Extrapolating Snow Measurements on the Marmot Creek Experimental Basin

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From 1969 to 1980, each March, snow depth and water equivalent were sampled around 249 pins of a grid covering the forested portion of Marmot Creek basin. Continuous record from four snow pillows and monthly data from six snow courses were used to extrapolate the spatially intensive grid data to other winter months. Snow courses were better estimators of grid data than snow pillows. Readings from about 80 % of the pins were correlated to the data from one or the other snow pillows with r^2 above 0.70. The ability of a snow course to track the year-to-year variations in the March data of individual pins of the grid was not related to similarities in elevation or aspects between the course and the pins.

Introduction

In areas with a significant seasonal snowpack, proper research and management of the water resource cannot be carried out without adequate snow measurements. Snowpack measurements from a small number of stations are often used as an index for the evaluation of spring streamflow or future soil water reserves. However, it is sometimes desirable to obtain accurate estimates of the actual amount of snow on the ground over specific areas. The sampling problem is complex because of the very large spatial and temporal variation of the snow cover.

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This paper presents the sampling and analysis methods that were applied on data from the forested portion of the Marmot Creek Experimental Basin to obtain winter-long (December to May) estimates of snow depths and water equivalent. The analysis also brings out some interesting properties of snow distribution on that portion of the basin.

Site and Methods

Marmot Creek Experimental basin, located in the Kananaskis valley, 100 km west of Calgary, covers 9.4 km^2 of sub-alpine and alpine terrain. Elevations range from 1,585 m to 2,805 m at the peak of Mt. Allen (Fig. 1). Forest cover is mainly old spruce-fir (*Picea* spp. and *Abies lasiocarpa* (Hook.) Nutt.) with a scatter of trembling aspen (*Populus tremuloides* Michx.). The lower tip of the basin is covered with even-aged lodgepole pine (*Pinus contorta* Dougl. var. *latifolia*). Alpine larch (*Larix lyalii* Parl.) occupies a narrow band just below tree line. About 40 % of total basin area lies above tree line.

Snowpack measurements have been carried out on the basin with snow courses, snow pillows, snow stakes, and an intensive snow grid surveying network. Twelve 10-point long term snow courses are sampled monthly, from February until May for snow depth and snow water equivalence (SWE). The six most representative courses were retained for this study. Their locations are shown in Fig. 1.

Seven large methyl alcohol-filled butyl rubber snow pillows are used on the basin. Variations in the pressure exerted by the snowpack on these pillows are recorded on strip chart recorders via a stilling well arrangement. Four of these pillows (Fig. 1) had a record length that was sufficient for the analysis.

The snow grid consists of parallel sampling lines, 200 m apart, covering the forested portion of the basin, along which snow depth and SWE were sampled every 20 m. Every five consecutive readings centered around a fixed marker or "pin" are averaged and expressed as the reading for that particular pin. There are 249 such pins on the basin. Measurements were taken once a year, during the third week of March, from 1969 to 1980 (no survey was done in 1979) for a total of 11 readings per pin.

Snow stakes, the last snow measurement network on the basin, are markers placed above the tree line where regular sampling is impossible. The snow depth at the stake is read from a convenient vantage point with a telescope. There are about 40 stakes in the alpine portion of Marmot. Sampling has been done monthly from February until June since 1974. These snow stakes furnish the only snow measurements from the large alpine portion of the basin, save for a recently installed snow pillow. The only use of the snow stake data in this work was in the generation of Fig. 5, page 89.
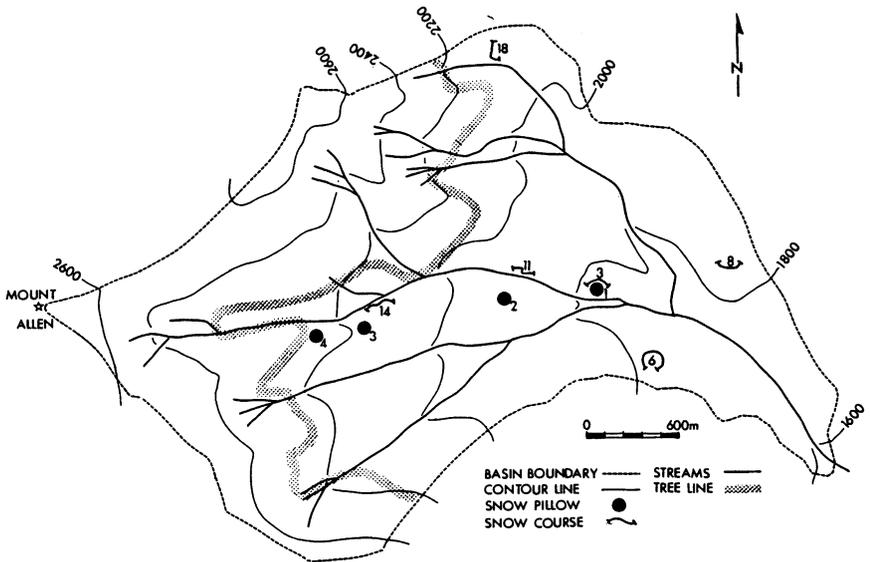
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Fig. 1. Map of Marmot Creek Experimental basin showing the location of snow courses and snow pillows. The contours are in m.

Analysis

Although both the snow depth and snow water equivalent were measured in the snow grid and snow courses, and were analyzed in this study, only the results achieved with the SWE data are presented here. The snow depth data behaved in much the same way (except that it was not obtained at the snow pillow sites) and presentation of its analysis would have been redundant.

The snow sampling methods listed above yielded two data types: a once-a-year (mid-March) snowpack measurement at 249 pins from the snow grid, and continuous or monthly snowpack measurements at four snow pillows and 6 snow courses. Areal estimates of SWE for winter months other than March could only be obtained by extrapolating the snow grid data in time. Previous work done by Golding (1974) showed that large-scale topographic and forest-related variables could account for no more the 48 % of the variation in SWE at snow course locations. Accordingly, such variables were not included in the present analysis. Simple linear regressions were derived between pin data and mid-March data from snow pillows or snow courses.

The production of these regression equations required the answering of three questions on snow distribution and measurement:
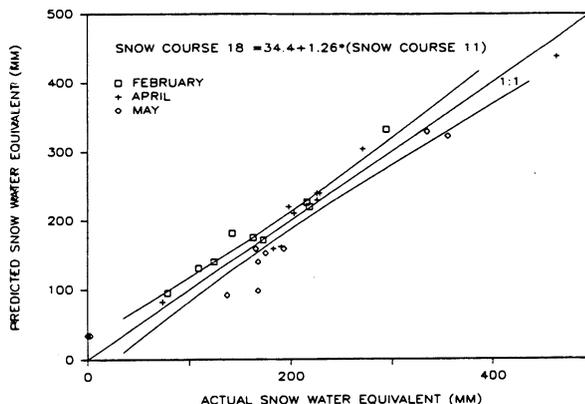
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Fig. 2. Computing 1969-1980 snow water equivalent at snow course 18 from a March-based regression with snow course 11. The 95 % confidence interval is also plotted.

1) Can a regression equation based on March data be used to compute snow water equivalents for other winter months?
2) Should the regressions use snow course or snow pillow data as the independent variable?
3) Finally, is the pillow or course "most similar in elevation and aspect" to a particular pin the best choice for the extrapolation of the pin data?

To answer the first question, regressions were developed between the March SWE readings of paired snow courses. One of the course in each pair, the dependent variable, would be used to "simulate" a snow pin. These equations were used to compute snow water equivalent at the dependent snow courses locations for the three other winter months with available snow course data. A comparison was then made between the computed snowpack properties at the snow course sites and the measured ones. Fig. 2 shows a typical result of the test, including the 95 % confidence interval. The predictor, in this case course 11, was used to estimate SWE at snow course 18 for February, April and May, from 1969 to 1980, from a regression based on all the March readings of those years. The non-linearity of the relation between readings at different sites is evident: mid-winter months are well estimated while May, the peak snowmelt month, shows a definite bias of estimation. This non-linearity is caused by differences in accumulation and snowmelt rates in response to differences in micro- and macro-exposure and elevation of the sites. Still, the good grouping around the 1:1 line indicates that, if snow pin data (March data only being available) had been used as the dependent variable, estimates for mid-winter months would have been close to reality.

Should snow pillows or snow courses be used as independent variables? To

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Table 1 – Coefficient of determination (r^2) between snow water equivalent at snow courses or snow pillows and at adjacent snow pins at three different sites on Marmot basin.

	Course 3	Pillow 1	Course 11	Pillow 2	Course 14	Pillow 3
r^2	0.96	0.96	0.98	0.87	0.99	0.97

answer this second question, three sites were chosen where a snow pillow was adjacent to a snow course. A covariance analysis was run between readings from these instruments and the average reading of 10 to 15 adjacent snow pins (remembering that each pin reading is the average of 5 measurements). The coefficients of determination (Table 1) showed no significant difference ($\alpha=0.05$) between goodness of fit obtained with snow courses or pillows. Consequently, the answer to the second question was sought in a second analysis (results not shown) where pin readings were correlated with the closest snow pillow and the closest snow course. This time, for many of the pins, the snow course network provided a better fit. The fact that there were more snow courses than snow pillows to assign pins to, and that the courses covered all of the 11 years of pin data (the first snow pillow was installed in 1972 only) probably helped tip the balance in their favor.

Snow courses having been chosen over snow pillows as independent variables, the question for each snow pin was: which of the six snow courses was the best predictor? In other words, how should the pairing of pins and snow courses be done to obtain the most useful relationships. The first pairing of pins and snow courses was done on the basis of similar water equivalent of snow. For the 11 years of March pin readings, for each pin, the difference between the SWE at the pin and the SWE at each of the six snow courses was computed. The absolute values of these six differences were summed over the 11 years of data. The course which showed the smallest sum of absolute differences was paired with the pin. An example of the pairing achieved in this way is shown in Fig. 3 for snow course 14. Also shown is the frequency distribution of the differences in SWE between the pins shown on the figure and the snow course. It is not surprising to find a good grouping by elevation (see Fig. 1 for elevation contours), since precipitaton increases with elevation in the forested portions of the basin (Storr and Ferguson 1971).

In a search for an even better grouping method, a second pairing method was tried. The criteria this time was the highest coefficient of determination (r^2) between the pin readings (mid-March) and March readings from the 6 snow courses. The pairing achieved in this way is shown in Fig. 4 for snow course 14. Also shown in the figure is the frequency distribution of r^2 when all 249 pins are correlated in this manner to the snow course. This pairing method was retained for reasons outlined in the discussion section.

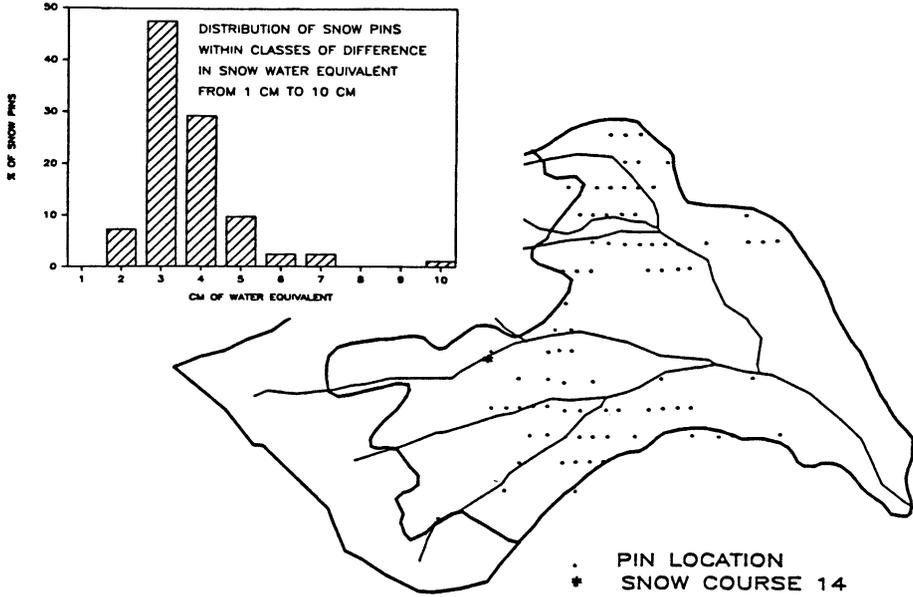In the final step, a regression equation was developed between the yearly SWE

Fig. 3. Pairing of pins and snow course 14 according to the smallest sum of absolute difference in snow water equivalent between the pins and the snow courses.
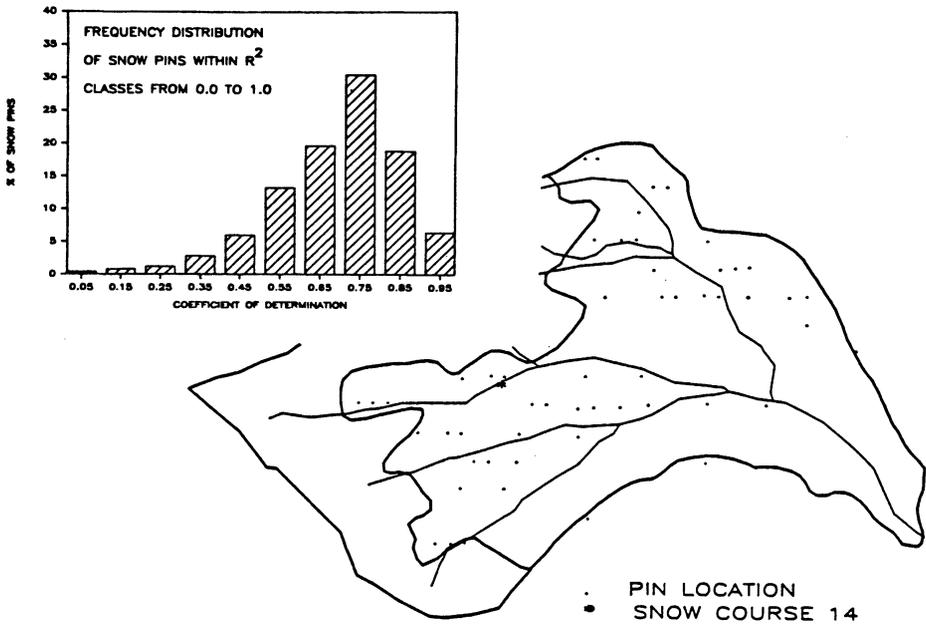

Fig. 4. Pairing of pins and snow course 14 according to the highest r^2 between March snow water equivalent at pins and snow courses.

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Fig. 5. Distribution of snow water equivalence in cm on Marmot Creek Experimental Basin for an average month of February, as computed from the extrapolated pin measurements.

readings of each pin and the March SWE readings of the snow course with which it was paired. The resulting 249 equations could now be used to estimate snowpack SWE at each pin site for dates when only snow course data was available. As an example of the final results, Fig. 5 shows a computer-generated map of SWE on Marmot Creek basin for an average month of February. Above tree line contours are based on snow stake readings of snow depth converted to SWE (assumed density of wind-hardened snow of 0.35 g/cm^3, from Kind 1981). These stake readings, because of their small number, cannot convey the extreme variability of snow cover in the alpine zone. The curves were smoothed to improve readability.

Assessment of Results

The difference in the pairing obtained from the two different methods is quite striking. The by-elevation arrangement shown in Fig. 3 has given place to a seemingly disorderly pairing in Fig. 4. This means that yearly pin readings are better *approximated* by the readings from a snow course of similar elevation but that their year-to-year variations can be better *tracked* by readings of a snow course that can be anywhere on the basin. The pairing in Fig. 4 must be the consequence of micro features of the sites. Such micro features could include aspect, slope, and vegeta-
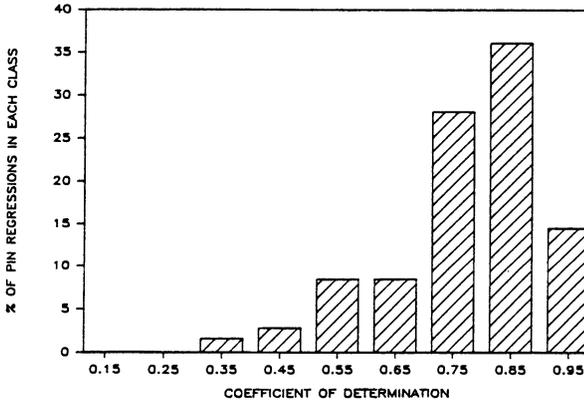
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Fig. 6. Distribution of r^2 of the final 249 pin-snow course pairs. The relations are based on the 11 yearly (mid-March) readings of snow water equivalent around pin locations, and the corresponding March readings at the snow courses.

tion characteristics such as canopy density and geometry, and even spatial arrangement of trees around the sampling sites. No test was made to verify this hypothesis.

The correlation-based pairing illustrated in Fig. 4 was retained for the final analysis because of the apparent better tracking of year-to-year variations in the snow cover. The large difference in elevation that can exist between a pin and the snow course chosen as its estimator is of course a problem. We see in Fig. 2 that the computed May SWE of course 18, using the lower elevation course 11 as an estimator, are always underestimated. However, similar tests done with the alternate pairing criteria (results not shown) revealed the same problem, although to a lesser extent. This should be expected since none of the two methods account for the influence of aspect, a variable that is of little importance in mid-winter, but of crucial importance in peak melt season. Classification of a basin by slope, exposure and elevation, such as in the work of Haston *et al.* (1985), would be useful in establishing a snow course or snow pillow network for extrapolating data from a once-a-year intensive sampling network.

It is very difficult to evaluate the error involved in a complex estimate such as the one presented in Fig. 5 since each point used in the generation of the contours was computed from a different regression equation with a different error term. The best representation of the "goodness of fit" of the analysis is probably a histogram (Fig. 6) of the r^2 of the 249 regression equations developed between the pins and their paired snow course. As can be seen, most regressions accounted for over 80 % of the year-to-year variations in March SWE at the pins. Some pins showed poor relation to any snow course, with r^2 in the 0.30 to 0.50 range, but there was no obvious geographical grouping of these pins which could indicate a large-scale unrepresented physical variable. These poor fits could be due to peculiar micro-characteristics of the sites.

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Conclusion

This study demonstrates the feasibility of obtaining winter-long estimates snow distribution from a once-a-year intensive sampling effort linked to a once-a-month sampling of a few snow courses. Equations developed with data from one winter month only can be used to compute snow pack properties for other winter months with limited error. Pairing of points on the basis of goodness of fit appears to yield good extrapolating relations. But, since in most cases, the best fit pairing is unknown *a priori,* the pairing by proximity is a reasonable alternative. One last remark on pairing, from Fig. 4, we see that if all pins had been paired with snow course 14, over 50 % would have had fits with $r^2 > 0.65$, a surprising fact in such varied terrain.

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