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Estimating Total Snow Volume in a Small Alpine Watershed Using Remotely Sensed Data and Ground-Based Surveys

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ABSTRACT

Ground surveys of snow water equivalence and snow cover maps derived from Landsat TM imagery provided the basis for investigating different methods to estimate total snow volume in a small watershed of the eastern Sierra Nevada of California. Snow density profiles and Federal Snow Sampler observations along ground transects made up the measurements used to estimate the snow water equivalence at several points. The area of the snow cover was estimated with two techniques, a supervised classification and a method based on spectral mixture modeling. Total snow volume was obtained by distributing snow water equivalence over the snow-covered area with the help of a digital elevation model. Snow volume estimates, in terms of their water equivalence, were compared with the estimated total snowmelt runoff. Total snowmelt runoff was estimated by subtracting baseflow determined with a graphical technique. The comparisons were evaluated in the context of potentially combining remote sensing data with traditional snow course measurements to determine total snow cover volume.

INTRODUCTION

Probably the most important hydrologic variable in watersheds whose annual runoff is derived mostly from snow is the total snow cover volume, expressed as the watershed snow water equivalence. A major factor characterizing the hydrology of alpine watersheds is the dominance of snow melt over other forms of precipitation. While snow-covered area can be measured with a variety of methods, such as mapping from aerial photography and satellite imagery, most measurements of snow water equivalence in alpine areas are made on the ground at points along transects. Measuring snow water equivalence with airborne techniques, such as gamma ray attenuation along flight lines, or satellite techniques, such as microwave emission from areas, either are not suitable or have not been sufficiently developed for deep snow cover in rugged alpine terrain. However, opportunities to measure snow-covered area at high spatial, spectral and temporal resolutions, combined with advances in spatial analysis tools to distribute point or line ground measurements, will soon improve operational forecasting of snowmelt runoff from alpine basins.

METHODS

The snow water equivalence (SWE) of a watershed is the equivalent depth of water that would result if the snow were melted instantly and distributed uniformly over the basin. Watershed SWE can be obtained from the product of snow-covered area (SCA) and average SWE. We calculated the SWE of a small alpine watershed using different methods to estimate SCA from a Landsat TM image and different methods to distribute point measurements of SWE made on the ground. The SCA estimates of selected subimages were compared with the SCA derived from high resolution aerial photography for the same areas. The basin SWE estimates were compared against independent estimates of the total basin SWE, made from measured snowmelt runoff and rough estimates of the snow melt season water balance.

The ground-based measurements of SWE, and the satellite and airborne measurements used to estimate SCA were made on May 10, 1992.

Study Site

The study was conducted in the Ruby Lake watershed, in the eastern Sierra Nevada, California, just outside the eastern border of the John Muir Wilderness, Sierra National Forest. Ruby Lake, 37°25′ N, 118°46′ W, lies at an elevation above timberline, 3390 m, at the downstream end of the watershed. A chain of small shallow tarns extends upstream from Ruby Lake to a small remnant glacier, which occupies less than 5% of the total basin area of 441 ha, at the northeast face of Mt. Abbot. Lake surface comprises 23 ha, or about 5% of the total area. The basin elevation ranges from 3370 to 4177 m, a total relief of 807 m. Very little soil or vegetation cover the basin, which has the high cirques, steep ridges, a flat valley floor and stepped longitudinal profile characteristic of glaciated terrain.

Snow Covered Area

Snow cover was mapped from Landsat Thematic Mapper data using Bayesian maximum likelihood classification, which is the most common supervised classification method used with remote sensing image data. The discriminant function for maximum likelihood classification is based on the assumption that each channel DN histogram for each training class can be approximated by a normal distribution (Richards, 1986). Training sites were selected from the May 10 Landsat TM image for two snow classes, one vegetation class, and one bare ground (rock) class. Sites were repeatedly selected until the brightness histograms of the classes appeared to have normal distributions in bands 2, 4 and 5. This method produced a binary snow map, that is, pixels are assigned to a snow class or to another class; a pixel is either snow-covered or it is not.

Another snow map was constructed from the Landsat TM data in which snow cover fraction was estimated for each pixel based on the spectral "unmixing" of the major components of the scene. Spectral mixture analysis is a quantitative method that allows the measured spectrum of an image pixel to be decomposed into the spectra of the individual scene components within that pixel, plus an error term (e.g. Adams and Adams, 1984). In the basic linear mixing model the contribution of each component is proportional to its fractional abundance within the pixel.

Spectral mixture analysis was used to identify scene components that were significant at a sub-pixel level so that a sufficient number of pixels of varying composition could be selected to generate a model image. Three spectral classes were used to model an image of the Sierra - snow, rock, and vegetation - from which random samples of 50,000 pixels were drawn for the learning sample of a decision tree classifier (Rosenthal, 1993). A separate decision tree was trained to classify clouds. Five draws were used to train five trees, which were then compared and found equivalent. The decision tree was then used to generate a SCA fraction map from the image acquired over the Sierra.

An aerial photography mission was flown in the early afternoon of May 10, 1992. The average altitude was 6,700 m and the trend of the flight track was along the axis of the watershed. Six frames were photographed with a standard large format metric camera, producing the standard nine-inch format. While the Landsat TM image was acquired in the morning during clear skies over the area, the aerial photography mission took place after the local weather had changed, winds exhibiting moderate turbulence and convective cloud cover forming over parts of the area. The photograph set showed that the basin was approximately 10% cloud covered, and cloud shadows occupied slightly more area. Because of these problems, an orthophoto mosaic, registered to the terrain, was not constructed.

The SCA fraction map (subresolution method) was therefore compared to subsections of the aerial photography set. Each aerial photograph was digitized at a resolution corresponding to 4 m ground distance per pixel. Snow was classified in each image based on a brightness threshold, iterating to obtain the best visual fit in comparison to the original color prints. Test areas for comparison were selected from the central regions of the snow maps produced from the digitized aerial photographs. These areas were large enough, in terms of the area-to-perimeter ratio, so that errors due to mistakes in precisely defining the same areas from the Landsat SCA fraction map would be small. Twelve test areas were selected to represent a range of SCA fractions.

Snow Water Equivalence

Snow water equivalence was measured along transects with a Federal Sampler, which is a standard tool used for snow surveying in the western Unites States. The location of the transects represented terrain accessible by skis without high exposure to avalanche hazard. As is standard practice, each measurement was obtained by driving the corer into the snow cover to the base of the pack, weighing the loaded coring tube, then subtracting the tare weight of the tube. The net weight of the core was converted directly to SWE by the relationship between the tube diameter and the gradations on the spring-loaded scale. Snow depth and average density were also obtained from the coring. Snow water equivalence measurements obtained with the Federal Sampler are commonly biased (Goodison et al., 1981), so core observations were adjusted to compensate for SWE oversampling.

Streamflow

Two pressure transducers were used to measure the stream water surface height a few tens of meters downstream from Ruby Lake. Both transducers were located in natural reaches so that rating curves had to be empirically determined. This was computed by measuring discharge with the slug injection, or dilution gaging method (e.g. Elder et al., 1992; Church and Kellerhals, 1970), rather than the velocity-area method, which could not be used in this reach. A single measurement under ideal conditions using slug injection has been estimated to have uncertainty of about ±5% (Herschy, 1985). Errors associated with the measurements in this study were probably higher.

Data Preparation

Data were analyzed using a combination of the *ipw* image processing software (Frew, 1990) and the GRASS geographic information system (GIS) package (CERL, 1991). Calculations of SCA were made using *ipw* and the results were transferred to the GIS for SWE volume analysis. SWE point measurements were registered to a 30 m resolution U.S.G.S. digital elevation model (DEM) by taking the UTM coordinates from the field map, a U.S.G.S. 7.5 minute quadrangle, and entering them into the GIS.

Interpolation of Point Data

Points measurements of SWE were extrapolated over the basin using several different conventional methods of interpolation. We found it was not suitable to apply an elevation-gradient technique because the variation among the data points was greater than the weak relationship between SWE and elevation above timberline (c.f. Davis and Burak, 1988). This is because the highest elevations in this basin are characterized by slopes too steep to hold much snow. Additionally, it was not possible to apply more sophisticated physically-based SWE distribution methods such as that of Elder et al. (1991) because the location of the field measurements was limited to a relatively narrow range of terrain aspects. However, this makes the study more representative of typical snow course measurements made in alpine areas on an operational basis. The results are therefore applicable to pragmatic problems of current operational runoff forecasting, rather than theoretical or research-oriented problems.

The most simple method for treating point data in a spatial context is to take the mean of the point values and apply it to the area of interest, which we carried out.. In addition, three interpolations of the point SWE measurements were made using different numbers of nearest neighbors. We chose interpolation with 5, 10, and 50 nearest neighbors to get a range of results. SWE was mapped over the entire watershed area using these techniques.

The interpolated SWE maps described above were combined with both the subresolution SCA image and the binary SCA image to calculate volume. Each grid cell was either 100% snow covered or 100% snow-free in the binary SCA map case. The SWE value in each cell was multiplied by the percent cover of the corresponding cell using the subresolution SCA image. In both cases the sum of the cell SWE values was then taken to obtain the basin SWE volume. These combinations allowed us to examine the effect of different interpolation techniques and different SCA mapping techniques.

RESULTS

Snow Covered Area

Figure 1 shows the Ruby Lake watershed masked from Band 2 of the Landsat TM image (left), the SCA binary map (center) and the SCA fraction map (right). Grayscale values from Band 2 (Figure 1a) show the DN values from the image. Grayscale values in the SCA fraction image (Figure 1c) are linearly scaled, black to white (0-255), from the snow cover fractions returned by the algorithm (0-96). Snow covered area was clearly dependent on the method used. A summary of the two SCA maps shown in the Figure 1 is listed in Table 1.

The binary method, which produces a result similar to most conventional classification methods, gave SCA equal to 370 ha or 84% of the basin. SCA was classified to be 100% in 4112 of the 4896 grid cells or pixels included in the basin; 784 cells were classified as 100% snow-free. In the subresolution method, all cells in the basin were assigned one of nine values of snow covered area, ranging from 0 to 96%. This method classified 87 cells or 7.83 ha as 100% snow-free. Based on this value the method showed a greater snow covered area than the binary method. However, since the percent coverage of each cell was multiplied by the cell area and summed over all cells in the basin, then the snow covered area

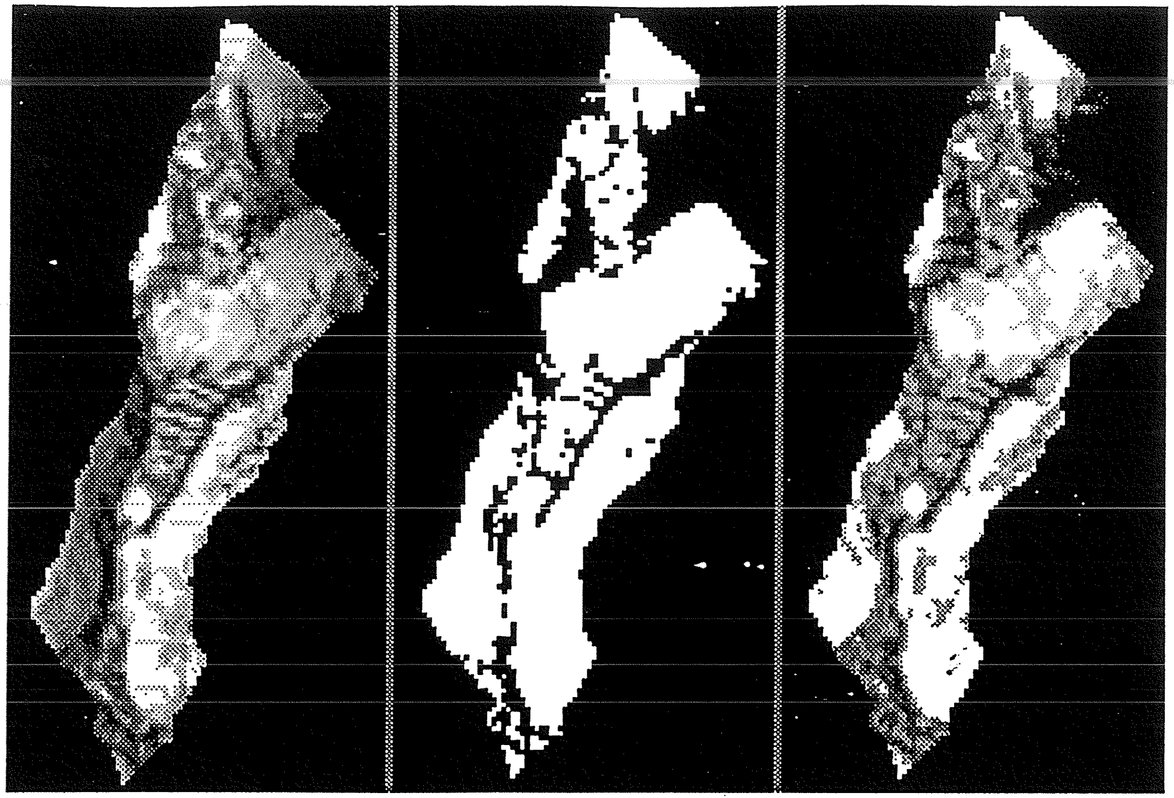

Figure 1. 1a. Masked image of the Ruby Lake watershed (left) from Landsat TM Band 2 acquired May 10, 1992. 1b. Binary SCA map produced from Bayesian classification (center). 1c. SCA fraction map (subresolution) produced from spectral mixture analysis and decision-tree classification (right).

equaled 3635 cells or 327.15 ha, which is 74% of the basin. Applying this technique, there was a 10% difference in SCA between the binary and subresolution methods.

Table 1. Snow covered area calculated by two methods.

Method	Fraction SCA	Number of (%)	Total Area Cells	Percent of Total (ha)
subres.	0	87	7.83	1.78
	9	66	5.94	1.35
	22	237	21.33	4.84
	38	394	35.46	8.05
	50	331	29.79	6.76
	60	291	26.19	5.94
	72	659	59.31	13.46
	84	877	78.93	17.91
	96	1954	175.86	39.91
	0-96	4896	440.64	100.00
	9-96	4809	432.81	98.22
	%(N)†	3635	327.15	74.24
binary		4112	370.08	83.99

† %(N) is the percent SCA for each of the nine percentage classes multiplied by the number of cells within the class, summed over the entire basin.

The subresolution method was also compared to high resolution binary snow maps of areas within the watershed, constructed from the digitized and classified aerial photographs. Twelve subimages from both the SCA fraction map and the high resolution binary maps from the photography were measured to give the average snow covered area fraction within the subimage. Figure 2 shows the comparison between photographic estimated snow cover fraction and the Landsat TM estimated snow cover fraction.

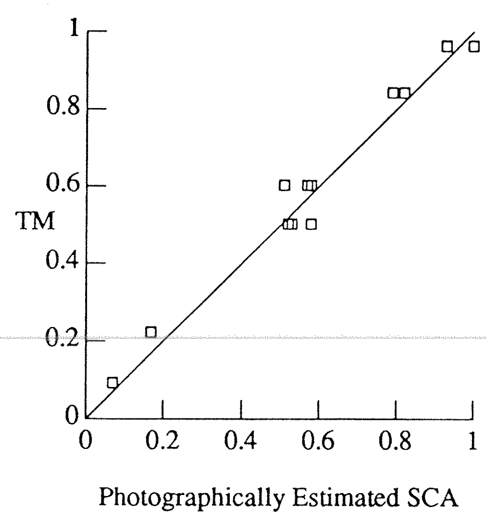

Figure 2. Comparison between SCA fractions in subimages from Ruby Lake watershed, estimated from digitized and classified aerial photographs, and SCA fractions from Landsat TM subimages.

The worst case error was about 9%, with the average difference much less. With precise registration this technique has shown differences on the order of only a few percent (Rosenthal, 1993). Some of the differences occurred because the subimages could not be precisely registered.

Snow Water Equivalence

The snow measurements consisted of 50 SWE measurements along the axis of the watershed and 10 SWE measurements up a hanging snowfield to the north. Figure 3 shows the basin outline with the SWE measurement site locations plotted as points.

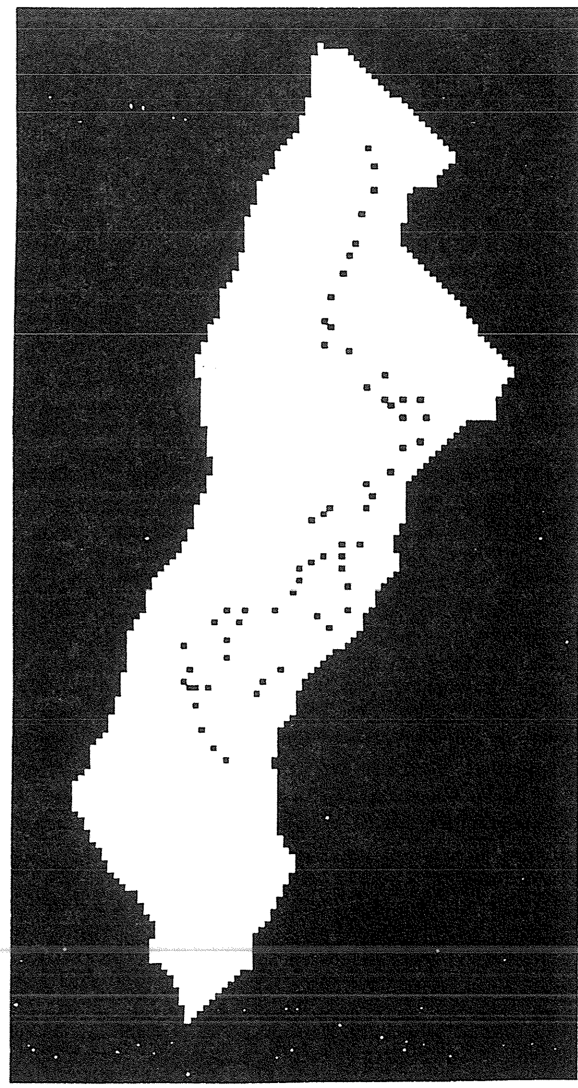

Figure 3. Basin outline of Ruby Lake watershed, showing measurement sites of SWE, plotted as points.

We distributed the mean value of 0.43 m SWE over the basin area of 441 ha. Again, three interpolations of the point SWE measurements were made using different numbers of nearest neighbors; interpolation with 5, 10, and 50 nearest neighbors were used.

Total volume of water stored as snow in the basin varies markedly depending on the method used, with a 15% difference between the extremes. Results are summarized in Table 2.

Table 2. Calculated basin SWE volumes for different methods of interpolation and snow-covered area mapping.

Interp. Method†	SCA Method††	SCA Area (ha)	SWE Vol. (m^3)
mean	binary	370.08	1,599,000
mean	fraction	327.15	1,413,000
nn(5)	binary	370.08	1,662,000
nn(5)	fraction	327.15	1,472,000
nn(10)	binary	370.08	1,622,000
nn(10)	fraction	327.15	1,436,000
nn(50)	binary	370.08	1,595,000
nn(50)	fraction	327.15	1,412,000

† Interpolation methods: mean is the mean SWE applied uniformly to the entire basin; nn(5) is nearest neighbor with 5 points; nn(10) is nearest neighbor with 10 points; nn(50) is nearest neighbor with 50 points.
†† SCA methods: binary is snow-covered versus snow-free; percentage is SCA with percent coverage in individual cells.

The largest volume (1,662,000 m^3) was produced by the nearest neighbor method using five points and the binary SCA map. The nearest neighbor method with ten points and the binary SCA map was the second largest with 2.4% less SWE. Regardless of the interpolation technique, all SWE volumes calculated with the SCA fraction map were significantly smaller than those calculated with the binary SCA map. For a given interpolation method, the volumes ranged from 11.4 to 11.6% less for the SCA fraction map as opposed to the binary case.

Streamflow

The average measured daily runoff for the standard water year 1992 is shown in Figure 4. We made simple assumptions regarding the annual snowmelt flow: 1) lake storage requirements were met before day 200 (Figure 4), and 2) while "true" baseflow should gradually decay as the annual melt-derived flow does, the reductions in flow were probably offest by flow from the small remnant glacier. The assumed baseflow contribution to the total flow was graphically interpolated between dates when the residual flow was relatively constant and is shown as a dashed line in Figure 4. The measurements of daily discharge showed that the rating curves for two pressure transducers, which were used to measure stage height could be improved, particularly at higher flows. The differences in the two pressure transducer readings became clear as the snow melting season progressed, as shown in Figure 5, where the disparity was as much as 20%. Therefore we used the average of the two sensors. Our best estimate for snowmelt runoff after the survey date (day 200) is 1,034,000 m^3.

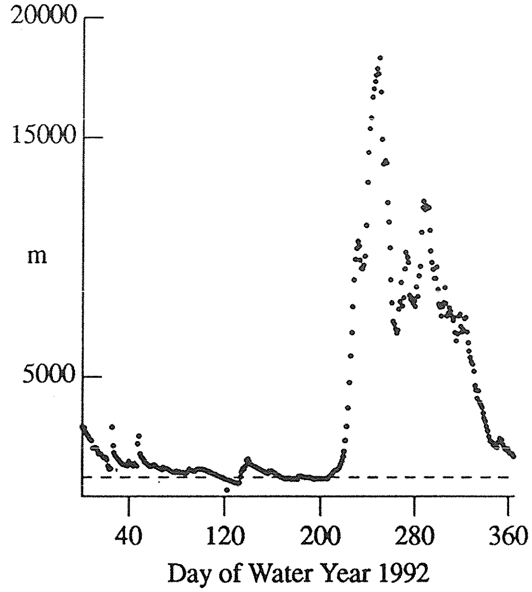

Figure 4. Streamflow (m^3) observed during Water Year 1992 from Ruby Lake Basin (top). Dots show total daily runoff, m^3, averaged from measurements of two stage height sensors.

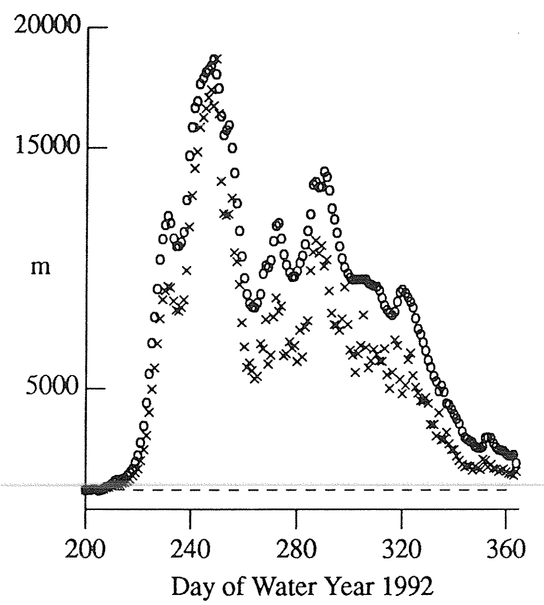

Figure 5. Streamflow (m^3) observed during the snow melting part of Water Year 1992 from Ruby Lake Basin (bottom). The x's show one gage and o's show the other gage. Dashed line shows graphically determined baseflow.

DISCUSSION

The results show that the basin total SWE volume is dependent on the method of estimating both snow-covered area and snow water equivalence. In this study the primary sensitivity is based on the method used for mapping SCA.

Basin SWE Comparison

The difference between the two methods was consistent (11.4 to 11.6%) for each point-SWE interpolation technique. Clearly this is a direct result of the 10% difference in SCA between the binary and subresolution methods. The method used to estimate snow water equivalence caused a 4% difference in volume, for a given SCA method. SWE volumes are unrealistically high for the estimates based on the binary SCA method. The volumes produced by all four interpolations using the subresolution method seem more reasonable because they are less than the volumes produced by using the binary SCA map.

It is difficult to say which of the point-SWE interpolation methods used is preferable. Because of the narrow spatial distribution of the field measurements, the simple mean and the 50-point nearest neighbor methods are probably the most reasonable representations of the distribution of SWE. Based on the runoff data for the water year, it appears that the estimates that produced the lower volumes are most accurate. Our estimate for runoff was 1,034,000 m^3. The SCA fraction map combined with the 50 nearest neighbors interpolation gives a SWE volume of 1,412,000 m^3, which overestimates the observed discharge by 36.6%. If we use a total evaporative loss of about 20%, suggested by literature on the Sierra (e.g. Kattelmann and Elder, 1991), then our SWE estimate is reduced to 1,130,000 m^3. With this adjustment to the runoff-derived SWE volume, our overestimate is 16.6%. The observed discrepancy could be attributable to several possibilities. We may be overestimating the SWE volume, or underestimating the discharge volume; our estimates of the baseflow contribution to the seasonal hydrograph may be too high, the estimate for sublimation may be too low, and the basin or our control structure may be leaky.

SCA Mapping Techniques

If the subresolution method gives a more accurate value of snow-covered area, as suggested by Table 1 and Figure 2, then the difference between the two methods shows an overestimate of snow-covered area of about 10% by the binary method. The patterns of snow-covered and bare terrain in this basin at this time led to the difference. If the number of pixels in the basin containing between 50% and 96% percent SCA were higher, and skewed toward the lower values of this range, then the binary method would have predicted even more SCA than the subresolution method.

Another consideration for operational hydrology is the implementation of the two techniques. The binary method requires interaction with the user to select and test training classes for each image, while the subresolution technique is automatic, and can be carried out for several images, such as a time sequence. These results are important because the binary method is analogous in principle and practice to conventional methods of mapping snow-covered area. Future snow mapping efforts should explore this problem in more detail.

Application to Snowmelt Modeling

It is interesting to note that for use in snowmelt modeling, the method of distributing SWE within a partially snow-covered cell may have a profound effect. For example, if a hypothetical cell has 1.00 m of SWE according to a SWE distribution map, but the same cell has 50% snow-covered fraction according to the SCA fraction map, then we can assume 2.00 m SWE over 50% of the cell area. With the binary SCA map the 1.00 m of SWE would be distributed over the entire pixel, if it was classed as snow-covered, or we would have to accept the error in the SWE interpolation if the pixel was classed snow free. The difference becomes important when considering the difference in the way that the two scenarios melt. Although this is not important for a single cell in our study basin of 4896 cells, over 42% of the cells have 72% or less snow-covered area. This value translates to a difference of 25% in snow-covered area if the snow is spread over the entire pixel or assigned to its actual fractional area. This large difference in SCA will dramatically affect the results of any realistic, spatially distributed snowmelt model.

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