across the site at each time interval. We also evaluated the influences of canopy closure and weather on SWE using regression. For these trials, weather data were used as hourly, daily, weekly and monthly data running arithmetic averages and sums to account for cumulative effects. Running averages were developed with a moving window approach incorporating data across time steps. Incoming shortwave radiation in mega joules was treated as a sum from Dec. 1st. Correspondence analysis (CA) was used to identify potential predictors. CA is a non parametric principle component depicting the strength of associations based on the chi-square distance between each data point and the expected value (Carr, 2002, Nagpaul, 1999). All potential predictors were initially included in regression analysis. Potential predictors (using the criterion of $P \leq 0.20$) were sequentially eliminated using the criterion of $P < 0.05$ to retain predictors.

RESULTS

SWE and SD measurements are shown in Figures 3a and 3b, respectively. The ratio of SWE/SD at each node is shown in Figure 4. We chose node 3 as an index for the site, in part as a surrogate for data from the meteorologic station, which had a faulty SD sensor during the experimental period.

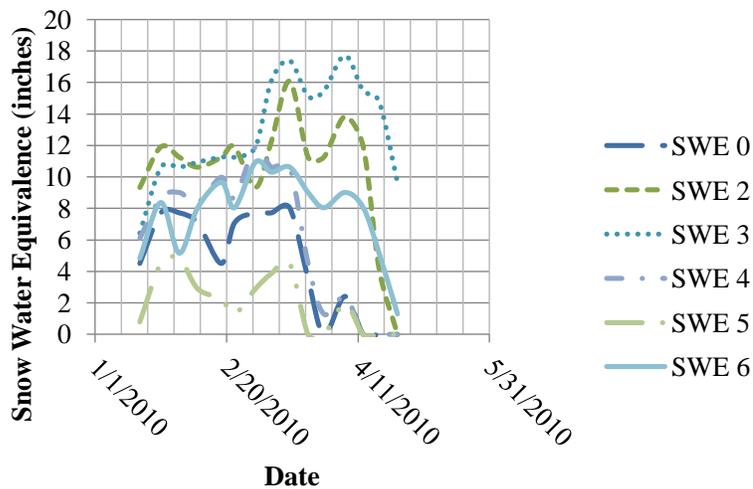
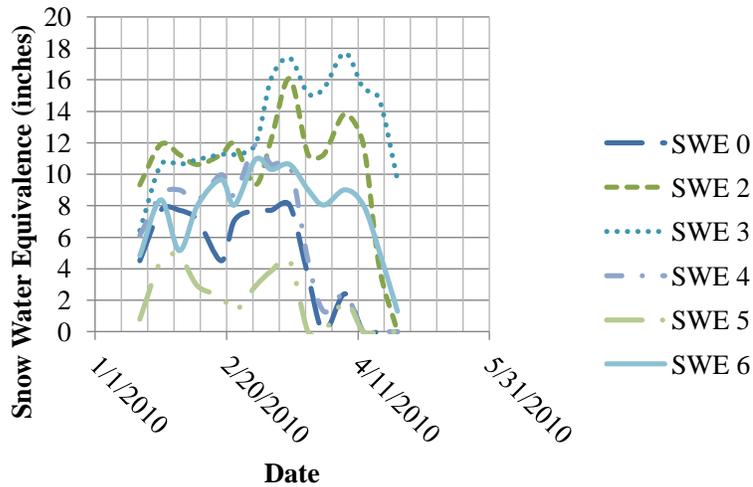


Figure 3a (top) and 3b (bottom): Snow water equivalence and snow depth trends respectively at the Sagehen Creek experimental site from January—April, 2010.

Figure 5 displays $SWE_{\text{observed}} - SWE_{\text{estimated}}$ values at each Snowcloud node for the entire experimental period. In Figure 5, values >0 indicate that the ratio underestimated SWE at a node, while values <0 indicate that the ratio was overestimated. An analysis of variance of the differences as a group failed to reject the hypothesis that these were different than 0 ($P=0.71$). The average difference between observed and estimated SWE at the Snowcloud nodes was 1.0 cm (0.41 in), with a standard deviation of 2.95 cm (1.16 in).

The potential predictors identified from correspondence analysis were:

1. Canopy cover with a northern azimuth (%)
2. Canopy cover with a southern azimuth (%)
3. Snow depth (in)
4. SWE from the snow pillow (in)
5. Snow density at the snow pillow (lb/in^3)
6. Weekly incoming solar radiation (megajoules)
7. Monthly average temperature ($^{\circ}\text{C}$)
8. A composite of average weekly temperature, relative humidity and wind direction

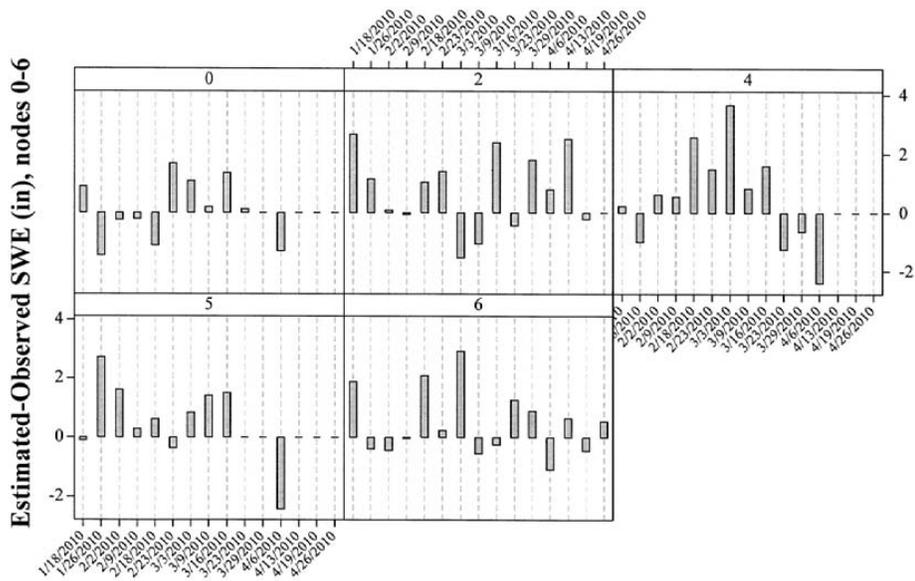


Figure 4: Differences between observed and predicted SWE at Snowcloud nodes, based on the ratio of SWE/SD from node 3, from January—April, 2010.

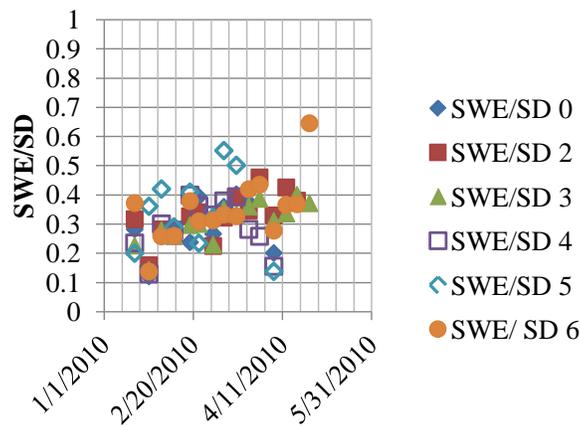


Figure 5: The ratio of SWE/SD at each node in the Snowcloud network from January—April, 2010.

Regression analysis identified the factors in Table 1 as having significant associations with SWE observed at each node.

Variable	P-value
Canopy closure to the north	0.000
Weekly total incoming solar radiation	0.0014
Monthly average temperature	0.001

Table 1: Predictors identified by regression as being significant, with P values for regression coefficients.

DISCUSSION

Across the site, SD varied significantly between nodes, especially in late March, when SD ranged from 0 cm at node 5 (which had a low seasonal accumulation within the canopy) to 83 cm (33 in), at node 2. SWE also varied significantly, with approximately the same trends as SD. However the ratio of SWE/SD was reasonably consistent between nodes, which suggests values of the ratio from the index site could be used with distributed measurements of SD to extend data from a snow pillow to an area. This agrees with an approach used by the U.S. Department of Agriculture's Soil Conservation Service snow surveys used to estimate snow depth from SWE observations at Montana SNOTEL sites, Grand Teton National Park and the Snake River watershed above Jackson, WY (Farnes, personal communication, 2011). In these areas, families of linear relationships between SD and SWE varied by month, from December 1—June 1 (for Montana SNOTEL sites, based on observations from 1961—1985) and a table from October through July for the Grand Teton National Park and Snake River watershed. Although the purpose of the linear relationships depicted in these graphs and tables is the inverse of that applied in this study (using a SWE/SD ratio to predict SD from SWE), these illustrate that the ratio of these measurements can be considered approximately constant across large areas, though varying through time.

Estimates of total water content in an area could be refined by using more than one index site to develop SWE/SD scaling factors appropriate for different site conditions, based on specific characteristics, such as canopy closure in a specific orientation. Regression analyses indicated that several site characteristics were important, including canopy closure. It also identified two meteorological variables related to energy balance likely to be affected by canopy closure: weekly incoming solar radiation and monthly average temperature. In addition, canopy closure may have also accounted for interception losses that led to decreased snow accumulation at node 5. The SWE/SD ratio at node 5 consistently differed from the other nodes. The consistent difference indicates that conditions at node 5 would have been best characterized by a SWE/SD ratio that represented a high percentage of canopy closure. In this study, snow accumulation within canopy (nodes 5 and 6) was less than that observed in open areas. However, there were only three data points beneath canopy (3, 5, and 6), which did not provide enough information to generalize the effects of canopy closure on SWE, SD and SWE/SD.

This trial demonstrated the utility of a WSN that measures SD to extend SWE measurements from a point to an area to estimate the total volume of water in snowpack. Multiyear data sets could increase accuracy of SWE estimates based on the ratio of SWE/SD developed at appropriate index sites. Significant predictors of SWE may not be properly characterized or found from the analysis of a single year data set (Erickson, et al., 2005).

The study area within Sagehen Creek did not include significant topographic variation, with the majority of the field either flat or with less than a 10% slope. Slope, especially with respect to azimuth, has been used to estimate SWE and SD (Anderton, et al., 2004, Cline, et al., 1998, Elder, et al., 1991, Erickson, et al., 2005, Golding et al., 1986, Jost, et al., 2007, Molotch, et al., 2005). The inclusion of these factors could enhance SWE predictions from WSN measurements in a range of topographic conditions.

Wireless snow depth sensors can extend SWE measurements to reduce the biases due to placement of weather stations and improve spatial resolution of SD measurement and SWE distribution. A sufficiently dense sensor network could provide the foundation for spatial extrapolation using techniques such as kriging (Mooser, 2010). Wireless sensor networks could also be coupled with weather stations in forested areas to expand information available about snow depth and, with appropriate SWE/SD ratios, water content held in snow pack. As an example, the Remote Area Weather Station (RAWS) network currently includes 2200 stations in the United States designed primarily to monitor and assess fire danger (<http://raws.fam.nwcg.gov/index.html>, last accessed July 2011). By adding one or more SWE and SD measurements and snow depth sensing networks at key stations, this network could provide estimates of snow pack water content and weather conditions that would be useful for model estimates of annual discharge volumes. In addition, wireless sensor networks cost considerably less than SNOTEL sites are designed to be temporary installations. A three to eight node Snowcloud system costs range from 9—25% the cost of a single SNOTEL site and can be easily moved and redeployed.

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