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THE YIELD OF AVALANCHE SNOW AT ROGERS PASS, BRITISH COLUMBIA, CANADA

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ABSTRACT. The annual mass of snow moved by avalanches was observed at 45 avalanche paths over a period of 19 years by measuring the volume and density of each individual avalanche. Several other methods to estimate the total annual avalanche mass were applied but they were found less efficient owing to inaccuracy and difficulties in timing.

For the data set, the yield ratio, i.e. the percentage of snow removed annually by avalanches, had a mean value of 11.2% and a 30 year maximum of 30.9%. The yield ratio varied strongly among avalanche paths and yearly, and could not be explained satisfactorily. The exposure to wind, inclination of the avalanche track, control by artillery, and the winter weather can all have an influence on the value of the parameter.

The temporal variability of avalanche yield is erratic but weather patterns frequently associated with high or low yield ratios could be identified. High values are usually associated with large avalanches triggered by major weather events in the late part of the winter.

INTRODUCTION

Information about the amount of avalanche snow that may be brought down from the catchment into the run-out zone has several applications. For example, snowsheds, deflection dams, and brakers in avalanche run-out zones must be designed for the maximum amount of snow that could accumulate at them. Avalanches contribute significantly to the mass of glaciers and some glaciers would not even exist if they were not fed by avalanches. Snow in deep, dense avalanche deposits melts slowly and can delay run-off in rivers. Conversely, avalanche deposits can dam water and then release it suddenly to cause a flood.

Avalanche-control structures in western Canada were usually built at sites where several avalanches per winter deposit snow. When such structures were designed, knowledge of the amount of snow that could accumulate proved to be critical; therefore, the National Research Council of Canada initiated relevant studies. The National Research Council of Canada maintains a research station at Rogers Pass in British Columbia for the observation of the properties of avalanches. The objectives of the study on the mass of avalanches were:

(a) To evaluate different methods of data collection and to develop the most efficient method.
(b) To collect data on the mass of individual avalanches and the total deposit mass per winter over a long period of time.
(c) To correlate the mass data with characteristics of the terrain, the weather, and avalanche control, and to develop models for the prediction of the amount of avalanche snow.

An earlier paper (Schaerer and Fitzharris, 1984) contains the results of a study of the mass of individual avalanches, and this paper presents the observations of the annual yield of avalanche snow.

Few previous studies are known. Allix (1924) estimated from data in the French Alps that the quantity of snow carried down-hill by avalanches is between 10 and 25% of the total snow accumulation on the slopes. Sosedov and Seversky (1966) reported that in Central Asia between 5 and 32% of the snow cover in the starting zone was removed by avalanches. The data show strong variations from year to year and with exposure of the slopes. For example, Zhalikanov (1975) determined a mean value (1964–69) for the Central Caucasus:

$$V = 0.69A^{0.5} \qquad (1)$$

where V is the volume of avalanche snow in m^3 and A the catchment area in m^2. In the heavy snowfall winter of 1962–63, the volume V of avalanche snow was $2.3A^{0.5}$.

DEFINITIONS

Avalanches transport snow over well-defined paths from high parts of mountains to lower slopes. An *avalanche path* is commonly divided into a zone of origin where the snow breaks away, a zone of deposition where the avalanches decelerate and come to rest, and a track, the transition zone between the two. The combined surface areas of the zone of origin and track define the catchment.

Yield is a term that refers to the quantity of a product from natural resources. In hydrology, it describes the quantity of water available from a stream at a given point over a specified duration of time. Similarly, yield Y of an avalanche path is the mass of avalanche snow that moves into the run-out zone during an entire winter.

The *yield ratio* f is the quotient of the yield and the amount of snow available for avalanching,

$$f = \frac{Y}{(A \times S)\rho}\,. \qquad (2)$$

In Equation (2), A is the surface area of the catchment, S is the total water equivalent of snow (including rain) from the first snowfall in the zone of origin until the last avalanche, and ρ is the density of water.

DATA COLLECTION

Location

The yield measurements were carried out along a 34 km long section of the Trans-Canada Highway at Rogers Pass, British Columbia, Canada. Rogers Pass is well suited for the studies because it has numerous and frequent avalanches, the result of steep terrain and heavy snowfall (Mount Revelstoke and Glacier National Parks, 1978). Also, the zones of deposition of the avalanches are easily accessible.

Forty-five avalanche paths, each with at least one avalanche per year, were selected for the study (Fig. 1). The paths vary in aspect and they are located on the west as well as on the east side of the mountain range. The fall heights between the top of the paths and the zones of deposition range from 500 to 1300 m, the track inclinations are between 30° and 46°, and the catchments contain areas between 27 000 and 560 000 m^2.

Fig. 1. Example of an avalanche path at the east side of Rogers Pass (BRS 9377).

The data set has complete, homogeneous measurements of the annual avalanche mass in 1966–85 for 45 avalanche paths. The mass (yield) is defined as the product of the volume of snow and its average density using two different methods: (a) summation of mass estimates of individual avalanches soon after occurrence, and (b) surveys of the total deposit mass at the end of the winter.

Observation of individual avalanches

The lengths and widths of the deposits of individual avalanches were measured by tape and the depths by probing with a steel rod, within 2 d after the avalanches had occurred. Visual estimates of the dimensions proved to be adequate for small- to medium-size avalanches with depths less than 0.8 m. The errors of visual estimates were within ±15% compared to accurate volume measurements. The densities of the deposited avalanche snow were determined by weighing samples of volume 0.5 l (Table I).

TABLE I. OBSERVED MEAN DENSITIES OF DEPOSITED AVALANCHE SNOW (IN kg m^{-3})

*Size of avalanche**	*Snow type in deposit*	
	Dry	*Wet*
2	291	514
2.5	344	503
3	324	477
3.5	367	527
4	411	557

*The size number of the avalanches refers to the Canadian avalanche-size classification (Avalanche Research Centre, 1986).

Observations at the end of the winter

The total deposit volume at the end of the winter was observed either with a measuring tape and probing or by applying techniques that are common in the survey of earth quantities. The latter included cross-section surveys, mapping of ground and snow surfaces by photogrammetry, plane table, and stadia (method of measuring distances and elevations with a theodolite from a fixed position).

Probing proved to be the most accurate method. It consists of depth measurements with steel rods in a grid pattern with points spaced 15 m in the direction of the slope and 10 m across the slope. This procedure was limited to snow depths of 5 m because the probes bend in deep snow. Photogrammetry is an attractive alternative but requires good light on the snow surface, ideally with the Sun low on the horizon at the side of the avalanche path (Meister, 1983). Aerial photogrammetry could not be applied in the study because of difficulties of organizing flights when both the avalanche and the light conditions were optimal at Rogers Pass. Terrestrial photogrammetry from the opposite valley side was applied but dense shrubs in the zones of deposition made mapping of the ground surface difficult and inaccurate.

The densities of avalanche deposits at the end of the winter obtained from samples in pits and (for depths greater than 1.5 m) with a 76 mm [3 in] diameter CRREL ice-coring auger ranged between 400 and 580 kg m^{-3}. The densities are those of dry snow because the measurements were carried out just before the snow melted. In depths greater than 3 m, the snow density ranged between 540 and 580 kg m^{-3} with little variation in the same avalanche deposit.

Comparison of observation methods

The length of time required, being able to choose the right time for observation, and accuracy are the principal considerations in selecting the observation method. Timing is critical because the observations must be made after the avalanches had run, when there is no hazard from further avalanches, and before the snow melts. Table II lists the characteristics of the various methods; it shows that observation of individual avalanches during the winter is the best method. The procedure was efficient because research personnel were present continuously during the winter and allowed the collection of homogeneous, reliable data from a large number of avalanche paths. Therefore, the measurements of individual avalanches were used exclusively in the analysis of yields.

The mass measured at the end of the winter differed from summed masses of individual avalanches by an average of 9.5% and a maximum of 22%. The stadia and cross-section surveys had the greatest deviations. The steep terrain and windy conditions mainly accounted for the errors of the instrument surveys. The probing at the end of the winter proved to be very accurate, differing on average by 2% from the measurements of individual avalanches. Settlement of the snow was taken into account by the density measurements.

VARIABLES OF YIELD

The significance of a number of variables with respect to the yield and yield ratio was investigated in single- and multiple-variable correlation analyses.

Area of catchment

The effective catchment area, A, is the total land surface of the catchment from which unstable snow could fall into the zone of deposition, excluding areas of dense forest where avalanches should not develop. At Rogers Pass, the lower boundaries of the catchments are well defined by the top of colluvial and alluvial fans with slope inclinations less than 30°. The area was measured for each avalanche path on topographic maps at scales of 1 : 5000 or 1 : 2400 with contour intervals of 7.6 m [25 ft] and 5 m, using area boundaries determined from both ground observations and air photographs. The accuracy of the standard maps at a scale of 1 : 50 000 of the National Topographic System of Canada proved to be insufficient.

TABLE II. METHODS OF OBSERVATION OF AVALANCHE MASS

Method	*Person days per path per winter*	*Timing*	*Accuracy*
Measurement of individual avalanches	2	Good with personnel in area during winter	Good
Probing at end of winter	3–5	Working time limited to periods of low avalanche hazard; a limited number of paths can be observed	Very good
Cross-section survey	2–7		Moderate
Stadia	6		Poor due to steep terrain and wind
Photogrammetry	3	Poor, because light is critical	Good with good light and slopes without vegetation; poor at Rogers Pass

As expected, the area of catchment had a strong influence on the yield. The correlation was best when the area was taken as $A^{0.8}$ (correlation coefficient $r^2 = 0.79$), a slight improvement only over $A^{1.0}$ ($r^2 = 0.77$).

Weather

The annual amount of snowfall had the second strongest influence on the yield ($r^2 = 0.71$) in the single-variable analysis. Snowfall was expressed as the maximum water equivalent of the snow on the ground in the centre of the catchment, inferred from observations at various elevations for the west and the east sides of Rogers Pass. Annual variations of the yield ratio led to the conclusion that weather factors other than snowfall are significant, but the complexity of the weather in the mountains and the difficulty of collecting information for each avalanche path did not allow a quantitative analysis of the additional factors. Typical weather patterns resulting in either high- or low-yield ratios are described later.

Wind exposure

The exposure of the avalanche zone of origin with respect to the prevailing wind was taken into account by assigning each path a nominal index ranging from 1 to 5 according to the magnitude of snow drifting expected. Details were given by Schaerer (1977).

The exposure proved to be third in significance; the yield increases with exposure. Frequent avalanches as a result of overloading of snow-packs and snow-slab formation by wind-driven snow is probably the reason for high avalanche yields in avalanche paths subject to snow-drifting.

Slope angle of zone of origin

The angle of slope is defined as the average incline measured over a slope distance of 100 m in the highest part of the zone of origin. The angles, ranging between 35° and 54°, were determined from the contour maps.

Surprisingly, no significant correlation was found between the slope angles and the yield of avalanche snow. A conclusion is that steep slopes may have numerous small avalanches and low inclined slopes fewer but larger ones, but on average all inclines produce about equal amounts of avalanche snow.

Average slope angle of avalanche path

The slope angle of the path is defined as the mean incline from the zone of origin to the beginning of the zone of deposition. Owing to the steep and uniform terrain at Rogers Pass, the angles vary in the narrow range of 34–46°, but even those variations proved to be significant. The yield increased with incline, probably because the steepness of the track determines whether or not avalanches reach the zone of deposition.

Ground roughness

The roughness of the ground surface was expressed by the water equivalent of the snow in the zone of origin when the first avalanche of the winter reached the zone of deposition. Although the snow on the ground for the first avalanche varies annually, minimum characteristic values ranging between 0.13 and 0.4 m water equivalent could be determined for each avalanche path.

The avalanche yield did not have a significant correlation with ground roughness due to the deep and dense snow at Rogers Pass. The 2–4 m deep snow-pack in the avalanche starting zones covers well the irregularities of the ground.

Control by artillery

The objectives of artillery control are to release avalanches when an exposed area is closed and to bring down the snow in small amounts. This procedure could influence the yield since more snow may be released than under natural conditions.

Of the avalanche paths under study, 18 paths were treated with artillery regularly for the protection of the highway and 27 paths had natural avalanches only. Paths controlled by artillery proved to give slightly more avalanche snow (average yield ratio 11.8%) than uncontrolled paths (10.9%). The small difference leads to the conclusion that, at Rogers Pass, the artificial release of avalanches does not bring significantly more snow into the valley than natural avalanches. Apparently, avalanching occurs sooner or later on the steep slopes and in the deep snow, with or without artillery.

Schaerer (1977) has shown earlier that artillery produces on average 1.9 times the number of avalanches than could be expected to run naturally. An equal amount of avalanche snow, together with a larger number of avalanches, proves that artificially released avalanches on average are smaller than natural avalanches.

OBSERVED YIELD RATIOS

Since catchment area and amount of snow dominate the yield of avalanche snow, the yield ratio may be expressed according to Equation (2) with the wind exposure, path incline, and artillery control used as modifying parameters. Table III contains the observed yield ratios stratified according to the different parameters. The mean yield ratio of all avalanche paths and years is 11.24% with a standard deviation of 8.09% of the mean.

From Table III, and an analysis of variance, a much stronger variation was found among avalanche paths and groups of paths than due to differences in the wind exposure, incline of track, and application of artillery. The variations could not be explained by ruggedness, orientation,

TABLE III. OBSERVED MEAN YIELD RATIOS (IN PER CENT)

Incline of track	*Wind exposure*			
	Low	*Moderate*	*High*	*All exposures*
No artillery control				
<40°	9.0 (3)	7.3 (4)	13.2 (3)	9.6 (10)
40–42°	10.8 (5)	11.5 (3)	13.5 (3)	11.7 (11)
>42°	11.1 (4)	9.0 (2)	13.7 (2)	11.2 (8)
All inclines	10.5 (12)	9.2 (9)	13.5 (8)	10.9 (29)
With artillery control				
<40°	8.2 (1)	11.0 (8)	– (0)	10.8 (9)
40–42°	17.6 (1)	10.1 (4)	12.8 (2)	12.2 (7)
>42°	11.6 (1)	– (0)	19.2 (1)	14.5 (2)
All inclines	12.5 (3)	10.7 (12)	14.9 (3)	11.8 (18)

The numbers in brackets are the numbers of avalanche paths in each category.

exposure to Sun, elevation, and location within the study area. Perhaps spatial differences of the catchment structure that could not be identified from maps and air photographs, and delicate interactions between terrain and weather are responsible. Uncertainties and inaccuracies in defining the catchment might be other reasons for the variations.

Fitting extreme-value frequency distributions (Gumbel distribution) to annual data allowed definition of 30 year maximum yield ratios for each avalanche path (Figs 2 and 3). For a sample size of 19 years, the yield ratio f_{30} that would be reached or exceeded once in 30 years can be determined as

$$f_{30} = \bar{f} + 2.71 S_f . \tag{3}$$

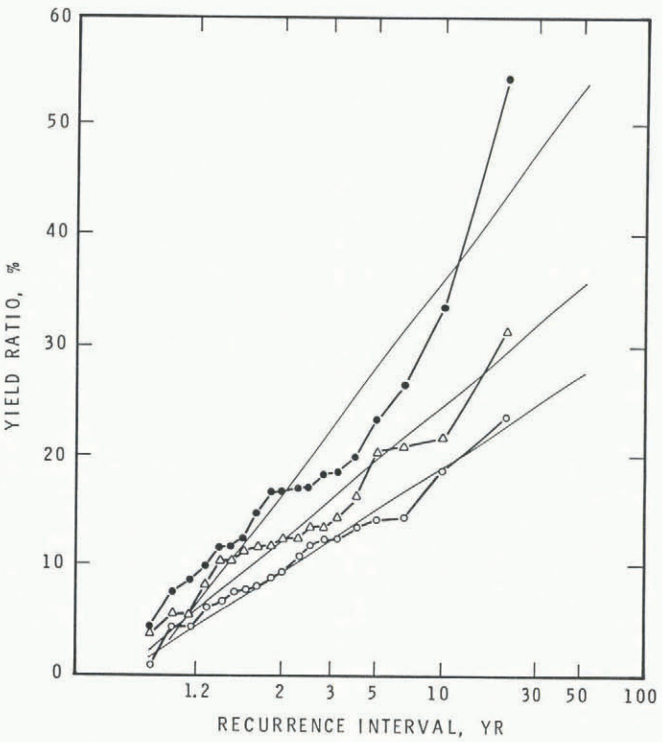

Fig. 2. Examples of frequency distribution of yield ratios for paths without artillery control.
● Avalanche path "Cheops 4". Low exposure to wind; average slope angle 38°; open slope; catchment area 81 500 m².
o Avalanche path "Tupper 2". Moderate exposure to wind; average slope angle 42°; cirque and gulley; catchment area 493 000 m².
Δ Avalanche path "Pioneer". High exposure to wind; average slope angle 46°; gulley; catchment area 51 000 m².

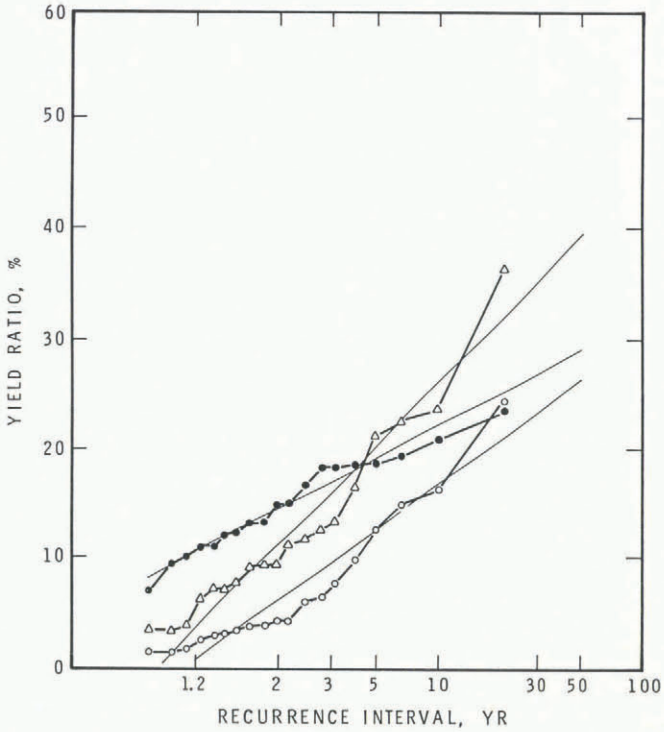

Fig. 3. Examples of frequency distribution of yield ratios for paths with artillery control.
● Avalanche path "Double Bench". High exposure to wind; average slope angle 41°; gulley; catchment area 220 000 m².
o Avalanche path "Twin West". Moderate exposure to wind; average slope angle 36°; gulley; catchment area 341 000 m².
Δ Avalanche path "Bench Unconfined". Moderate exposure to wind; average slope angle 41°; open slope; catchment area 115 000 m².

In Equation (3), $\bar{f}$ is the mean and S_f the standard deviation of the annual yield ratios (Gray, 1970). The coefficient of variation $S_f/\bar{f}$ has a wide range between 0.29 and 1.5; this is another evidence of the strong variation of avalanche characteristics among paths.

The predicted 30 year maximum yield ratios ranged between 19.1 and 38.6%, with mean values of 29.9% for paths without artillery control and 32.4% for controlled avalanche paths. The predicted 30 year maxima were reached or exceeded 16 times during the 19 years of observation at 45 avalanche paths. The highest yield ratios observed were 54.4 and 59%; these correspond to about a

50 year return interval for the specific paths. The 30 year maximum values must be used with caution because of the short observation period and the strong, unexplained variations among avalanche paths.

TEMPORAL VARIABILITY

The annual yield ratio averaged for all avalanche paths ranged from a low of 7% in 1973 to a high of 17.3% in 1981. Individual avalanche paths produced avalanche snow in an erratic manner. Paths having high-yield ratios and paths with low-yield ratios could be observed in any winter, although a larger number of paths displayed high-yield ratios in avalanche-active winters than in winters with generally low activity. It appears that Nature makes a random selection in any given winter on one or several paths to yield large amounts of snow even in winters with few avalanches.

Figure 4 shows the annual total yields, average yield ratios, amount of snowfall, and number of avalanches. The total number of avalanches contains all those that contributed to the yield. Major avalanches are those that exceed a characteristic minimum mass as defined by Schaerer and Fitzharris (1984). The annual snowfall is the accumulated new snowfall at the summit of Rogers Pass.

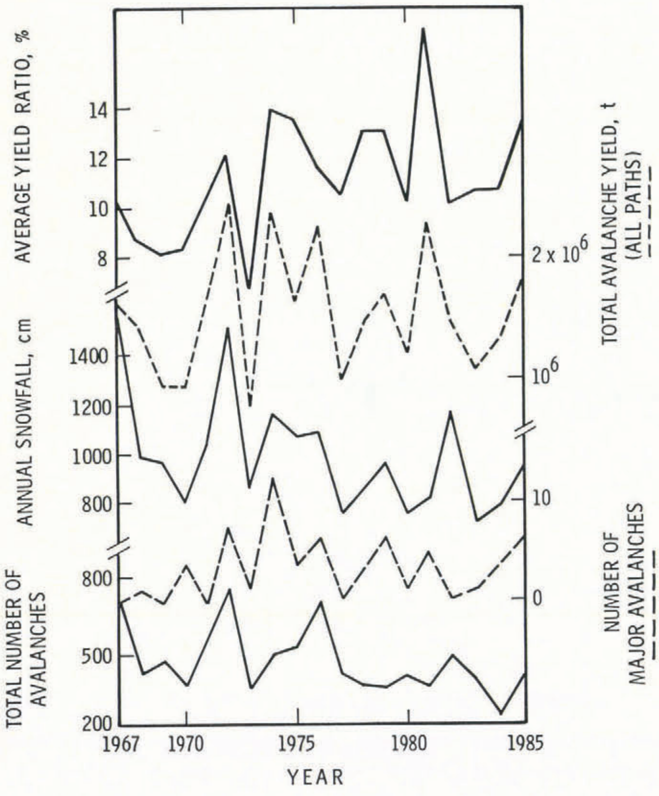

Fig. 4. Annual number of avalanches, snowfall at Rogers Pass summit, total yield, and average yield ratios.

A good linear correlation exists between the total number of avalanches per winter and snowfall (correlation coefficient $r^2 = 0.8$), a consequence of the steep terrain at Rogers Pass. The correlation is poor, however, between the total yield, the average yield ratio, and snowfall. Since the correlation of yield to snowfall is good for individual avalanche paths, the poor correlation of the means of all paths is an expression of the erratic behaviour of avalanche paths.

A winter with a high total snowfall usually has many avalanches but they could be small in size and might not bring down much snow. Conversely, high avalanche yields and yield ratios are possible with any amount of annual snowfall. The distribution and magnitude of snowfalls over a winter, the air temperatures, and the structure of the snow-pack rather than the total snowfall seem to determine the yield ratios. Weather patterns that influence the average yield ratio can be recognized but they represent trends only, not rules. There are winters that have departed from the trends for no obvious reasons.

High avalanche yield ratios usually had average amounts of snowfall associated with a low to moderate avalanche activity in October to January, followed by major violent weather events such as a heavy snowfall or rapidly rising temperatures between mid-January and April. The major weather events triggered large avalanches which in turn removed much of the earlier snow. Often, but not always, the major snowfalls were preceded by cold weather which created a weak snow base. Large avalanches seem to be more effective in removing snow from the catchments than numerous small avalanches and this is responsible for the fair correlation between the numbers of major avalanches and the average yield ratio (Fig. 4). Maximum observed yield ratios coincided with the largest recorded avalanche for 33 of the 45 avalanche paths, and the large avalanches contributed 80–90% of the yield.

A typical winter with an *average yield ratio* had frequent avalanches from November until January, a consequence of heavy snowfall, then a below-average amount of snowfall in the later part of the winter. The temperatures were generally moderate.

Winters with *low yield ratios* were characterized by moderate air temperatures in the range of 0° to −15°C and few major snowstorms with snow deposited in small daily amounts. The combination of minor daily amounts of snowfall and high temperature tends to produce a stable snow-pack so that avalanches are small, since they usually contain new snow only. The winter of 1966–67 is an example. It had a 30 year maximum total snowfall but a yield ratio below average (8.3%). Snow fell almost continuously from 5 November until 27 March, avalanches ran frequently but they were small to medium size. The winter of 1972–73 is another example of a low yield ratio (7.0%). It had a below-average snowfall and a below-average number of avalanches.

CONCLUSIONS

The study has confirmed the heterogeneous nature and erratic behaviour of avalanches as a result of the complexity of avalanche terrain and mountain weather. It proves that predictions of the amount of avalanche snow in a specific avalanche path and winter are difficult and uncertain.

Mean and 30 year maximum avalanche yield ratios for Rogers Pass range within wide limits, but the observed yield ratios are in the range of those reported earlier in the literature. Maximum yields of avalanche snow are much larger than average yields; therefore, the amount of snow in an extreme year might be surprisingly large. Variations of the terrain have a stronger effect on yield than variations due to the weather. Although several terrain variables were investigated, the variations in the yield ratio do not have a satisfactory explanation. Probably, the terrain needs to be described in greater detail than was done for this study. Even within the small area of Rogers Pass, with a climate that favors frequent avalanches, the variations were strong. They could be even stronger in other terrain and climate; therefore, cautious application of the results to other areas is advised.

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