EFFECTS OF SAMPLING DENSITY ON ESTIMATIONS OF SNOWPACK CHARACTERISTICS

by

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INTRODUCTION

Water supply forecasts in the western United States have traditionally been made using regression techniques which provide an estimate of seasonal runoff volume. Newer simulation models which provide both runoff volume and timing forecasts could be extremely valuable in many cases where reservoir storage must be balanced to accommodate the needs of multiple users. However, in order to be completely flexible, data concerning conditions on the basin would be needed on a much more frequent basis, probably weekly or daily rather than the previously used monthly snow course and seasonal precipitation values. Also, because the newer models are based on physical processes, it is advantageous to know the distribution of snowpack and precipitation characteristics over the basin rather than just a point index of the conditions. Whereas it would not be feasible to obtain this amount and type of data by conventional means, new developments in remote sensing and data transmission such as the National Weather Service satellite snow cover maps and the Soil Conservation Service SNOTEL automatic data systems, offer great potential. New methods need to be developed for interpreting the available data and incorporating the results into the models. This requires the development of relationships between conventionally-acquired ground truth data and the remotely sensed data. In developing these relationships it is important to know how many conventional measurements are required to describe the spatial variability of the conditions encountered in nature. Several rather detailed studies have been conducted to help answer this question.

Most previous studies designed to determine snow accumulation and distribution have been concentrated in regions with fairly uniform snowpack conditions, or on the development of methods for measuring snowpack characteristics (Cooper, 1967; Goulding, 1968; Leaf and Kovner, 1972; Rawls, et al, 1980; Carroll and Carroll, 1989). Several studies have been conducted in Canada where melt did not usually occur until spring and the snowpack was rather uniform (maximum depth of 3-4 meters). Results from these studies indicated that a combination of a few snow courses and a more wide spread grid, in which many depth and a few density measurements were made, was adequate to describe snow distribution (Goulding, 1968; Dickinson and Whitely, 1972; Steppuhn and Dyck, 1974; Adams, 1976; and Dickison and Daugharty, 1978). Leaf and Kovner (1972) came to essentially the same conclusions for a forested site in Colorado. Another method sometimes used to reduce the number of samples required is to stratify sampling sites based on topographic features such as elevation, slope, and aspect, or vegetative varieties (Meiman, 1968; Leaf and Kovner, 1972; and Larson, et al, 1974). Studies conducted by Rawls, et al, (1980) and Elder, et al, (1989) were based on a large number of depth determinations and a few density measurements over one or two seasons. Results are not completely comparable with the work reported here, but both studies seem to indicate less overall variability based on sampling requirements and statistical measures. Mathematical and statistical attempts to determine the optimum density and spacing of sampling points have included cluster analysis, pattern recognition, factor analysis, and principal component analysis, among others. These methods have been used individually or in combination, but either ground truth data was lacking or ancillary procedures have not been developed for proper verification (Galeati, et al, 1986; Gunderson, et al, 1987; Solomon, et al, 1968; Chemerenko, 1972; Elder, et al, 1989).

In this study samples of snow depth and density were obtained on a 30 by 30 meter grid over a 26 hectare wind swept basin in southwestern Idaho under conditions of extreme spatial and temporal variability. These data were used along with aerial photographs of snow covered area to determine the number of samples needed to describe the areal coverage. Estimates of basin snow water storage were also determined for a range of grid and sample spacings.

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STUDY AREA AND INSTRUMENTATION

The 26 ha Upper Sheep Creek subbasin used in this study is a headwater area located on the east side of the Reynolds Creek Experimental Watershed (Robins et al., 1965). The basin is about 850 m long by 400 m in width with a southeast to northwest drainage through the center. Average slope is 25 percent, over an elevation range of 1840 to 2036 m. The primary runoff usually occurs from February through July, and is generated by snowmelt, mainly from deep drifts on the northeast-facing slopes. Average annual precipitation is a little over 400 mm. Vegetation varies in response to soils and moisture distribution, and includes grasses, sagebrush, shrubs, and aspen thickets. The Upper Sheep Creek soils developed from basaltic parent material and vary considerably in depth and profile development depending on aspect and micro-climate (Stephenson, 1977).

Instruments designed to continuously monitor precipitation, incoming solar radiation, wind direction and speed, air temperature, relative humidity, snowmelt (snowpack outflow), and soil moisture and temperature at four depths have been in operation since mid 1983. In addition, snow depth and snow density measurements at 30 m grid spacing (Figure 1.), and aerial photographs were obtained during the latter part of the accumulation period, and during the melt period each year from 1984-1989. Streamflow is monitored continuously at two permanent v-notch weirs using strip chart recorders, and at four temporary v-notch weirs using pressure transducers and an automatic data acquisition system (Cooley, 1988). Snow samples were obtained from each grid point using standard snow sampling techniques and the Rosen type snow sampler (Jones, 1983). Manpower limitations were such that when more than 50 percent of the area was covered it required two days to collect a 30 m grid sample (Fig. 1), and sampling criteria dictated that the two days be storm free so that measurements on the different days would be comparable.

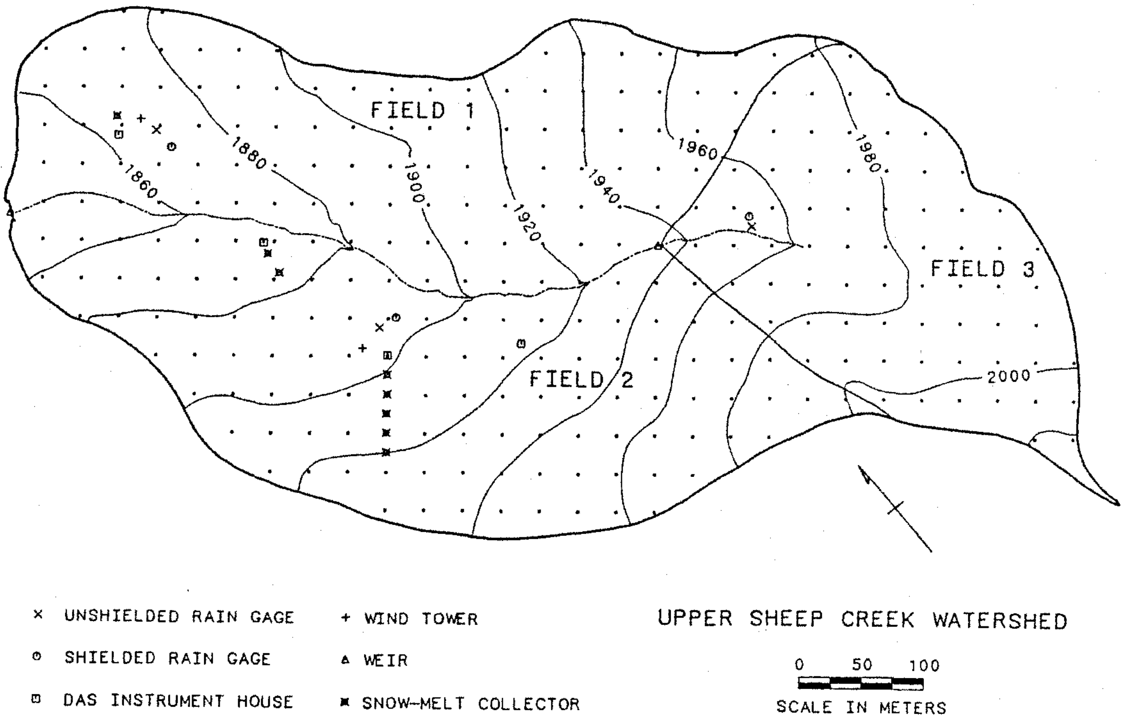

Figure 1. Upper Sheep Creek Watershed showing 30 m grid network (small dots), elevation contours, fields, and instrumentation.

SNOW CHARACTERISTICS

Typically, snow accumulation and melt on the basin follow a certain pattern. Snow accumulation usually begins in November and first appears on north-facing slopes and in brushy pockets. As snowfall increases, the upper edges of drifts start to build on the leeward side of the ridges, and a general snow cover forms over most of the remaining watershed area. Ridges and south-facing exposures usually experience several periods of snow accumulation and melt during the winter due to strong winds and solar radiation. The general snow cover and drifts normally continue to increase in depth (and width in the case of drifts), often absorbing rain or melt which occurs during occasional warm periods, until maximum accumulation is reached, typically near the first of April.

After maximum accumulation occurs (about the first of April) and the melt season begins, new snow may cover the basin, but the ridges and south-facing slopes are generally depleted of this snow in a matter of hours. The general snow cover melts next, usually within a few warm days, leaving only the isolated drifts. The remaining drifts often cover only 10 to 15 percent of the surface area of the basin. Ablation of the drifts does not usually occur until the general or surrounding snow cover is gone. Ablation then occurs mostly from the edges inward, and snow in these drifts usually lasts until early June.

Immediately after snowfall events the entire watershed is covered, but this condition usually persists for only a short time. Strong winds, common for this area and period, soon redistribute the snow, blowing it from exposed source areas mostly on ridges and south slopes that are dominated by low growing vegetative varieties that have adapted to the low moisture regimes and shallow soils associated with these areas to the lee side of ridges where snow depths may exceed 7-8 m. Radiant energy also contributes to snow loss from these same source areas, especially when patches of darker vegetation and soils become exposed and absorb more heat. A typical snow depth distribution is shown in Figure 2 for April 4, 1984, which represents conditions near the time of maximum accumulation for 1984, and shortly after a snowfall event. Snow depth distributions like those depicted in Figure 2 make it difficult to properly describe average snowmelt conditions over field areas such as fields 2 and 3 as shown in Figure 1 (Cooley, 1988).

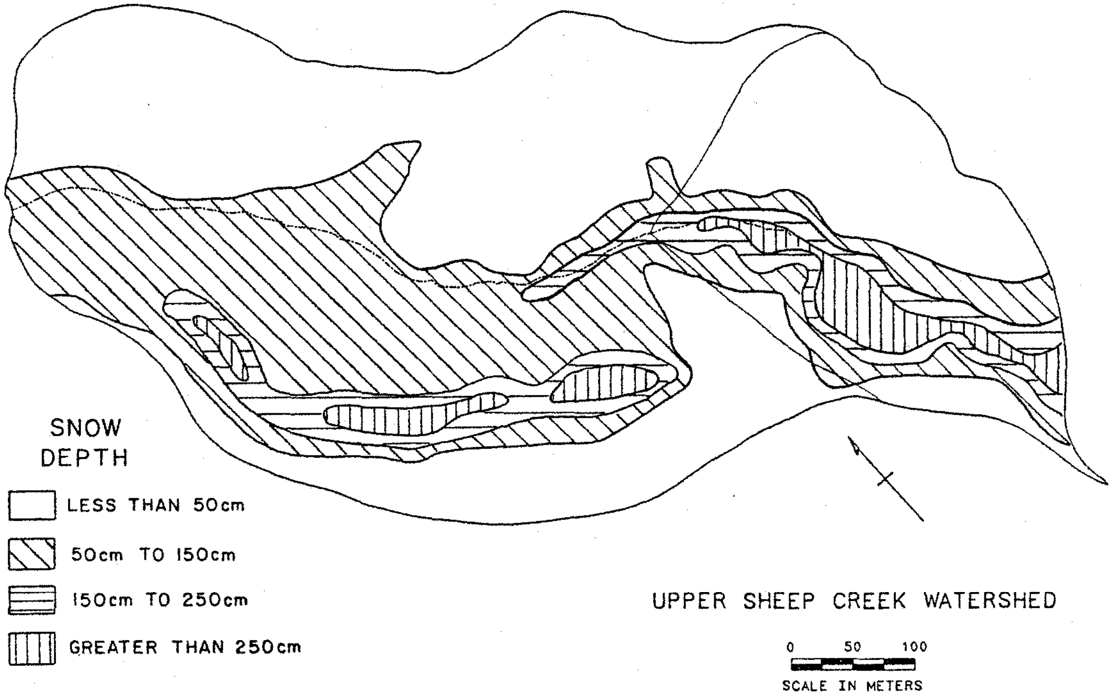

Figure 2. Snow depths at Upper Sheep Creek Watershed on April 4, 1984.

Aerial photographs taken at about two-week intervals during the 1984-1989 snowmelt seasons (April-June) indicate that similar snow drift patterns form each year. Earlier studies also indicated similar patterns of drift formation from year to year at a nearby basin (Rawls and Jackson, 1979). Snow depth measurements indicate that the depth of the drifts and more particularly the width of the drifts vary from year to year depending on the amount of precipitation falling as snow, even though general drift patterns remain relatively consistent.

Snow density is often assumed to be rather uniform, varying much less over short distances than does snow depth. For some purposes such as providing ground truth for remote sensing techniques, snow samples to determine density are taken only once out of each five snow depth samples (Jones, 1983). An often cited "rule of thumb" indicates that 305 mm of snow produces 25 mm of water, thus implying a uniformity of new fallen snow with a density of only 8.3 percent. In reality, snow density is found to vary with time, depth, distance and climatic region. In this study, density was determined for each sample at each grid point if conditions permitted. There were situations after very dry snowstorms when it was impossible to keep a core in the snow tube, and times when in very shallow snow, density could not be determined. The spatial variations in density for April 4, 1984 are shown in Figure 3. Densities on this day were noted to vary from less than 15 to over 50 percent, and appeared to be related mainly to time, depth and vegetative cover. The range of densities shown are typical of values obtained in the other study years also. Variations in density with time and accumulation of snow are also observed each year. First, as snow accumulates in the drifts, the density increases, and second, as the snowmelt season begins, the snowpack ripens and the densities increase. Again, it is obvious that an assumption of uniform conditions over the three fields indicated would not be truly representative.

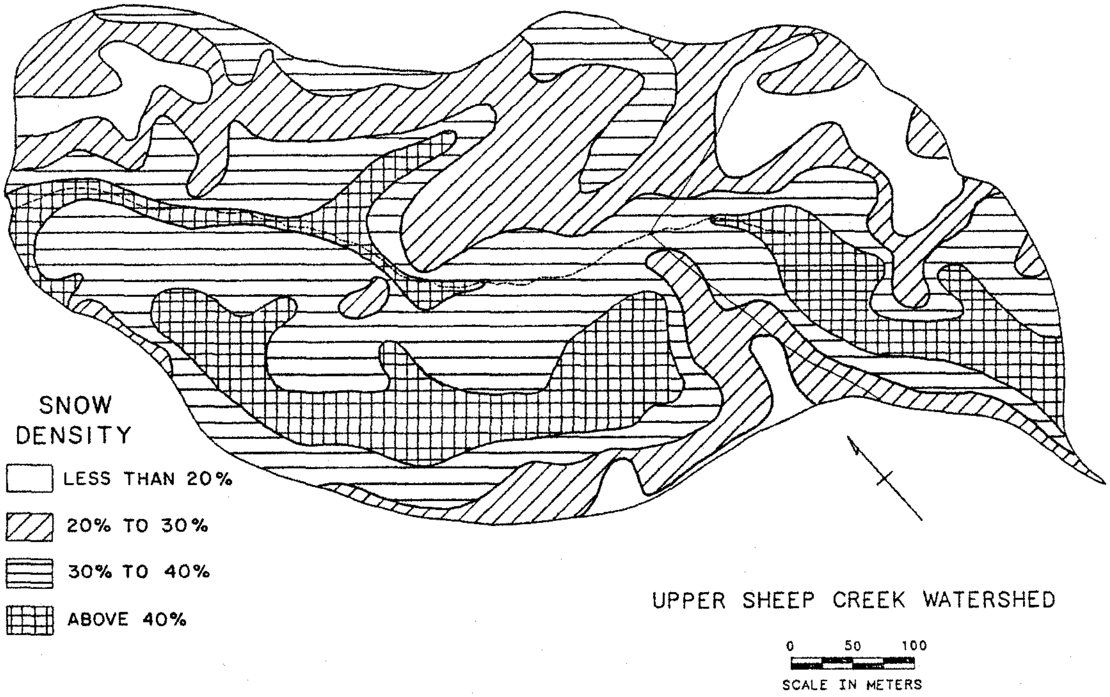

Figure 3. Snow density at Upper Sheep Creek Watershed on April 4, 1984.

Values of snow water equivalent (SWE) at each grid point can be obtained using the depth and density values shown in Figures 2 and 3. A map of snow water equivalent for April 4, 1984 would appear quite similar to the pattern in Figure 2 of snow depth. For April 4, 1984, SWE ranged from zero to over 1500 mm, and represents the amount of water stored in the snowpack that is available for evaporation, infiltration, and runoff. The location of this stored water with respect to the stream channel is important in understanding and modeling this hydrologic system. In this case, most of the stored water in fields 1 and 3 is located along or adjacent to the stream. In field 2, however, the majority of the water is stored 90 to 150 m upslope from the stream, thus causing a different response to streamflow upon melting.

ANALYSIS

The first step in data analysis consisted of converting the aerial photographs of snow cover on the basin to digital information that could be used to determine the percent of snow covered area. The snow cover on Upper Sheep Creek for May 7, 1984 as obtained by aerial photography is shown in Figure 4a, and a digitized representation of the same photograph of snow cover is shown in Figure 4b. For the six years of the study (1984-1989) there were sixteen periods during which it was possible to obtain both aerial photographs and grid snow samples on the same days.

The percentage of area covered with snow was next determined from the grid point data by simply adding up the area represented by grid points on which snow was recorded and dividing by the total basin area. The grid size was then increased in multiples of 30 m, and the same procedure followed. For each grid size larger than 30 m there are a number of combinations of the sample points that are used to determine the percent of area covered. The number of combinations increases according to the square of the multiple of the base grid size. Since the number of combinations increases so rapidly, only 60 m (four combinations) and 90 m (nine combinations) grids were used in this analysis. Results obtained using the 30 m grid, which included 282 sample points, were used as a standard of comparison for all thirteen combinations and the aerial photographs. Because the basin boundary is irregular the number of grid points varied slightly for the 60 m (68 to 72 points) and the 90 m (29 to 35 points) grids.

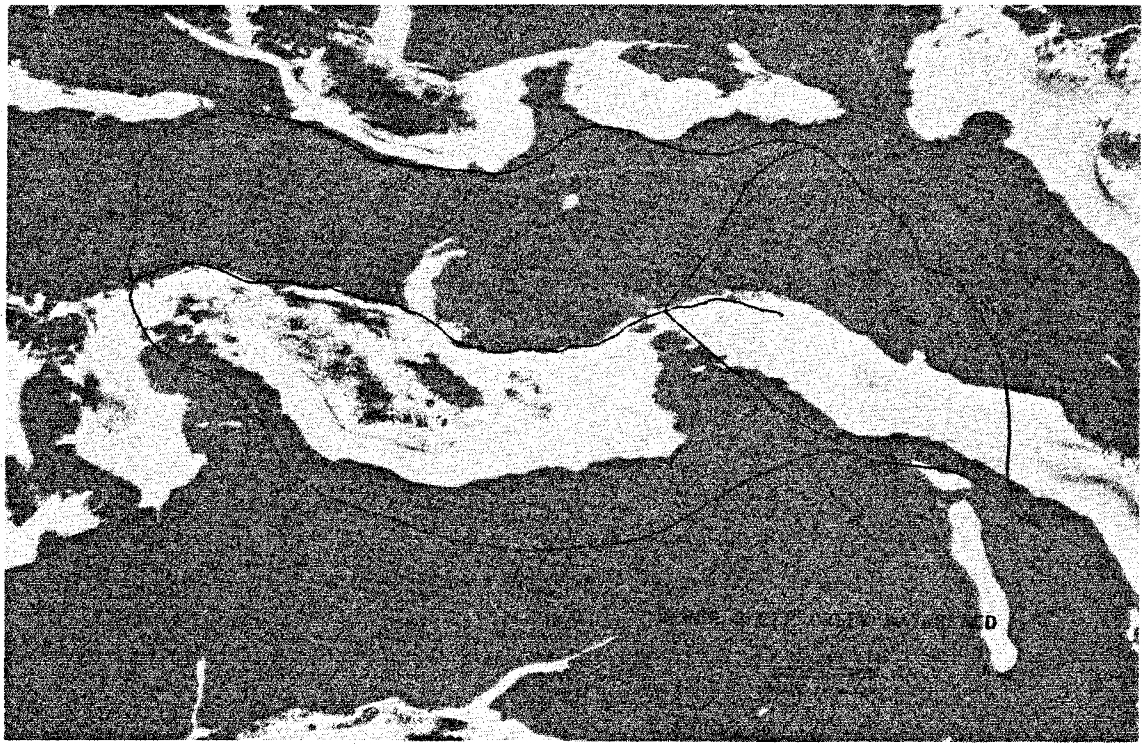

Figure 4a. Aerial photograph of Upper Sheep Creek Watershed on May 7, 1984.

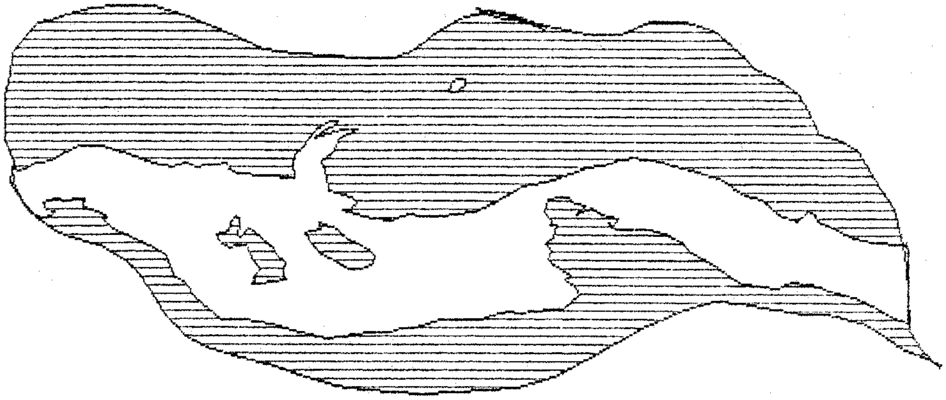

Figure 4b. Digitized representation of Upper Sheep Creek Watershed on May 7, 1984. Crosshatching indicates area without snowcover.

The percent of snow covered area determined from two of the 60 m and two of the 90 m grid spacings and the aerial photographs are presented in Table 1, for the sixteen sample periods. The values determined for the 60 m and 90 m grid spacings shown in Table 1, were selected as examples of the "best fit" and the "worst fit" for each of the two spacings. The values determined for the other two 60 m and the seven 90 m spacings were in-between those shown as determined from statistical analysis.

Table 1. Percent of snow covered area determined from aerial photographs and 30, 60, and 90 m grid measurements at Upper Sheep Creek basin, for 16 sample periods.

				Percent Snow Cover			
Sample Number	Sample Date	30 m Grid	Air Photo	60 m Worst	60 m Best	90 m Worst	90 m Best
1	4-05-85	40.1	47.1	38.0	40.3	27.3	43.3
2	5-07-84	33.3	39.2	31.0	36.1	27.3	30.0
3	4-12-85	29.1	31.7	31.0	31.9	24.2	23.3
4	4-12-89	22.7	23.0	26.8	23.6	18.2	23.3
5	5-01-85	13.8	14.2	14.1	13.9	12.1	10.0
6	4-16-87	8.9	9.1	7.0	11.1	6.1	6.7
7	5-02-89	8.5	9.7	11.3	8.3	3.0	6.7
8	5-13-86	7.8	11.3	5.6	8.3	6.1	10.0
9	5-08-85	7.4	7.8	5.6	8.3	6.1	6.7
10	6-14-84	5.0	3.4	2.8	6.9	0.0	6.7
11	5-22-85	4.6	5.1	1.4	5.6	0.0	6.7
12	4-24-87	4.3	4.9	4.2	5.6	3.0	3.3
13	5-27-86	4.3	3.5	1.4	5.6	0.0	6.7
14	4-30-87	2.8	1.5	1.4	4.2	0.0	3.3
15	5-30-85	2.1	2.1	1.4	4.2	0.0	0.0
16	6-03-86	1.1	1.2	0.0	1.4	0.0	0.0

Standard regression analysis was performed between values of areal coverage based on the 30 m grid and the digitized aerial photographs, and between the 30 m grid values and values obtained from each of the 13 other grid combinations. The Nash-Sutcliffe coefficient of efficiency was also determined for each of the above combinations and the digitized aerial photograph results (Nash and Sutcliffe, 1970).

Basin snow water equivalent, expressed as volume of water on the basin, was determined by multiplying grid point snow depth and snow density to obtain SWE at each grid point. The grid point SWE was then multiplied by the area represented by that grid and the resulting products were summed for the entire basin. The value thus obtained could be divided by the basin area to obtain a mean basin SWE expressed as a depth.

RESULTS

The regression analysis indicated that there was a very good correlation between areal snow cover determined from the 30 m grid data and any of the other grid combinations or the aerial photographs, as expressed by the correlation coefficient (Table 2). The coefficient of efficiency which measures not only the correspondence or association of the trends, but also provides an indication of the proportion of deviation or variation accounted for by the regression model, shows a slightly better relationship for the aerial photograph method and the 60 m grid results than the 90 m grid results.

The same analysis applied to the snow water in storage on the basin also produced coefficients of correlation above 0.93. However, the coefficient of efficiency values indicate significant differences between results obtained using the 60 m and the 90 m grid combinations. The 60 m grid coefficients of efficiency are all above 0.92, but the 90 m grid coefficients range from 0.61 to 0.93 indicating that the selection of the grid is important. As noted in Table 2, grids B3, C1 and C2 produced results that were much better than the other six 90 m combinations, and were nearly equivalent to the least responsive 60 m grid results. These results suggest that the percent of snow covered area could be determined using any of the grid combinations, but if one is interested in determining the amount of water in storage on the basin, for water balance or water supply forecasting purposes, it will be necessary to use a selective grid or one with more measurement points.

Table 2. Regression relationships between 30 m grid values and aerial photograph, 60 m, or 90 m grid values of areal snow cover and snow water storage at Upper Sheep Creek basin.

Source	Areal Coverage		Snow Water Storage	
	r^2	CE	r^2	CE
Aerial Photo	.9908	.9507	-----	-----
60 m Grid				
A0	.9741	.9656	.9599	.9220
AE	.9801	.9766	.9910	.9697
B0	.9944	.9835	.9766	.9574
BE	.9767	.9748	.9941	.9905
90 m Grid				
A1	.9564	.9540	.9702	.7672
A2	.9585	.9162	.9827	.7864
A3	.9586	.9373	.9579	.7568
B1	.9566	.9435	.9343	.6643
B2	.9643	.8348	.9493	.6147
B3	.9587	.9152	.9721	.9273
C1	.9524	.9289	.9502	.9109
C2	.9575	.9419	.9390	.8986
C3	.9480	.9270	.9330	.7268

r^2 = Correlation Coefficient
CE = Coefficient of Efficiency

The relationship between water stored on the basin and the grid density is shown in Figure 5 for the 16 different sample dates corresponding to aerial photograph availability. The water storage values obtained using the 30 m grid are assumed to be the actual or true amount of water stored on the basin. It can be seen that as the density of the grid decreases, the variability of the water storage estimates increases. The standard errors of the estimates of the water storage for the different grid densities are shown in Figure 6, expressed as a percentage of the mean and again assuming the 30 m grid values are correct. The standard error was approximately 18 percent for a 60 m grid and 40 percent for the 90 m grid. If it was desired to keep the standard error within 10 percent of the mean it would require about 100 sample points and a grid spacing of about 50 m. The value of the standard error shown in Figure 6 is somewhat larger than values presented by other investigators, probably due to the greater variability in snow cover associated with the Upper Sheep Creek site.

Attempts to relate areal coverage or snow water storage to topographical characteristics such as slope, elevation, and aspect at the Upper Sheep Creek basin, did not produce the good relationships obtained in other studies. While there is a general increase in snowpack with elevation on a larger scale, the effect of the wind and the topography on the distribution and/or redistribution of the snow is apparently greater than the elevation effect. The relationship with aspect indicated the strongest relationship, but only because all of the snow occurred in the range of 295 to 55 degrees from north, which are essentially the only exposures found at Upper Sheep Creek.

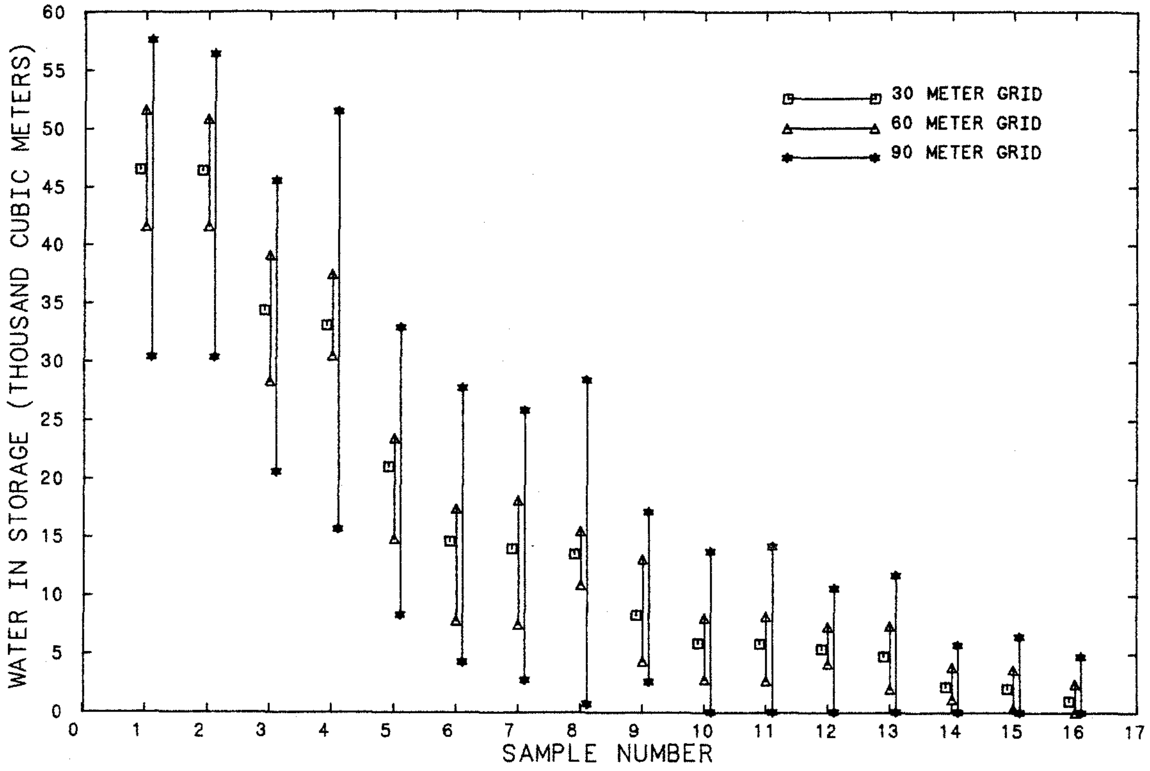

Figure 5. The volume of water in storage as snow (expressed as thousands of cubic meters) on the Upper Sheep Creek Watershed for sixteen sample periods defined in Table 1, for 30, 60, and 90 meter grid spacings. The 30 m grid values are considered as actual values. The high and low estimates of the four 60 m and nine 90 m grid values are shown with a connecting line, the length of which indicates the amount of variability in estimates obtained using these two grid spacings.

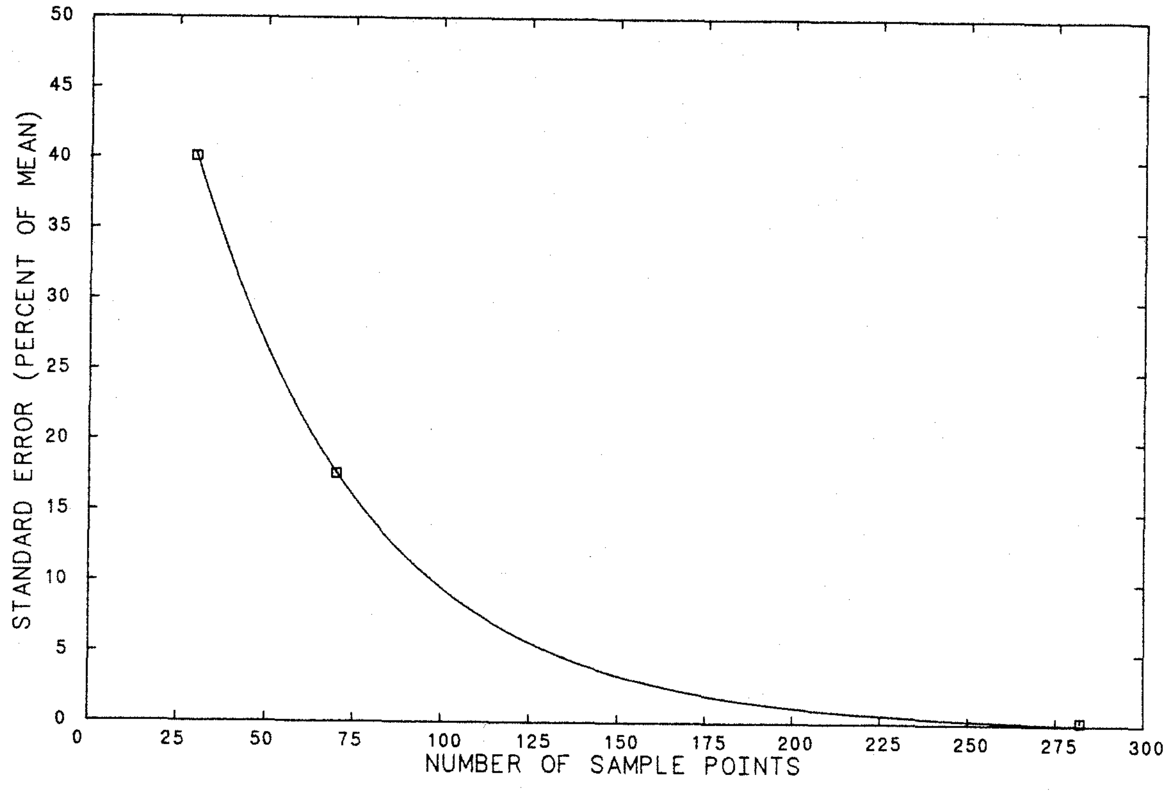

Figure 6. The standard error of the estimate expressed as a percentage of the mean verses the number of sample points, which are a function of the grid spacing. In this case, the 30 m grid contained 282 points, the 60 m grids had 68-72 points, and the 90 m grids had 29-35 points.

CONCLUSIONS

In recent years basin snow covered area has been shown to be valuable information for snowpack characterization in addition to conventional ground measurements of snow density or water equivalence and depth. Aerial photographs (and sometimes satellite imagery) can be used to show the spatial distribution of snow cover with time. Analysis in this study has shown a high correlation to exist between percent snow cover determined from aerial photographs and that indirectly obtained from a grid network of snow measurement sites. In the absence of remote observations, e.g. during cloudy conditions, it has been shown that point measurements at a 90 m grid spacing, even under the extremely variable conditions found at Upper Sheep Creek, can adequately describe the areal coverage of the snowpack.

Analysis of the 30, 60, and 90 m snow water equivalent data showed that selected 90 m and all 60 m grid networks adequately characterized the distribution of water stored in the snowpack on the highly variable Upper Sheep Creek basin. Certain combinations of the 90 m grid spacing did not produce adequate snow water equivalent distributions. Further analysis of the standard errors of the water equivalent estimates indicated that a spacing of about 50 m would keep the standard error within about 10 percent of the mean. Because of the extreme variability of snow cover on this basin, the 50 m grid spacing may be the minimum resolution needed for snow water equivalent measurements. For areas with a more uniform snowpack, it is expected that the necessary grid spacing could be considerably larger.

Results from this study should be compared to other detailed studies as far as similarities will permit so that criteria for sampling under a range of conditions can be established. Future research is needed to develop relationships between areal coverage and snow water storage using information on snowpack patterns and snow measurements at index points. This information, when extended to larger basins will be useful for improving water supply forecasts and evaluating climate change studies, using remotely sensed index point information such as that provided by SNOTEL.

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