Modeling Snowdrift Distribution in a Small Mountain Watershed: Spatial and Temporal Scale Limitations

Richard A. Sommerfeld[1] and Jennifer Smith[2]

ABSTRACT

A model of total yearly accumulation using daily degree days and monthly snow covered areas from aerial photos was tested against a 25 m gridded probe survey for the years 1990, 1992, and 1993. Agreement of the model with the survey was within ± 5% which is the estimated accuracy of the probe surveys. The snow depth distribution for the survey years was modeled by assigning depth contour values, derived from the degree day model, to the edges of the snow drifts delineated on the aerial photos. The rational was simply that shallower snow had melted away and deeper snow remained. The correlation between the modeled snow distribution and the probe survey was very good down to a resolution of approximately 1 hectare when the correlation became poor. The poor correlation at finer resolutions was attributed to the coarse spatial resolution of the 25 m probe survey and the coarse time resolution of the monthly aerial photos.

INTRODUCTION

The original purpose of the experiment described in this paper was to perform a test of a simple degree day snowmelt model used to estimate the yearly accumulation in the Glacier Lakes Ecosystem Experiments Site (GLEES). GLEES is approximately 575 ha consisting of three small watersheds located at an elevation of 3200 to 3500 m in the Snowy Range 55 km west of Laramie Wyoming. A complete site description is given in Musselman (1994). The model which sums the estimated daily melt throughout the melt season to estimate the yearly accumulation (Martinec and Rango, 1981, 1986; Sommerfeld *et al.*, 1991) was tested against an intensive snow probe surveys and shown to be very accurate. The high accuracy of the estimate encouraged us to attempt to model the snow distribution, *i.e.* the depth and location of the snow drifts in the studied area and to test the model using the same probe surveys. This goal was partially achieved and significant information regarding scale problems in estimating snow distribution was gained in the process.

SNOW DISTRIBUTION

Snow does not form a uniform cover on mountainous catchments. Wind interacts with the terrain so that areas under microscale atmospheric convergence hold less snow while areas under divergence or separation hold more. It would be desirable to have accurate estimates of snow distribution to test prediction models and as inputs to snow melt models. Models that include snow distribution could provide more accurate information on runoff volume and timing (Rawls and Jackson, 1979; Rawls *et al.* 1980; and Cooley and Rango, 1991). Snow distribution information is also needed to model chemical hydrographs accurately (Bales and Harrington, 1995). The direct measurement of snow distribution using snow corers and depth probes is very labor intensive and therefore can only produce a limited amount of data (Elder *et al.*, 1989). Sequential aerial photos, taken during the melt season, might provide an efficient and accurate means of estimating snow distribution. The basic idea is simply that the boundaries of snow drifts visible on the aerial photos may represent snow depth contours, at least to some approximation: snow less deep than the drift has melted away while deeper snow remains A model of depth-of-melt versus time is necessary to estimate the depth that each contour represents.

SNOWMELT MODEL

We have tested a simple degree day snowmelt model at the Glacier Lakes Ecosystem Experiments Site (GLEES) in south east Wyoming (Musselman, 1994; Sommerfeld *et al.*, 1991). The model is part of the Snowmelt Runoff

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[1] Geologist, US Forest Service, Fort Collins, Colorado, USA.
[2] Technician, US Forest Service, Fort Collins, Colorado, USA.

Paper presented at the 66th Western Snow Conference, Snowbird, Utah, USA

Model (SRM) as described by Martinec and Rango, (1981, 1986). In this model the depth of snowmelt for a given day (H) is,

$$H = 1.1\, D_D$$

where D_D is the number of degree days above 0° C for the day, calculated by summing the hourly temperatures above 0° C for each day and dividing by 24. Note that the depth of melt is independent of the snow density in this portion of the SRM.

We estimated the average snow depth over a test area by summing the daily product of the depth-of-melt and the daily area fraction covered by snow, for the entire melt season. The daily area fraction was estimated from monthly aerial photos by interpolation using a plot of the area fraction versus D_D (Sommerfeld *et al.*, 1991)

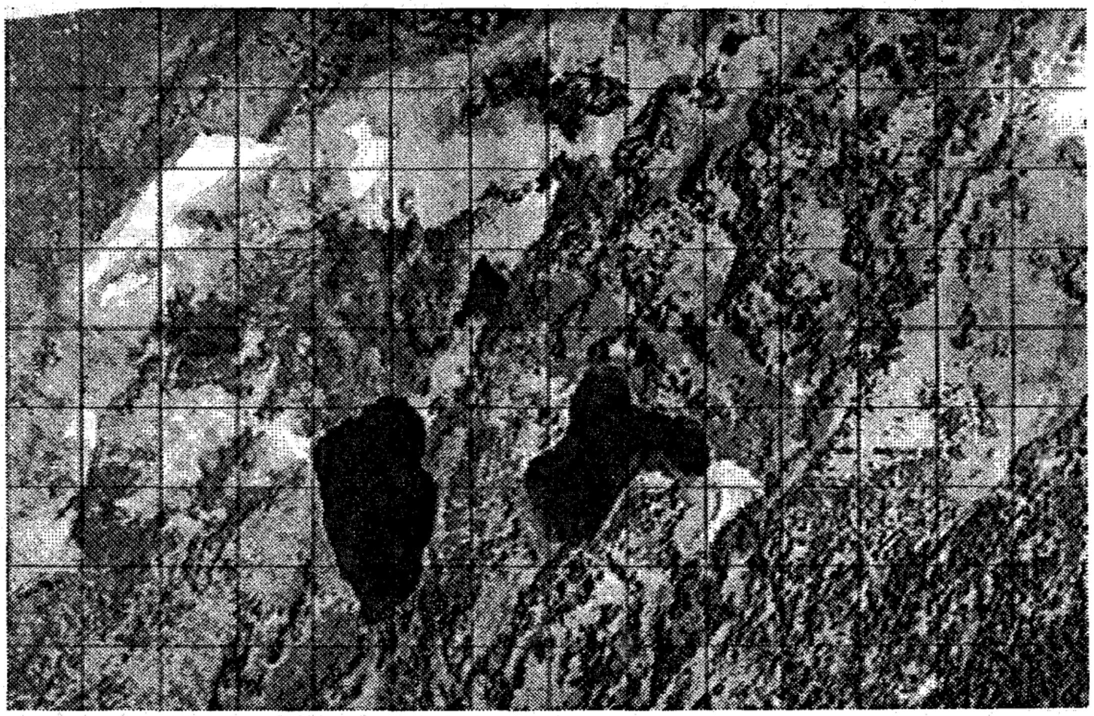

Figure 1. Orthophoto with 1 ha grid lines taken in late September. Note the small remnant snowdrifts and the permanent snow field.

Table 1. A comparison of the 25 meter girdded probe survey and the Martinec-Rango model of yearly snow accumulation.

	Probe (m)	Area (ha)	Model (m)
1990	2.00	≈80	1.90
1992	1.53	≈50	1.61
1993	1.85	≈40	1.92

To test the model results we conducted snow probe depth surveys at maximum accumulation on a 25 m grid over approximately the same areas for the years 1990, 1992 and 1993. Areas surveyed varied from about 80 to 40 ha, and consisted of approximately the center 1/3 of the area in figure 1. Estimated accuracy of the snow probe surveys was about 5% (Rawls *et al.*, 1980: and Kelly Elder, pers. comm.). The results of the test of the model are shown in

Table 1. The agreement of the modeled snow accumulation with the depth survey is within 5%, the estimated accuracy of the probe survey. The high accuracy of the results compared to the probe survey indicate that the degree day model is accurate, at least when averaged over the areas studied, and at maximum accumulation.

This paper addresses another question; does the simple degree day model give an accurate estimate of the depth of melt that forms the edges of the snow drifts visible on the monthly aerial photos. If it does, we could obtain accurate estimates of the snow depth contours represented by the snow drift edges and an accurate map of the snow distribution at maximum accumulation.

SNOW DEPTH MAPS

To estimate the snow distribution, aerial photos were taken monthly between May and September of each year using a special Hasselblad camera mount attached to the passenger seat rails of a single engine Cessna. This system could acquire aerial images at about 10% of the cost of commercial aerial photography while maintaining similar resolution. As discussed below, high resolution was necessary to resolve the last remnant snowdrifts which represented the deepest snow. Also, by using local airplane services, advantage could be taken of short breaks in the weather during spring when cloud cover is frequent. The photos were digitized, and Boolean images created by thresholding at a brightness level between snow brightness and the brightness of areas without snow. The edges of the snow patches were extracted from the Boolean images. Each snowdrift edge was assigned a depth contour value estimated from the degree day depth-of-melt up to the date of the aerial photo. The edge maps were registered to an orthophoto (Figure 1) by matching features on the aerial photos with features on the orthophoto and then overlaid to form contour maps. Registration between edge maps was within 3 pixels at any point on the image and averaged less than 2 pixels. Crossing of edges, which indicated registration errors, was minor (Figure 2) and did not appear to affect subsequent interpolation between the contours. A snow depth surface was generated by interpolating the contours using a routine in the IDRISI (1996) GIS software. The resolution of these maps is estimated as the pixel size of the digitized aerial photos; 2.7 m on the ground.

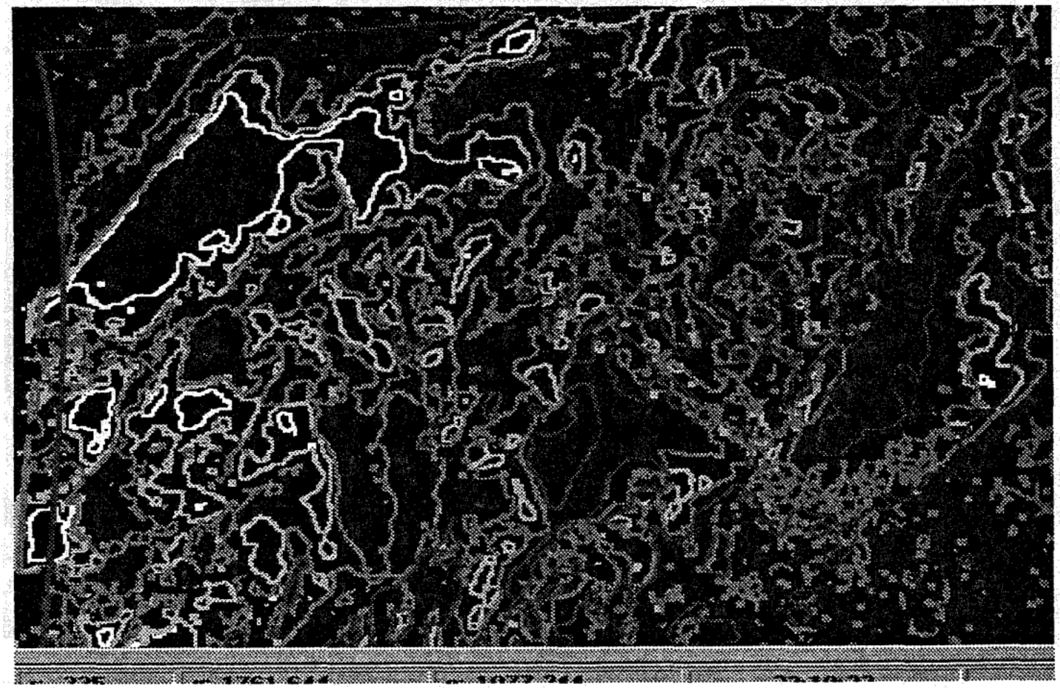

Figure 2. Snow contours derived from the 1990 photos. Model snow depth contours from white to dark grey are: 756, 475, 226, and 34 cm.

Maps of snow depth were also generated from the snow probe surveys by interpolating between the survey grid points using another IDRISI routine. One map was then regressed on the other to estimate the correspondence between the model and the probe survey. Coefficients of determination, R^2, are shown in the first column in Table 2. It is seen that the correlations are poor.

Table 2. Coefficients of determination, R^2 for regressions of model map versus probe map.

YEAR	Original	Processed*
1990	.124	.198
1992	.004	.069
1993	.004	.195

* Data adjusted for May snow free areas and snow on lakes as discussed in text.

ERROR SOURCES

We would like to evaluate the errors in the snow distribution model caused by the depth-of-melt model itself. However, there are also sources of spatial error which can obscure the evaluation of model errors.

Figure 3. Result of spatial error of 3 m. The snowcat is lying on about 0.3 m of snow on a lake while the drift from which it fell is more than 4 m deep.

Errors involved in the snow probe survey include:

1) Mislocation of the sampling points off the map grid points; estimated at ±5 m.
2) Errors in locating the grid points resulting in a possible 25 m displacement of a sampling line.
3) Probing errors which include errors in striking objects above the ground and errors in reading the probe markings.
4) Errors caused by the coarse grid where the interpolated snow depths do not correspond to the actual snow depths between the measurement points.

Errors involved in the model include:

1) Grid point errors generated by registration errors, estimated at a maximum of 3 pixels or 8 m.
2) Interpolation errors between contours. Because aerial photos were a month or more apart, there is as much as a 3 m difference between the modeled depths which determine the contour levels. A snow drift that melted just after a flight would be assigned the same depth as one which disappeared just before the next flight. This may result in significant inaccuracies in the snow drift profiles generated by the interpolations.
3) Errors of estimation of the snow depth at the time of the aerial photo using the snow melt depth model; the main subject of this paper.

Grid point errors can be significant. At some points in the experimental area a displacement of 5 m could change the measured snow depth by 5 m. Figure 3 illustrates a serious consequence of a spatial error of a few meters. The snow drift seen in the background illustrates that the snow depth can change more than four meters in the space of a few meters.

Twenty five meter displacements of the grid point from the nominal map coordinates would cause more serious errors. However, these errors are very difficult to detect in the data set and generally must be accepted. These two types of error preclude making an accurate comparison of the depths at the probe points with the depths nominally at the same points on the model map. Our recourse is to estimate the correspondence between the snow surface maps generated from the probe survey and the model.

Errors in reading the probe depth are probably 0.1 m or less and not significant except, as noted below, in the depths assigned to the snow on the lakes. Larger errors may occur but are probably small in number with an experienced crew. One clear problem with the comparison was that both the lakes in the model map showed significant depths of snow while the lakes in the probe survey showed none. The reason appears to have been that the field assistants were reluctant to venture onto the lake ice and did not survey the lakes. To compensate for this problem, the snow depths over the lakes on the model map were forced to zero to correspond to the survey data. There are still a significant number of points that show no snow on the model map and significant snow on the probe map. This is the result of the low spatial resolution of the probe survey. Small features, such as rocks and trees, are resolved at the 3 m level on the model map and model to zero snow. However, these are not resolved on the 25 m probe map. Often significant snow will be interpolated between the survey points when the aerial photos show small areas of no snow.

RESULTS AND DISCUSSION

Spatial resolution problems generate significant "noise" in a test of modeled snow distribution against a probe survey. The probe survey inherently contains less information than the aerial photos because the resolution of the probe survey is 25 m compared to 2.7 m for the aerial photos.

The solution to the spatial problems is not the obvious one of degrading the overall resolution of the aerial photos to correspond to the resolution of the probe survey. The deepest snow on the model maps is determined by small remnant drifts in July or August. If the resolution of these months were degraded, the deepest snow would be lost from the model. Although blanking the lakes and removing the small areas of zero snow depth to more closely correspond to the interpolated probe map improved the fit somewhat, the resulting correlations were still very poor (Table 2).

The final process we applied was degrading the resolution of the model maps, as opposed to degrading the resolution of the original aerial photos. This was accomplished by averaging over a successively increasing number of pixels from 8 X 8 to 64 X 64 resulting in resolution ranging from approximately 20 to 175 m. The regression results given in Table 3 show a considerable improvement in R^2.

Table 3. Coefficients of determination, R^2 for regressions between the probe survey maps and the Martinec-Rango model maps at different spatial scales.

YEAR	Pixel size			
	175^2 m^2	86^2 m^2	43^2 m^2	21^2 m^2
1990	0.80	0.55	0.37	0.27
1992	0.92	0.46	0.21	0.15
1993	0.88	0.67	0.43	0.29

When averaged over a hectare, the fits between the images are very good. For the probe surveys, about 12 points are included in a 85 m (32^2 pixel) average and about 50 in the 175 m (64^2 pixel) average so that an accurate average depth is probably achieved. These results indicate that the aerial photo method, combined with the simple degree day depth-of-melt model can provide useful information on the yearly distribution of snow in alpine areas at least on a hectare spatial scale. The question of whether or not better spatial resolution could be achieved with this model was not answered by this test.

Improvements to make a test of the model more definitive are:

1) . Finer spatial resolution of the probe surveys. Because probe surveys are very labor intensive, this would probably require stratification of the surveys where finer resolution is applied to subareas where more detail is required. Such areas could be determined from previous aerial photos.
2) More precise location of the probe points through the use of geographical positioning systems. Precision comparable to the digitized aerial photo resolution of 3 m would be fairly easy to obtain.
3) Finer temporal resolution of the aerial photos. The one month spacing of the aerial photos is adequate for 5% accuracy in estimates of the average snow accumulation over a small catchment as shown in Table 1. However, the snow drift profiles would be delineated more accurately if the time period were shortened to 1 to 2 weeks especially toward the end of the melt period. In the area studied here, the amount of melt between July and August photos is between about 2 and 3 m. The most extreme example is 1993. Assuming the model is accurate, if a drift was slightly less the 5.8 m deep, it may have been assigned a depth of 2.7 m. More closely spaced contours would give more accurate maps of the snow drifts.
4) An improvement in the modeling would be expected from using a more accurate depth-of-melt model, perhaps including a radiation model. However, the tests presented here do not give information on the amount of improvement to be expected

The conclusion from this study are:

1) The Martinec-Rango model provides estimates of the yearly maximum snow depth at the GLEES which are within 5% of the maximum depths determined by a 25 m gridded snow survey.
2) There is poor correspondence between the model map and the probe survey map at spatial scales less than 1/4 hectare.
3) Quantitative information on snow distribution is obtained from the proposed model using the Martinec-Rango depth-of-melt model when the spatial scale is 1 hectare or greater.
4) Further refinement of a test of the proposed model would be justified. It probably would result in the ability to model the distribution of snow drifts accurately on the scale of a few meters.

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