Local and Regional Estimation of Snow Using SNOTEL

B.L. GWILLIAM[1]

ABSTRACT

One aspect of snow research is concerned with understanding the spatial distribution of snow. Snow distribution includes the influence of locational attributes such as latitude, longitude, elevation, and canopy cover. The 1990 snow data from six USDA Soil Conservation Service Snow Telemetry (SNOTEL) sites on the Mogollon Rim of Arizona provide an opportune case study of snow distribution as a function of locational attributes. Study results show that percent canopy cover effectively describes the variation between the study sites and a derived regional average. Canopy cover is included in a locationally adjusted spatial snow cover model, which provides strong predictive estimates of snow cover as shown by concurrently collected snow course data.

Key words: Canopy cover, SNOTEL, snow cover, snow water equivalent.

INTRODUCTION

Snow science is concerned with understanding the controlling factors of time and space (Colbeck 1987). These concerns include measurement and estimation of snow cover extent and water content (Elder et al. 1989). Knowledge of where and how much snow is present is also necessary for effective snowmelt-soil moisture runoff relationships, management and understanding of the accumulation and ablation zones of glaciers, avalanche forecasting, seasonal snowpacks, and transient snow covers (Gray and Male 1981). Many practical problems are related to data acquisition and interpretation of point data to larger areas (Marsh 1990). Although many methodologies and techniques exist, none resolve the issues of limited data and areal interpretation within snow environs (Terjung 1976, Brazel et al. 1991). This paper addresses the need to estimate and predict snow cover over a mesoscale region given limited data.

Little has been done to understand the spatial nature of snow covers. Limited work (Bilello 1967, Grant and Rhea 1974, Adams 1976, Miller 1976) describes the influence of location on snowpacks. Difficulties include converting point observations to areal estimates and defining the influence of canopy cover (Marsh 1990). The current focus of snow research includes complex modeling of snow processes from grain to basin to region scales (Colbeck 1987) and integration of spatial factors for increased management of snow water (Elder et al. 1989). Use of point data identifies the need to include the influence of locational attributes.

Within the arid/semi-arid southwestern United States, less then 10% of all precipitation is actively managed (Ffolliott et al. 1989). Also, it is noteworthy that between 50% and 75% of all runoff originates from western snowpacks (Schafer 1985), and within Arizona, the estimates are between 89% and 99% (Ffolliott and Throud 1974, Warren 1974). Coupling increasing demands for water with limited snow observations, it is necessary to understand the spatial distribution of the snow cover to maximize its contribution to limited water resources per point, drainage basin, and regions (Viessman 1989, Brooks et al. 1991). This study focuses on the use of limited snow cover observations and their locational attributes to estimate snow cover along the Mogollon Rim of Arizona during snow year 1990.

SNOTEL DATA AND SITES

Six USDA Soil Conservation Service Snow Telemetry (SNOTEL) sites are situated along the Mogollon Rim extending from near Flagstaff to Show Low, Arizona (Figure 1). The Rim is the southwestern section of the Colorado Plateau, a topographic barrier that rises more than 300 m and causes orographic precipitation from moist westerly air masses. This precipitation is monitored on a daily basis at these six SNOTEL sites for rainfall, snow water

[1]Remote Sensing/GIS Center; U.S. Army Cold Regions Research and Engineering Laboratory (CRREL); 72 Lyme Road; Hanover, New Hampshire 03755-1290 USA

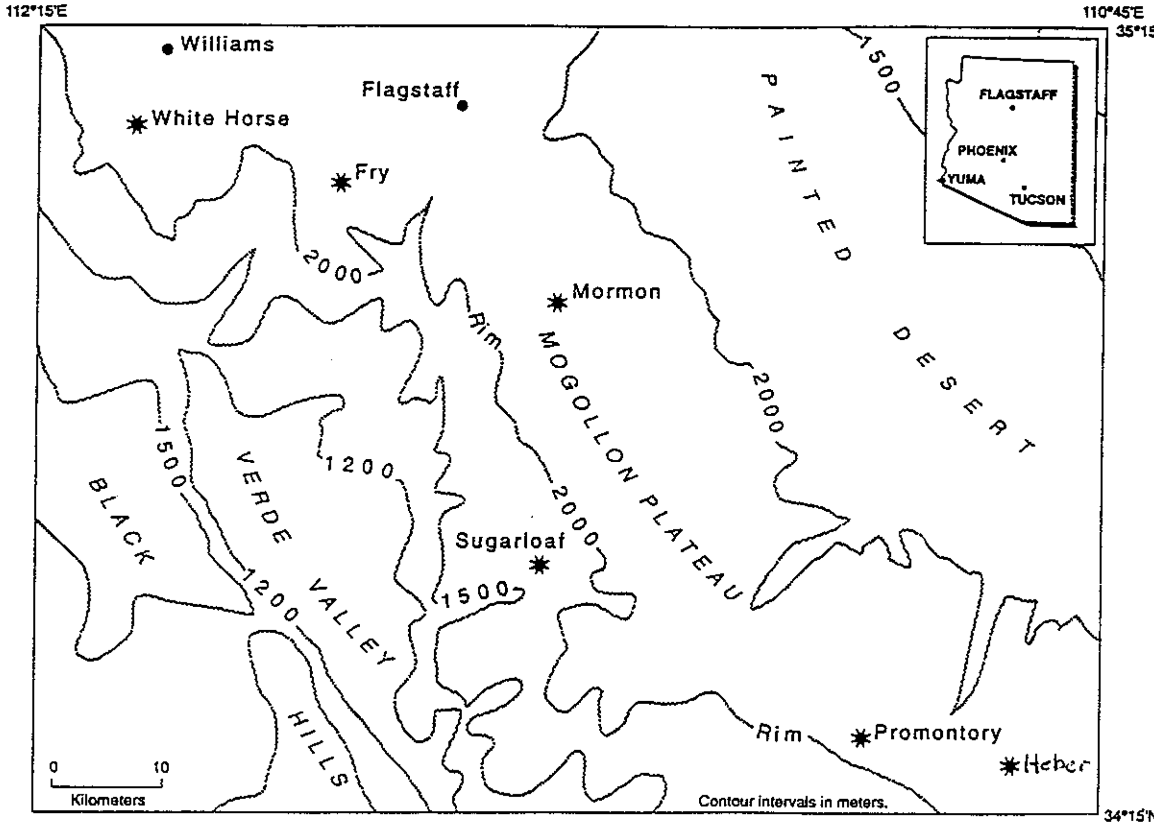

Figure 1. Map of study region: Mogollon Rim, Arizona.

Table 1. SNOTEL Sites and Locational Descriptors.

Site	*Latitude*	*Longitude*	*Elevation (m)*	*Canopy Cover (%)*
Fry	35.07	111.51	2194 m	39.4%
Heber	34.32	110.75	2329 m	37.3%
Mormon Mountain	34.93	111.52	2286 m	41.2%
Promontory	34.37	111.02	2417 m	63.0%
Sugar Loaf	34.62	111.52	1865 m	27.8%
White Horse	35.13	112.15	2188 m	57.6%

equivalents, and snowmelt. Locational descriptors for each SNOTEL site are listed in Table 1.

The study region ranges from 34°15' to 35°15' north latitude and from 110°30' to 112°15' west longitude. Topography rises from below 1000 m to over 2400 m. To graphically portray the region, representative elevations were collected at 15-minute intervals, resulting in an eight-by-five matrix. The elevations at the six SNOTEL sites were added to the forty-point matrix. Topographic lines of elevation were then derived using an inverse square procedure within the Surfer software program. This elevation map (Figure 2) portrays three locational attributes—latitude, longitude, and elevation—and is used as the base map to display the spatial distribution of snow cover.

Canopy cover, the fourth locational descriptor, varies from 0% over open fields and meadows to nearly 100% under the transitional montane forest along the upper zone of the rim. Canopy cover reflects the regional precipitation pattern and local influences of topography (Viessman 1989). The combined influence of colder temperatures and increased precipitation with elevation result in lower rates of evapotranspiration and comparatively higher soil moisture retention and vegetative cover. Canopy

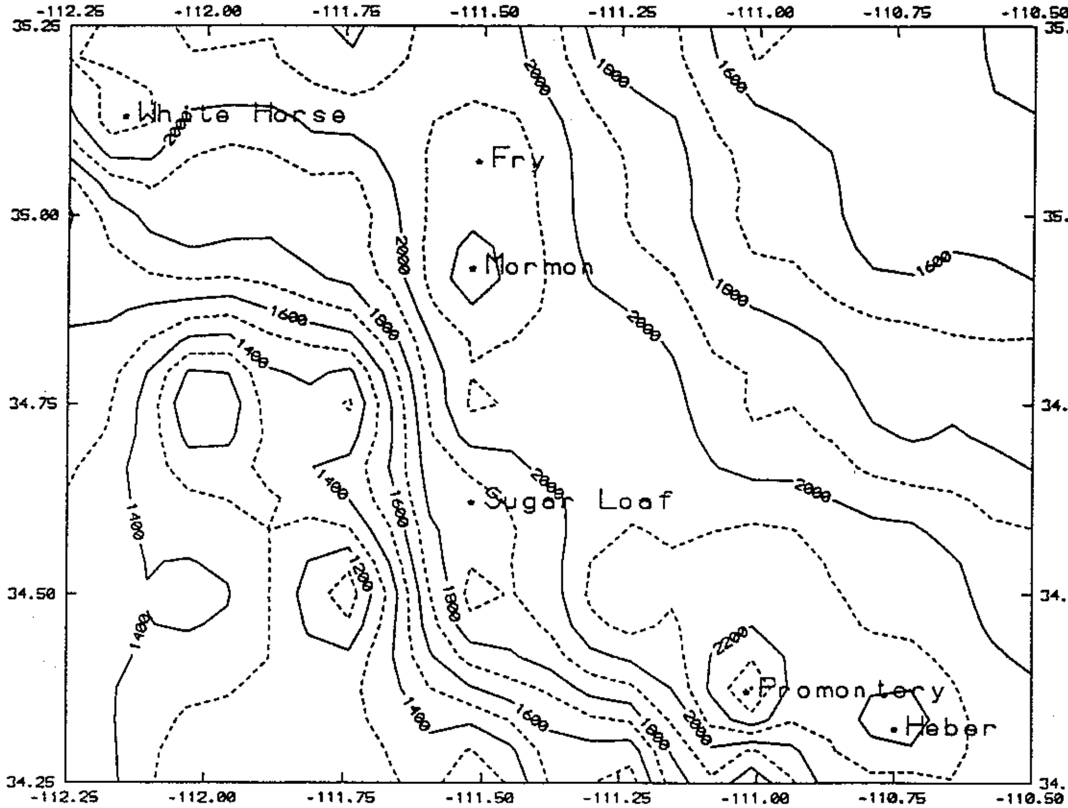

Figure 2. Elevation map of Mogollon Rim study region (m).

cover decreases daytime air temperatures near the ground, and through interception and subsequent evaporation decreases the amount of precipitation that reaches the ground (Brooks et al. 1991). This relationship has been observed with snowfall and affects the snowfall distribution and resultant snow cover depth (Elder et al. 1989, Marsh 1990).

Ffolliott et al. (1989) observed that canopy cover in Arizona decreased depth of snowfall and snow cover. Within ponderosa pine stands, these variables have been shown to increase (Warren 1974). The differing influences may be due simply to varying canopy coverage and density. Ponderosa pine displays extensive areal coverage but with limited density due to thin layers of needle leaf. Clearly, canopy cover can strongly affect snow cover formation, thus indicating its importance and required inclusion in spatial analysis of SNOTEL data.

Canopy cover at each site was measured using a grid overlay on top of hemispherical photographs taken at each site. For example, the photograph taken at Promontory (Figure 3) is shown with a point grid overlay. Whenever a point above the horizon is in contact with vegetation, it is circled and counted. The sum of the circled grid points is then divided by the number of points above the horizon to derive percent canopy cover. Canopy cover is similar to sky view factor and other measures of hemispherical obliquity that describe the vegetative interference between clear sky and snow cover. A top down perspective (a satellite image) would provide a similar measure of total canopy coverage.

These locational descriptors—latitude, longitude, elevation, and canopy cover—will be used independently and collectively to help explain the observed variation in the SNOTEL snow cover data collected along the Mogollon Rim during Snow Year 1990.

METHODOLOGY

Spatial variability is predicted for point-to-basin estimates using either statistical or physically based process analysis. This allows interpolation for points within the study region (Schafer 1985). The region, as represented by the six SNOTEL sites, is treated as a single unit with each site as a discrete observation of the whole. Since all observations are collected on a daily basis and represent the same time period, they can be averaged to represent the region. As each site differs from the regional average, the differences may be explainable as functions of locational attributes.

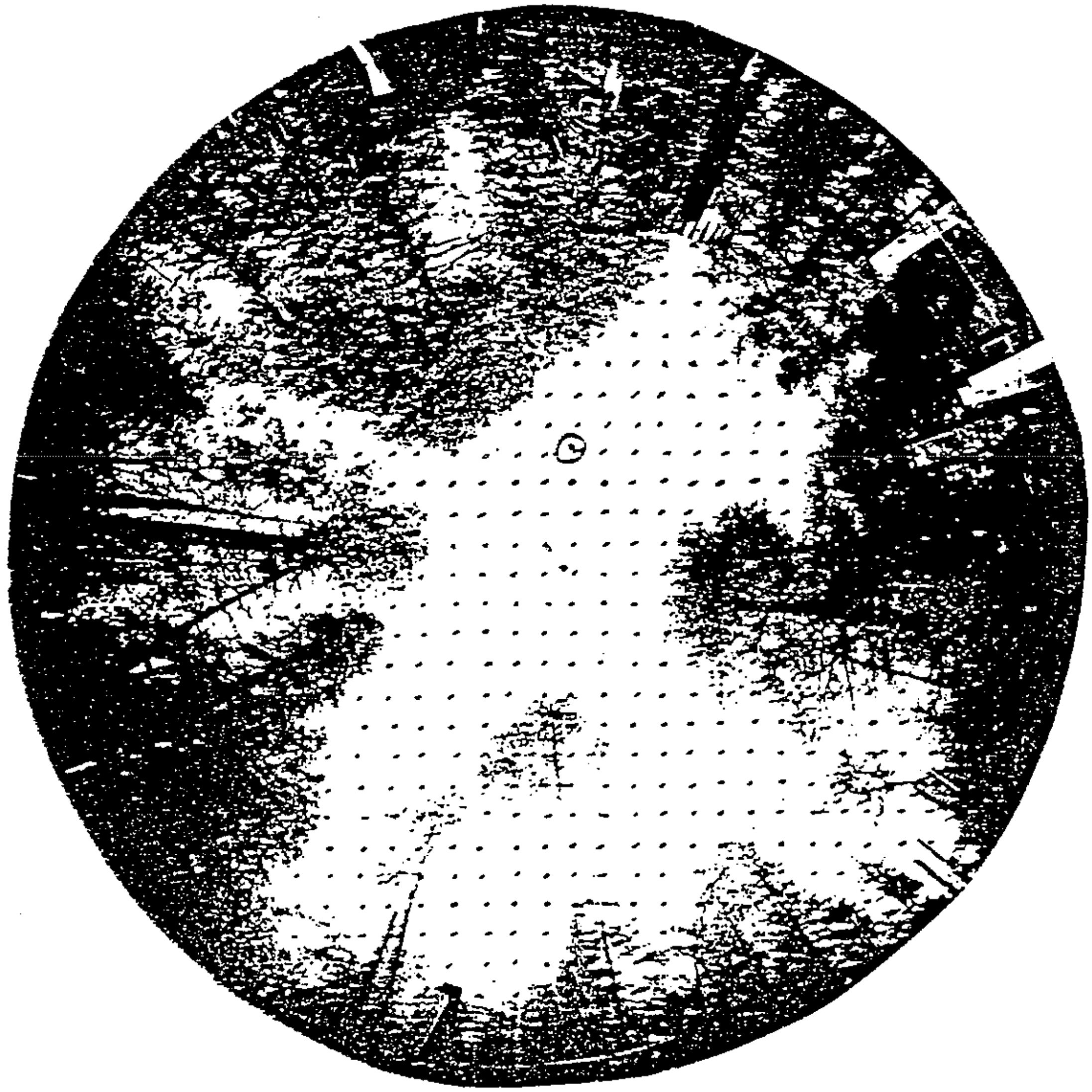

Figure 3. Canopy cover of Promontory SNOTEL site.

A new matrix is created for snow cover with 123 rows for each day in the study period and seven columns representing the six SNOTEL sites and regional average. Simple regression analysis is conducted with the daily site observations as the dependent variable and the regional average as the independent. The simple regression equation takes the form of

$$\text{Snow cover} = a + b*\text{Avg} \qquad (1)$$

where daily site observations of snow cover (cm of snow water equivalent) is the independent variable, a is the intercept, b is the slope, and "Avg" is the daily regional average. The intercept will show whether the site varies above or below the regional average while the slope indicates higher or lower variability from the regional average.

A second matrix is then developed with six rows for each site and six columns representing the four locational attributes (e.g., latitude, longitude, elevation, and canopy cover) and the statistically derived intercept (a) and slope (b). Stepwise multiple regression analysis is then used with the intercept and slope as the dependent variables and the locational attributes as the independent values. Due to the small number of SNOTEL sites, all six sites are used for this analysis. A significance threshold of 0.10 is used to maintain statistical rigor with the limited number of sites (n = 6).

Knowing the regional average and the regression coefficients as a function of locational attributes, it is possible to estimate daily data at intermediate locations within the study region. Modeling snow cover requires two further logical adjustments. First, if the regional average is zero, then the model estimate is zero. Second, if the predicted variable is physically invalid (e.g., snow cover is a negative value), the predicted value is zero.

The spatially adjusted model is constructed to predict daily site values knowing a regional average. This model may be used to interpolate between the known boundaries without adjustment (Table 1): 110.75° and 112.15° west longitude, 43.32° and 35.13° north latitude, 1865 and 2417 m elevation. Predicted values require no adjustment within observed ranges [e.g., 0 to 29.5 cm of snow water equivalent (swe) for the individual sites and a maximum regional value of 14.6 cm]. Finally, within spatial and observational bounds, these equations can provide daily predictions without requiring recalculation of their fundamental relationships, thus allowing spatial analysis per location for the study period.

SNOW COVER

Snow cover is represented by the measured daily amount of snow water equivalent on the ground at each SNOTEL site. This amount of snow water equivalent is key to understanding the potential water resources within the drainage basins and potential flood water available during melt event. This variable needs to be spatially definable for effective management and for prediction of areal snow water equivalent estimates per drainage basin, especially within Arizona (Elder et al. 1989, Viessman 1989, Ffolliott et al. 1989, Marsh 1990). Snow cover, the combined result of snowfall and snowmelt, does reflect the regional deposition and should include the influence of canopy cover on regional melt patterns.

Using the regional average (Avg) as the independent variable and the snow cover observations from each site individually and from all six sites together, a simple linear relationship results (Table 2). All equations are statistically significant. Promontory, the only site with a positive intercept, effectively offsets the five other site intercepts, identifying it as retaining the largest and longest snow cover. Fry, Mormon Mountain, Promontory, and Whitehorse receive greater amounts of snowfall, as shown by the slope values, which are greater than one. Heber and Sugar Loaf both receive much smaller amounts of snowfall (note the very small slope coefficients).

The statistical coefficients (a, b) are fitted to the locational attributes (e.g., latitude, longitude, elevation, and canopy cover) using stepwise multiple regression. No linear equation for the intercept is defined. Zero, the regional intercept, is therefore used as the intercept for all locations. The linear equation for the slope coefficient follows.

$$b_{All} = -1.09 + 0.047*\text{Canopy};\ r^2 = 0.72;\ p = 0.00 \quad (2)$$

Where canopy cover is present, a significant relationship is defined between the snow cover slope and canopy cover. The slope shows that snow cover increases as canopy cover increases. Inserting the slope equation back into the basic model provides a locationally adjusted snow cover model:

$$\text{Snow cover} = 0 + (-1.09 + 0.047\ \text{Canopy})*\text{Avg}. \quad (3)$$

This equation defines a common regional signal and a local signal that uses the percent canopy cover to modify the regional average. It is important to compare the predicted values with the observed. The predicted intercept and slopes were calculated and used to determine the fit of the simple statistical relationship for the locationally adjusted snow cover model (Table 3). The locationally adjusted snow cover model reduces the standard error from 5.83 cm to 3.24 cm of snow water equivalent. The coefficient of determination (r^2) made a statistically significant increase from 0.36 to 0.80. Snow cover is spatially variable and predictable from a regional snow cover average and by knowing canopy cover at a site.

Using the maximum seasonal snow cover average for all six sites (14.6 cm) in the locationally adjusted

Table 2. Simple Linear Relationships.

Site	*a*	*b*	r^2	*p*	*se*
Fry	–0.33	1.28	0.81	0.00	1.46
Heber	–0.13	0.24	0.50	0.00	2.08
Mormon Mountain	–1.35	1.10	0.91	0.00	1.13
Promontory	2.45	1.08	0.79	0.00	3.79
Sugar Loaf	–0.09	0.05	0.14	0.00	0.90
White Horse	–0.61	1.53	0.95	0.00	1.67
All	0.00	1.00	0.36	0.00	5.83

Table 3. Predicted Intercept and Slope Coefficients.

Site	*a*	*b*	r^2	*p*	*se*
Fry	0	0.77	0.81	0.00	1.46
Heber	0	0.67	0.50	0.00	2.08
Mormon Mountain	0	0.85	0.91	0.00	1.13
Promontory	0	1.88	0.79	0.00	3.79
Sugar Loaf	0	0.22	0.14	0.00	0.90
White Horse	0	1.62	0.95	0.00	1.67
All	—	—	0.80	0.00	3.24

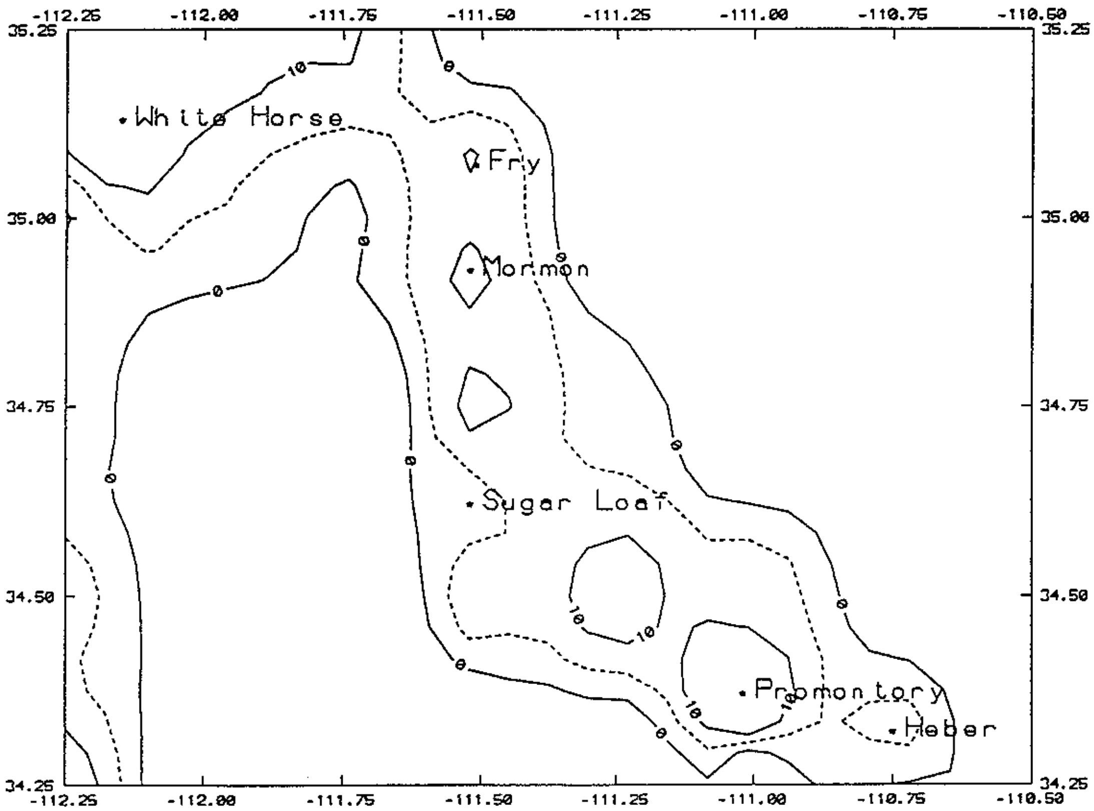

Figure 4. Snow cover map of Mogollon Rim study region (cm).

snow cover model, results are shown on the forty-six point grid of the study region (Figure 4). The western snow line occurs at about 1800 m elevation and the eastern snow line at about 2100 m elevation. The lower western snow line appears to define the earlier windward effect where the Rim acts as a topographic barrier. The eastern snow line, with its slightly higher elevation, defines the leeward boundary of the precipitation zone. The Rim is both a barrier and an accumulation zone for snow. These spatial patterns agree with the regional synoptic pattern of moist air masses moving over a topographic barrier. These air masses move eastward from the Pacific Ocean as part of the mid-latitude cyclones and experience orographic lifting.

Setting the snow cover slope to zero identifies areas with greater than 23% canopy cover as the snow line boundary. Canopy cover does not induce snowfall; rather, it represents the long-term, persistent precipitation synoptic patterns of this semi-arid region. Ponderosa pine, which dominates within this region, does not appear to decrease snowfall nor to increase melt. Areas with small canopy cover (<23%) experience small and more frequent melts shortly after snowfall. Areas with greater than 23% canopy cover receive larger snowfalls that are protected by the overstory from melt.

This relationship of vegetation to snow cover allows estimates of snow cover to be made using observed canopy cover for the study region. This esti-

Table 4. Correlation Between Predicted and Observed.

Site	*Latitude*	*Longitude*	*Elevation (m)*	*Canopy Cover (%)*	r^2
Newman Park	35.00	111.68	2057	42	0.79
White Horse	35.13	112.15	2188	44	0.89
Fort Valley	35.27	111.75	2240	45	0.88
Mormon Mountain	34.93	111.52	2286	46	0.96
Happy Jack	34.75	111.40	2325	0	0.91
Heber	34.32	110.75	2328	47	0.96
Williams Ski Run	35.20	112.20	2353	48	0.81

mate describes the snow water equivalent at a point that can be extended across the whole region or for specific points within a drainage basin. The ability to predict areal snow cover would help estimate snow water equivalent. Such estimates would provide additional information to better manage water resources per drainage basin.

SNOW COURSES

Lack of data from other areas limits the ability to validate the spatially adjusted snow cover model. There are, however, snow course data collected on the first and fifteenth day of each month at nineteen locations within the state of Arizona. Seven of these sites lie within the study region. Three of the snow courses are near SNOTEL sites and the others provide a measure of verification for snow estimates at point locations within the study region as a whole. Using the spatially adjusted snow cover model estimates and the recorded snow water equivalent, collected at each snow course, simple correlations were made (Table 4). Each of the seven snow courses shows strong correlation between the observed and predicted values for the 1992 snow season.

CONCLUSION

The focus of this research was the spatial variability of a snow cover. The use of the daily regional average (snow water equivalent) allowed determination of the common regional average and the local variance in the data set. Percent canopy cover modifies the regional average to describe the variance observed at each site. Knowing the canopy cover for uninstrumented sites allows estimation of the snow cover present on a daily basis for points, basins, or the entire study region.

Using the readily available SNOTEL data, hydrologists and water resource managers can apply this technique to improve their spatial prediction of snow water equivalents (Brooks et al. 1991). This method readily defines regional and local estimates from a limited number of point observations. It also is expected that regional estimates from satellites or global simulation models can be converted to specific point estimates within a study region and will improve spatial resolution and estimation. Future work in this area could enhance flood/runoff prediction and management.

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