Arctic, Antarctic, and Alpine Research, Vol. 35, No. 1, 2003, pp. 82–90

Magnitude and Frequency of Avalanches in Relation to Terrain and Forest Cover

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Abstract

This paper contains an analysis of magnitude and frequency of avalanches in relation to terrain and forest cover variables. The analysis was applied to 194 avalanche paths in four avalanche areas along highways in British Columbia with approximately 25,000 avalanches recorded. The magnitude and frequency for the avalanche paths were estimated from data collected along the highways by avalanche technicians. Results show that mean magnitude and mean frequency are weakly correlated for a set of avalanche paths in an avalanche area. In addition, with magnitude and frequency viewed as response variables, magnitude and frequency correlate with different sets of predictor variables from one area to another. This paper contains the first comparison of variables which correlate with magnitude and frequency from one avalanche area to another. The results show that previous studies conducted for single areas are simplistic. However, there is some consistency between areas. Avalanche frequency is most directly related to terrain steepness and snow supply. Average avalanche magnitude appears related to terrain steepness, starting zone, and track confinement and the scale (e.g., total vertical drop of the path) with only indirect evidence for a link to snow supply.

Introduction

The magnitude and frequency of avalanches must be known or estimated to calculate risk to facilities (highways, railways, buildings) located in terrain potentially affected by snow avalanches. In addition, magnitude and frequency must be known or estimated to estimate risk to forest cover affected by avalanches in and below clear-cuts made by logging and for clear-cuts intersected by avalanche paths above them. From a previous study (McClung, 2001), I have estimated that approximately 10,000 clear-cuts in British Columbia, Canada, have been affected either by avalanche initiation in clear-cuts or avalanches descending into clear-cuts.

In this paper, I present an analysis of the magnitude and frequency of avalanches and their relation to terrain and forest cover variables. The analysis is from 194 avalanche paths for four different avalanche areas intersected by highways in British Columbia for which magnitude and frequency of avalanches have been estimated from data records. The object of the study is to identify variables which correlate significantly with magnitude and frequency as a step toward construction of models relating the variables for guidance about decisions in land-use planning and forestry operations.

The pioneering work on frequency and terrain variables includes the work of Schaerer (1977) and Smith and McClung (1997) for avalanche paths at Rogers Pass and that Gleason (1994) for an area in Montana. The present study is much more comprehensive than previous works since it includes analysis from 194 paths from four different areas: Rogers Pass (Schleiss, 1989), Kootenay Pass, Three Valley Gap, and Bear Pass (Province of British Columbia 1982, 1983, 1989) in British Columbia.

The present study includes magnitude for the first time (Kootenay Pass, Three Valley Gap, Bear Pass). The results show that magnitude and frequency are related to terrain and forest cover variables in a complicated fashion with no general multivariate relationships yet available. Results about magnitude and frequency probability relationships do show consistent results: mean frequency for avalanche paths is approximately log-normally distributed and mean magnitude is approximately normally distributed. However, there is generally no significant correlation between mean frequency and mean magnitude for a set of avalanche paths in a given area.

Data Description: Response Variables

The response variables include the average magnitude and average annual frequency of avalanches for each avalanche path. The data used in this study consist of avalanche events recorded in four avalanche areas along British Columbia highways (Fig. 1). Table 1 depicts basic information about the areas and information recorded. Magnitude and frequency data were collected by staff of the British Columbia Ministry of Transportation and Highways for Kootenay Pass, Bear Pass, and Three Valley Gap. Frequency data for Rogers Pass were collected by staff of the National Research Council of Canada.

The data included avalanche events which reached, exceeded, or came close to highways with continuous recording of events from November 1 through April 30 (181 days: defined as one winter season). The average annual avalanche frequency was defined for each path as the total number of events averaged over the number of winters of records (Table 2).

Similarly, the magnitude data consist of the average sizes of avalanches recorded for the five-part Canadian size classification system based on destructive potential (see Appendix A for the size classification system). The Canadian avalanche size classification is somewhat analogous to the Mercalli scale for earthquake magnitude in that the size can be estimated after the event takes place from simple field observations related to destructive potential (McClung and Schaerer, 1993). Based on ex-

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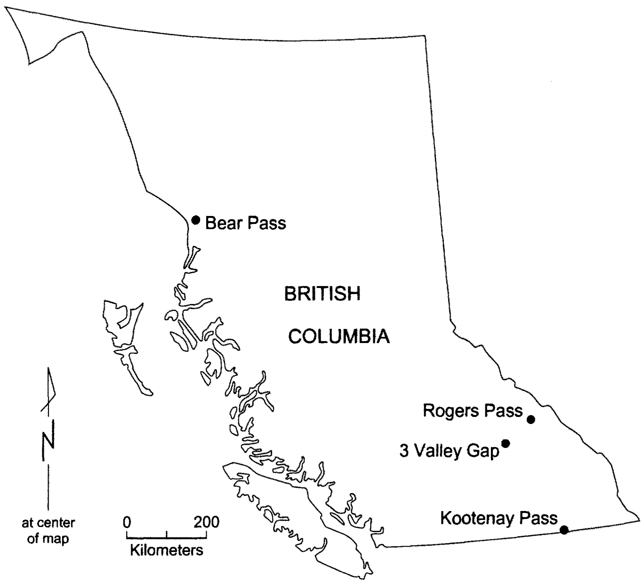

FIGURE 1. Map of British Columbia showing the four avalanche areas.

perience using the classification system in Canada for more than 20 years, it has been shown that most observers can agree on a size designation for half sizes for individual events. Therefore, avalanche forecasters recording sizes have recorded data using half sizes in the databases used here. The average magnitude for an avalanche path was defined as the sum of the sizes of all the avalanches recorded divided by the number of avalanches recorded.

The data used in this study do not generally include small avalanches (size 1) which may have stopped well above the highways. Poor visibility often prevents recording these small avalanches and they are not of great interest in highway operations. Therefore, the data used in this study will represent underestimates of true avalanche frequency for some avalanche paths and overestimates of avalanche magnitude (size) in some cases. The data records should be very complete for larger avalanches (size 2 and greater) and those smaller than size 2 which run close to the highways.

For each avalanche area, normal probability plots were compared with average avalanche frequency for the set of avalanche paths in the areas. These showed that average avalanche frequency has logarithmic character. Accordingly, the data were transformed by taking the natural logarithm of the mean frequency for each path. When the transformed data were compared with a Gaussian (normal) distribution a much better fit was found. When average avalanche frequency was used in regression and correlation studies in this paper, the log transformed data were used as the response variable, which is equivalent to an approximately lognormal distribution of mean avalanche frequency. Figure 2 shows normal probability plots for f (average frequency) and ln (f) for Bear Pass. The results from the three other areas show similar dependence. Other distributions were also tried including extreme value distributions [Type I (Gumbel) and Type II, Benjamin and Cornell, 1970] but the lognormal provided the best overall empirical relation to fit the data as evidenced by visual inpsection of probability plots for the various distributions.

Normal probability plots were constructed for average avalanche size, M, for each area. It was found that avalanche size may be approximated as a normal distribution and this assumption was used in the analysis below. Figure 3 shows average

TABLE 1

Frequency and magnitude information for four avalanche areas

Area	Number of Avalanche Paths	Winters of Record	Frequency Analyzed	Magnitude Analyzed
Rogers Pass	43	24	Yes	No
Kootenay Pass	49	15	Yes	Yes
Bear Pass	70	15	Yes	Yes
Three Valley Gap	32	15	Yes	Yes

avalanche size compared to a normal distribution for Bear Pass. Similar results were obtained for Kootenay Pass and Three Valley Gap. Since the Canadian avalanche size system is constructed to increase roughly in a logarithmic manner, it was expected that that avalanche size is roughly normally distributed and therefore M and ln f both may be approximated to fit a normal probability density function. Based on these results, M and ln f were used as response variables.

In general, I found that average frequency and average magnitude for a set of avalanche paths are nearly unrelated. The only area for which mean magnitude correlated significantly with ln f was Kootenay Pass, which showed weak, negative correlation of M with ln f. Figure 4 shows the scatter plot of M versus ln f for Kootenay Pass. The Spearman rank correlation coefficient, $r_s = -0.3$ (N = 48 avalanche paths) implying $P = 0.03$ where P is the probability that two variables are not independent. For Bear Pass, $r_s = -0.1$, N = 65, and for Three Valley Gap, $r_s = -0.06$, N = 32, neither of which is significant. For this paper, significant correlation is defined when $P \leq 0.05$ and highly significant for $P \leq 0.01$. These levels imply that $r_s = -0.24$ (for $P = 0.05$) and $r_s = -0.34$ (for $P = 0.01$) for N = 49 at Kootenay Pass. The correlation results imply that model construction for ln f and M as response variables may involve substantially different terrain and forest cover predictor variables since the average magnitude and frequency are so weakly related and this is illustrated in the analysis sections below. Table 2 gives basic descriptive data about avalanche frequency and magnitude for the four areas.

Accuracy and Determination of Predictor Variable Data from Avalanche Atlases

The predictor variable information was taken from avalanche atlases compiled by staff of the British Columbia Min-

TABLE 2

Descriptive statistics for mean avalanche frequency, f, and mean avalanche magnitude, M, for four avalanche areas[a]

Area	Mean	Standard Deviation	N	Range
Avalanche frequency, f (mean number per year per avalanche path)				
Kootenay Pass	4.5	6.9	49	0.05–26
Bear Pass	9.4	12.2	66	0.4–81
Three Valley Gap	4.3	5.6	32	<0.1–21
Rogers Pass	9.8	4.5	43	3.2–21
Avalanche size (M) (size on Canadian scale)				
Kootenay Pass	2.1	0.4	48	1.3–3
Three Valley Gap	1.8	0.7	32	1.0–3.1
Bear Pass	2.1	0.4	66	1.2–3

[a] N is number of avalanche paths.

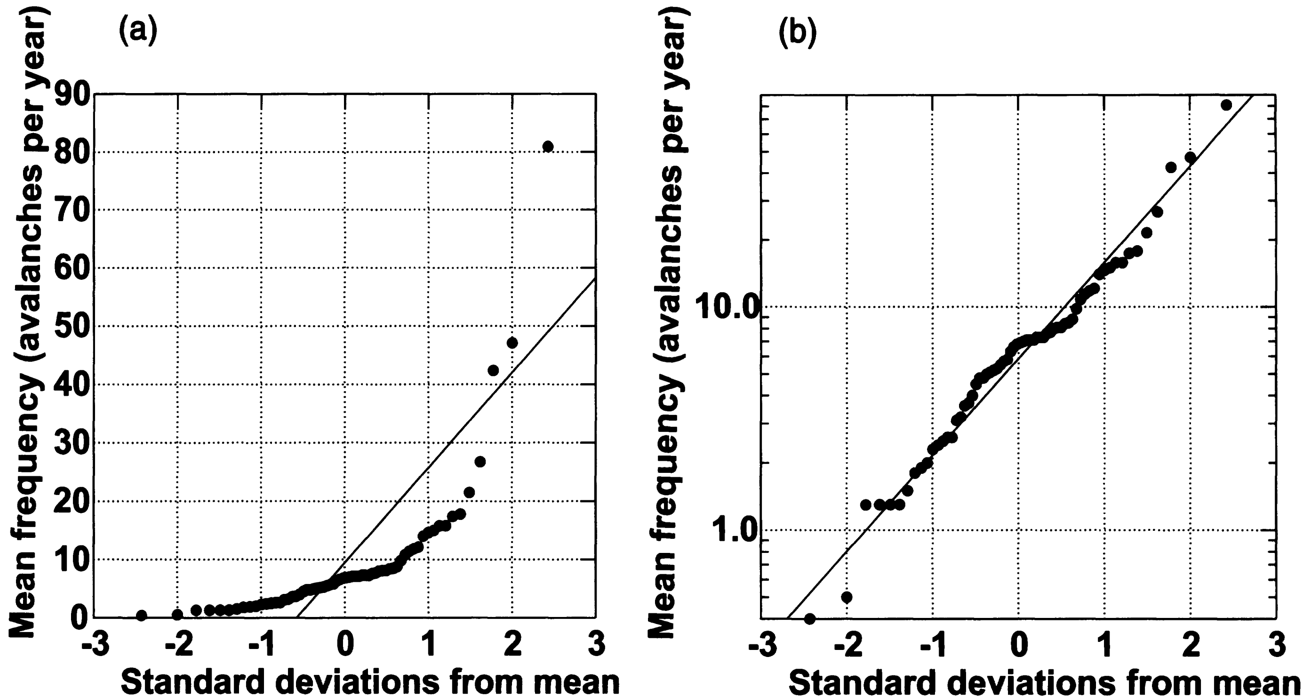

FIGURE 2. (a) Probability plot of mean avalanche frequency for Bear Pass. If mean avalanche frequency obeyed a Gaussian distribution, the points would fall on the straight line. (b) Lognormal probability plot for mean frequency for Bear Pass. The plot shows mean frequency is approximately lognormally distributed.

istry of Transportation and Highways (Province of British Columbia, 1982, 1982, 1989) and the avalanche atlas from Rogers Pass (Schleiss, 1989). The data were obtained from a variety of sources: contour maps (scale 1:50,000); air photos (scales 1: 10,000 to 1:32,000), field measurements using clinometers for angles and distance measurements in the field (accurate within several meters) and distances taken from maps 1:50,000 maps with contour intervals of 100 feet with accuracy within about half a contour interval (50 feet). Most of the distances in runout zones were measured in the field. Terrain and vegetation descriptions in the atlases were determined from a combination of air photo analysis and field observations.

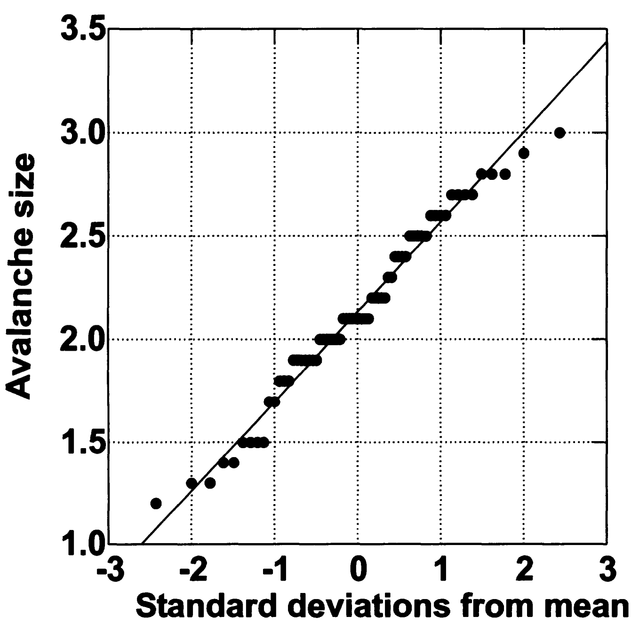

FIGURE 3. Probability plot of mean avalanche size for Bear Pass. The plot shows that mean avalanche size approximately follows a Gaussian distribution.

PREDICTOR VARIABLE DESCRIPTION AND ANALYSIS PROCEDURE

In addition to the response variables (ln f; M), 19 predictor variables were retained for Kootenay Pass, Three Valley Gap and Bear Pass. For Rogers Pass, one response variable (ln f) and 23 predictor variables were used. The predictor variables included continuous terrain variables (14 for Rogers Pass; 10 for Kootenay Pass, Bear Pass and Three Valley Gap) and 10 categorical variables related to terrain configurations, exposure to drifting snow, and vegetation types.

The study of predictor variables was on two levels:

1. First, single variable correlations and tests of significance for avalanche frequency (ln f) and avalanche magnitude (M) were completed. For this part of the study, Spearman rank correlations were calculated and only variables which were significant ($0.01 < P \leq 0.05$) and highly significant ($P \leq 0.01$) were retained.
2. To supplement the analysis above, step-wise multiple least squares regression analysis between response variables (ln f; M) and predictor variables which were significant or highly significant in the correlation studies were performed. The analyses yielded significant relationships for frequency at Rogers Pass and Kootenay Pass and for avalanche size (magnitude) at Bear Pass.

DEFINITION OF CATEGORICAL PREDICTOR VARIABLES

Categorical predictor variables were determined from photos of the avalanche paths in published avalanche atlases com-

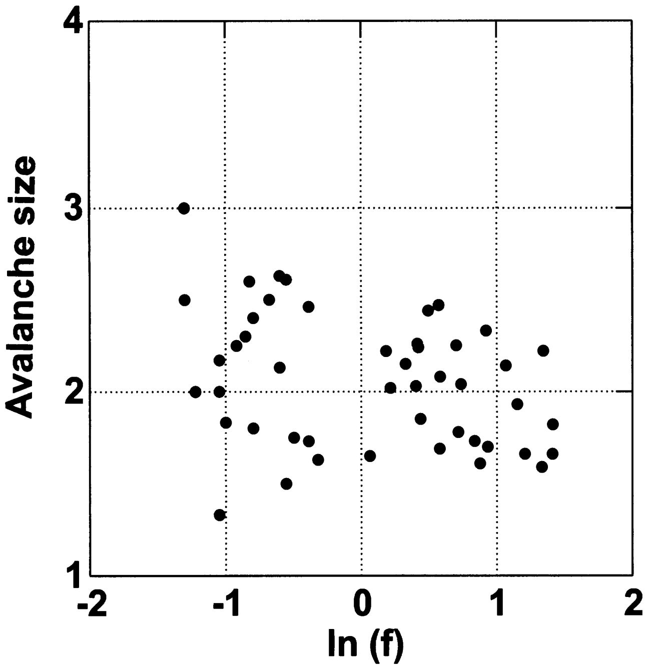

FIGURE 4. Scatter plot of mean avalanche size versus ln f for avalanche paths at Kootenay Pass. The plot shows a weak negative correlation for mean avalanche size versus frequency: mean size decreases as mean avalanche frequency decreases. For the other areas in this study (Bear Pass and Three Valley Gap) the correlation is not significant.

bined with other quantitative information obtained from maps and in the published descriptions for each path in the atlases, such as aspect, determined by the authors of the avalanche atlases. Descriptions of categorical variables are contained in the list below. Table 3 gives the ranges of the categorical variables and number of avalanche paths for each study area.

Wind Index (Schaerer, 1977; Smith and McClung, 1997): The Wind Index is introduced to give a progressively higher index (range 1–5) as more snow is expected in the starting zone. The categories are:

1. Starting zone completely sheltered from wind by surrounding dense forest cover
2. Starting zone sheltered by open forest or facing the direction of the prevailing wind
3. Starting zone an open slope with rolls or other irregularities where local drifts can form (e.g., gullies or bowls)
4. Starting zone on the lee side of a sharp ridge
5. Starting zone on the lee side of a wide rounded ridge or open area where large amounts of snow can be moved by wind

Starting zone, track, and runout zone type according to downslope terrain configuration (3 categorical variables):

1. Deeply channelized
2. Containing a shallow gully or gullies
3. Open slopes with essentially no deep channels or gullies

Starting zone, track, and runout zone vegetation density (3 categorical variables):

1. Very Sparse (≤ 100 stems per hectare)
2. Sparse (several hundred stems per hectare)
3. Dense (≥ 1000 stems per hectare)

TABLE 3

Range and number of avalanche paths (N) for categorical variables for four avalanche areas[a]

Variable	Area	Range	N
Starting zone type	RP	1–3	43
	BP	1–3	70
	KP	1–3	49
	TV	1–3	32
Starting zone density	RP	1–4	43
	BP	1–4	70
	KP	1–4	49
	TV	1–4	32
Starting zone veg.	RP	1–4	43
	BP	1–4	70
	KP	1–4	49
	TV	1–3	32
Track type	RP	1–3	43
	BP	1–3	70
	KP	1–3	49
	TV	1–3	32
Track density	RP	1–4	43
	BP	1–4	70
	KP	1–4	49
	TV	1–4	32
Track veg.	RP	1–4	43
	BP	1–4	70
	KP	1–4	49
	TV	1–3	32
Runout zone type	RP	2–3	43
	BP	1–3	70
	KP	3	49
	TV	1–3	32
Runout zone density	RP	1–4	43
	BP	1–4	70
	KP	1–4	49
	TV	1–4	32
Runout zone veg.	RP	1–4	43
	BP	1–4	61
	KP	1–4	49
	TV	1–4	32
Wind Index	RP	1–5	41
	BP	1–5	70
	KP	1–5	48
	TV	1–4	32

[a] Avalanche areas: RP—Rogers Pass, BP—Bear Pass, KP—Kootenay Pass, TV—Three Valley Gap.

The categories were determined for vegetation of heights greater than 1 m and higher and by estimating average spacing with the above amounts from atlas photos.

Starting zone, track, and runout zone vegetation type (3 categorical variables):

1. Coniferous or deciduous trees (greater than 1-m height)
2. Brush, grass, shrubs
3. Rocky

The categories were determined by examining atlas photos and atlas descriptions. As the category number increases, average height of vegetative cover decreases.

Aspect (Compass aspect divided into 4 sectors): 1: 1–90°; 2: 91–180°; 3: 181–270°; 4: 271–360°.
The values were determined from maps and atlases.

TABLE 4

Descriptive statistics for continuous terrain variables: Rogers Pass, B.C.

Variable	Mean	Std. Deviation	Range	N[b]
Starting zone angle (°)	38	5	32–47	43
Track angle (°)	38	4	31–46	43
Runout zone angle (°)	21	6	0–30	43
Vertical drop (m)	950	250	500–1450	43
Path length (m)	1700	450	850–2800	43
Starting zone elevation (m)	2050	250	1600–2600	43
Runout zone elevation (m)	1100	100	850–1300	43
Aspect[a] (1–4)	2.6	1.0	1–4	43
Area of catchment[a] (ha)	20	15	3–70	41
Start zone[a] roughness height (m)	0.25	0.06	.15–.45	41
30-Year Max. Ann. Water Equivalent[a] (mm)	1380	320	800–2000	41
Location[a] (km)	−0.8	6	−15–+6	43

[a] See text for discussion of these variables.
[b] N is the number of avalanche paths analyzed.

TABLE 5

Descriptive statistics for continuous terrain variables for Kootenay Pass (KP), Bear Pass (BP), and Three Valley Gap (TV)

Variable	Area	Mean	Std. Dev.	Range	N
Starting zone elev. (m)	KP	1900	200	1300–2150	49
	BP	1450	550	300–2350	70
	TV	1000	400	450–1950	32
Runout zone elev. (m)	KP	1450	250	850–1750	49
	BP	400	100	100–2350	70
	TV	550	50	450–700	32
Vertical drop (m)	KP	500	250	50–1150	49
	BP	1050	550	50–1900	70
	TV	550	350	50–1500	32
Aspect (1–4)	KP	2.5	0.7	1–4	49
	BP	2.6	1.0	1–4	70
	TV	3.3	1.0	1–4	31
Starting zone angle (°)	KP	39	9	24–70	49
	BP	41	7	27–62	70
	TV	41	8	25–65	32
Track angle (°)	KP	34	4	25–44	49
	BP	41	7	22–62	70
	TV	41	8	25–65	32
Runout zone angle (°)	KP	15	7	0–27	49
	BP	5	6	0–21	70
	TV	4	7	0–18	32

CONTINUOUS PREDICTOR TERRAIN VARIABLES: LIST AND DESCRIPTION

Other terrain and vegetation predictor variables included those taking on a continuous range of values. A list with accuracy description appears below.

- *Starting zone elevation (m):* Elevation of top of the starting zone (accuracy ± 30 m); determined from maps.
- *Runout zone elevation (m):* Elevation of top of the runout zone (accuracy ± 30 m); determined from maps from experience, slope angle changes, and vegetation patterns.
- *Vertical drop (m):* Elevation difference between top of start zone and bottom of runout zone (accuracy ± 50 m); determined from maps.
- *Starting zone angle (°):* This represents average downslope slope angle in the starting zone. Determined from maps. The definition of the starting top and bottom along the slope was estimated by experience. The maximum accuracy is ±1°.
- *Track angle (°):* Average downslope angle in the track. Determined as per starting zone angle with similar accuracy.
- *Runout zone angle (°):* This represents average slope angle in the runout zone. Determined from field measurements with a clinometer if possible, otherwise from maps. The accuracy is similar to starting zone and track angles.

Tables 4 and 5 contain descriptive statistics for continuous terrain and vegetation variables for Rogers Pass (Table 4) and Kootenay Pass, Bear Pass and Three Valley Gap (Table 5). Aspect is also included in Tables 4 and 5, even though it is a categorical variable as defined in this paper.

ADDITIONAL VARIABLES FOR ROGERS PASS

There are four continuous variables available at Rogers Pass which were used by Smith and McClung (1997) which are potentially important for the frequency study in this paper.

1. *Start zone roughness height (m):* The variable represents the average ground roughness height in the starting zone in meters water equivalent of snow. The accuracy is about ±0.05 m.
2. *Location:* Straight-line distances in kilometers, east-west from Rogers Pass summit, to where each path intersects the highway. The accuracy is better than 0.5 km. Negative values are east of the summit and positive values are west of the summit.
3. *Thirty (30)-Year Maximum Water Equivalent (mm):* This variable is based on snow depth measurements taken at several stations near Rogers Pass. Over a period of 15 to 20 years, maximum snow depth and density measurements were taken once a year at six stations increasing in elevation on both the east and west sides of the summit. The 30-Year Maximum Water Equivalent was calculated from the cube-root normal distribution (recommended by Atmospheric Environment Service, Canada to stabilize the variance) to give an estimate for each start zone elevation.
4. *Area of catchment:* Maximum area (ha) available for starting of avalanches determined from maps and photos by experience (see also Smith and McClung, 1997).

Results

RESULTS OF FREQUENCY CORRELATION STUDIES: NONPARAMETRIC STATISTICS

Since avalanche frequency is not a Gaussian variable, I calculated matrices for Spearman rank correlations of frequency with the predictor variables. The advantage of rank correlations is that the assumption that response and predictor variables are linearly related, both being Gaussian variables, as with the ordinary Pearson correlation coefficient, is avoided. Furthermore, many of the variables studied here are categorical rather than continuous, numerical variables so that rank correlation is more meaningful. I retained only variables for which correlation is

TABLE 6

Spearman rank correlation coefficients of frequency with predictor variables

Rogers Pass		Bear Pass	
Highly significant:		Highly significant:	
Start zone elevation	0.38	None	
Runout zone elevation	0.47		
Start zone roughness[a]	−0.64		
30-Year Max. Ann. Water Equivalent	0.55		
Wind Index[a]	0.50		
Location W or E of Rogers Pass	0.48		
Starting zone vegetation density[a]	−0.43		
Significant:		Significant:	
Runout zone incline	0.30	Aspect	−0.28
Start zone type	−0.32	Starting zone incline	−0.23
Track veg. density[a]	−0.32	Wind Index[a]	0.22
Runout zone veg. type[a]	−0.26	Track veg. type[a]	0.26
Starting zone veg. type[a]	−0.32		
Kootenay Pass		**Three Valley Gap**	
Highly significant:		Highly significant:	
Starting zone incline	0.38	Starting zone incline	0.54
Runout zone elevation	0.63	Track incline	0.56
Track incline	0.38		
Start zone elevation	0.47		
Wind Index[a]	0.77		
Significant:		Significant:	
Runout zone incline	0.31	Runout zone incline	−0.34
		Wind Index[a]	0.35
		Runout zone veg.[a]	0.38
		Runout zone elevation	0.40
		Track veg. type[a]	−0.31

[a] Denotes possible link to forest cover.

significant ($0.01 < P \leq 0.05$) or highly significant ($P \leq 0.01$) according to definitions given by Walpole and Myers (1978).

Variable correlations are summarized in Tables 6 and 7. It is clear that there are no general relationships between average avalanche frequency, terrain and forest cover variables because different variable sets are important in different avalanche areas. However, there are variables that are physically meaningful and satisfy either of the following criteria: (1) highly significant correlation in at least two areas or (2) variables which are significant enough to appear in multivariate relations between mean frequency and predictor variables (presented in a later section). The variables retained while meeting either of these two criteria are contained in Table 7. Table 7 also includes Max. Annual Water Equivalent which is highly significant at Rogers Pass: the only area where estimates were available. Most of the variables in Table 7 can be indirectly related to either snow supply or terrain steepness and this forms a possible correspondence with the model of McClung (2000) where return period in the runout zone is related to overall terrain steepness and local avalanche frequency (related to snow supply) through the distribution of extreme runout distances for a set of avalanche paths in a mountain range. Higher snow supply in the start zone insures a higher overall probability of avalanching (e.g., Salm, 1997) and steeper terrain (start zone, track and runout zone) may imply higher probability that avalanches which release continue to reach the runout zones where the frequency estimates were made for this study.

TABLE 7

Variables which have highly significant correlation with mean avalanche frequency or which are significant in multivariate relationships with avalanche frequency

Predictor Variable	Sign of correlation
Wind Index[a]	+
Starting zone[a] roughness or type	−
30-Year Max. Ann. Water Equiv.[a]	+
Starting zone elevation[a]	+
Starting zone incline[b]	+
Trace incline[b]	+
Runout zone incline[b]	+
Runout zone elevation[c]	+

[a] Denotes possible relation to snow supply.
[b] Denotes possible relation to terrain steepness.
[c] Runout zone elevation is likely to have positive correlation with frequency since higher elevations imply shorter distances to start zones so that more avalanches reach the runout zone where frequency is estimated.

RESULTS OF MAGNITUDE (AVALANCHE SIZE) CORRELATION STUDIES

A companion study of Spearman rank correlation of mean avalanche size with predictor variables was made using the same criteria for retention as the frequency study: highly significant if $P \leq 0.01$ and significant if $0.01 < P \leq 0.05$. The results are given in Tables 8 and 9. Using the same criteria for selection of variables identified as possibly important in Table 7 for avalanche frequency, a table of values was constructed for magnitude (Table 9). The variables retained are listed in Table 9 must be physically meaningful and satisfy at least one of the two following criteria: (1) highly significant correlation with magnitude for at least two areas or (2) significant in a multivariate least squares regression with avalanche size.

The relationships of the predictor variables (Table 9) to avalanche magnitude have plausible physical interpretations. Higher starting zone elevation and higher vertical drop may imply greater destructive effects which are implicit in the size classification scheme (McClung and Schaerer, 1993). Increased track incline possibly implies that smaller-size avalanches can be kept in motion to reach runout zones. Hence, smaller magnitudes on average can reach the runout zone, resulting in negative correlation with increasing track inclination.

Positive correlation of mean avalanche size with runout zone incline was found but there is no clear physical interpretation so this correlation should be discounted until a good physical explanation is provided. Salm (1997) notes that smaller avalanches tend to have higher basal friction than larger avalanches on average. Salm's suggestion implies that the correlations of avalanche size with runout zone incline should be negative.

Starting zone type and track type have negative correlation (the parameter increases as the terrain is less channelized) with magnitude, possibly implying that more channelized terrain delivers larger avalanches, on average, to the runout zone. This may be related to snow entrainment with more mass added in channelized terrain but this idea cannot be proven with the data in the present study.

Positive correlation with Wind Index comes only from the

TABLE 8

Highly significant and significant Spearman rank correlations for magnitude with predictor variables

Bear Pass		Three Valley Gap		Kootenay Pass	
Highly significant:		Highly significant:		Highly significant:	
Starting zone elevation	0.78	Starting zone elevation	0.62	Vertical drop	0.34
Runout zone elevation	0.39	Runout zone elevation	0.52	Starting zone elevation	−0.41
Vertical drop	0.80	Vertical drop	0.61		
Track incline	−0.43	Runout zone incline	0.47		
Runout zone incline	0.58	Starting zone type	−0.53		
Wind Index	0.62	Track type	−0.48		
Starting zone type	−0.45	Track veg. density	0.52		
Starting zone density	−0.62	Track veg. type	−0.41		
Starting zone veg. type	0.47	Track incline	−0.41		
Track type	−0.55				
Runout zone veg. density	−0.61				
Significant:		Significant:		Significant:	
Runout zone type	0.22	None		Starting zone type	−0.29
				Track type	−0.28

Bear Pass area and may indicate that starting zones adjacent to large areas of open, unforested terrain, as is characteristic of Bear Pass, are more prone to larger avalanches on average. From Table 9, there is positive correlation with variables that are related to snow supply (Wind Index, elevations), terrain steepness (track and runout zone incline) and path confinement (starting zone and track), and scale of the path (vertical drop, start zone elevations). However, any variables above which may be related to snow supply are only through indirect relationships and this makes the link of snow supply to average avalanche size somewhat doubtful. There is a clear physical link of snow supply to avalanche frequency and a direct link through correlation studies and the work of Schaerer (1977), Smith and McClung (1997), and the work in this paper. However, a direct link of magnitude and snow supply has yet to be made.

EFFECTS OF FOREST AND VEGETATION VARIABLES

Forest and vegetation variables had significant and highly significant correlation with avalanche frequency for all four areas (see Table 6) but the most important variable seems to be the Wind Index. The Wind Index was highly significant in two areas and significant for the other two areas (Table 6). Similar comments apply for avalanche magnitude: the Wind Index is the only variable which satisfies one of the two criteria for identifying it as truly important: highly significant in a multiple regression relationship (see next section). Thus, the vegetation/forest cover variables appear to be of secondary importance in this study.

TABLE 9

Important predictor variables correlating with mean avalanche magnitude

Variable	Sign of correlation
Starting zone elevation	+
Runout zone elevation	+
Vertical drop	+
Track incline	−
Starting zone type	−
Track type	−
Wind Index	+

MULTIVARIATE SIZE AND FREQUENCY REGRESSION ANALYSES

Here, I estimate size and frequency as functions of predictor variables in a multivariate sense. Since some of the predictor variables are similar to others, a proper multivariate relationship has the advantage that the only variables retained are significant in combination with others so that such redundancy is minimized. Therefore, I sought multivariate least squares regression relationships for each area separately for both size and frequency. Significant multivariate relationships for magnitude were found for Bear Pass, Kootenay Pass, and Three Valley Gap. Multivariate relationships for ln f were found for Rogers Pass and Kootenay Pass. The equations were all derived from step-wise multiple regression and exploratory data analysis techniques including scatter plots and significance testing of variables.

1. *Magnitude relationships.* For the equations below, VD = Vertical drop, RZE = Runout zone elevation, WI = Wind Index, SZE = Starting zone elevation, SZT = Starting zone type and M is avalanche size, R is correlation coefficient, F is F statistic, SE is standard error, and N is number of avalanche paths.

Bear Pass:

	M = 1.27	+ .50 (VD/1000)	+ 0.022 RZE	+ 0.072 WI
t-statistic:	20.3	8.2	6.3	2.8
p-(2-tail):	<0.001	<0.001	<0.001	0.006

$R^2 = 0.84$, $F(3,62) = 108$, $P < 0.01$, SE = 0.18, N = 66

Kootenay Pass:

	M = 2.41	− 0.014 SZE	+ 0.4(VD/1000)
t-statistic:	9.5	−2.6	2.1
p-(2-tail):	<0.001	0.013	0.042

$R^2 = 0.23$, $F(2,46) = 6.7$, $P = 0.003$, SE = 0.32, N = 48

Three Valley Gap:

	M = 0.004 RZE	− 0.254 SZT
t-statistic:	10	−2.7
p-(2-tail):	<0.001	0.012

$R^2 = 0.35$, $F(1,30) = 16.2$, $P < 0.001$, SE = 0.53, N = 31

2. *Frequency relationships.* For the relationships below, the following notation applies in addition to that above for magnitude relationships: R = Roughness, L = location east or west of

Rogers Pass summit (in km) (see also Smith and McClung, 1997), TKE = Track elevation.

Rogers Pass:

ln f =	1.07	− 1.47 R	+ 0.08 WI	+ 0.02 L
t-statistic:	9.7	4.8	4.1	4.9
p-(2-tail):	<0.001	<0.001	<0.001	<0.001

$R^2 = 0.69$, $F(3,37) = 27$, $P < 0.001$, SE = 0.12, N = 41

This represents an improved regression relationship over that presented by Smith and McClung (1997) because ln f was used as the response variable instead of f as used by Smith and McClung (1997).

Kootenay Pass:

ln f =	−6.4	+ 0.002 RZE	+ 0.065 TKE	+ 0.39 WI
t-statistic:	−7.8	7.3	3.5	6.4
p-(2-tail):	<0.001	<0.001	0.001	<0.001

$R^2 = 0.80$, $F(3,45) = 59.3$, $P < 0.001$, SE = 0.41, N = 48

Effects of Avalanche Control

Some of the avalanche paths in the present study are subject to avalanche control by gunfire and explosives and it is possible the relationships and correlations could be affected.

I performed correlation, exploratory data analysis, and stepwise regression for 27 of the 43 paths at Rogers Pass which were not subject to avalanche control. The result of the best stepwise regression gave:

ln f =	1.07	− 1.59 R	+ 0.08 WI	+ 0.02 L
t-statistic:	9.5	−5.0	4.4	5.1
p-(2-tail):	<0.001	<0.001	<0.001	<0.001

$R^2 = 0.80$, $F(3,23) = 31.1$, $P < 0.001$, SE = 0.10, N = 27

This analysis is nearly identical to that for the set of 41 avalanche paths which included those controlled by gunfire. Similarly, I calculated t-tests for the differences between means of the frequency data and the variables which had at least significant correlation with frequency and the results of these calculations showed no significant differences between the means.

For the other areas, the avalanche paths at Three Valley gap are not normally controlled by explosives and at Bear Pass, only about 10% of the paths are regularly controlled using explosives so the data there are not sufficient to assess the effects of avalanche control. Kootenay Pass is the lone exception here in that nearly all paths are regularly controlled by explosives and gunfire. I conclude that the relationships from Kootenay Pass may be significantly affected by avalanche control but the effects of avalanche control on the data from the other areas is likely to be small.

Summary

The present study of high-frequency avalanche paths is much more comprehensive than previous work (Schaerer, 1977; Smith and McClung, 1997; Gleason, 1994) attempting to predict frequency from terrain and snow supply variables. In the present study, more predictor variables are included and data from four avalanche areas are included instead of one area. Furthermore, the present study includes avalanche magnitude (size) for the first time as well as a selection of forest cover and vegetation predictors.

Primary results of this study are that frequency may be approximated as lognormally distributed for each of the four areas and avalanche size (magnitude) is approximately normally distributed. Furthermore, there is nearly no relation between average magnitude and average frequency except for Kootenay Pass, where there is a weak but significant relation between size and frequency: as average frequency increases average size decreases. This latter result may be affected by avalanche control at Kootenay Pass. I conclude that there is no strong relation between average magnitude and frequency for the areas studied here. This result is also indicated by the multiple regression results: different sets of predictors appear for magnitude and frequency for the same area. This suggestion should not be extrapolated to comparison of pairs of avalanche paths but it may have some importance for comparison between areas. For example, an individual path with lower average frequency may be expected to have higher average magnitude than one with higher average frequency in an area with similar snow supply but this relation does not seem to hold for a collection of paths in an avalanche area.

Important predictor variables for frequency are clustered in two sets: those related to snow supply (Wind Index, start zone roughness, 30-year Maximum Annual Water Equivalent, start zone elevation) and terrain steepness (starting zone, track and runout zone inclines). The results with respect to track incline (steeper track implies higher frequency) are compatible with those of Schaerer (1972) based on data at Rogers Pass. However, the results of this paper are not compatible with Schaerer's (1972) result that channelled tracks have higher frequency than open slope tracks either for Rogers Pass or the other three areas in the study. Further, correlation of frequency with track steepness is much weaker than in the study of Schaerer (1972). Instead, the present study indicates that channelled tracks tend to have higher average magnitude. Since 30-Year Maximum Annual Water Equivalent from Rogers Pass is directly related to elevation through snow course data, it is likely that this variable and start zone elevation (appearing from correlations at both Rogers Pass and Kootenay Pass) are providing similar information.

Important variables for avalanche size are related to path scale (start zone elevation, vertical drop), snow supply (Wind Index), and path confinement and steepness characteristics (start zone and track type, track incline). All these variables can be justified as physically plausible. Even though start zone elevation showed highly significant positive correlation with avalanche size for Bear Pass and Three Valley Gap, the correlation was negative for Kootenay Pass. The physical explanation of this result is lacking but it may be related to the specific terrain features at Kootenay Pass. Start zone elevation also is also present in the multivariate regression analysis for Kootenay Pass with a negative sign so that there is consistency with the sign of the correlation result for Kootenay Pass.

The collective results of this paper show that the prediction of average magnitude and average avalanche frequency is very complex with no general multivariate relationships available. However, both avalanche frequency and avalanche magnitude (assuming that size as defined by the Canadian system includes logarithmic increase in destructive potential between sizes) are approximately lognormally distributed for the areas studied.

The results about mean frequency in relation to runout zone incline may be revealing something important about avalanche behavior. Frequency has positive correlation with runout zone incline, implying that mean frequency increases as runout zone incline increases. There is also a plausible explanation: steeper runout zones make it easier for a higher frequency of events to reach the highway locations where data were collected.

Even though the Wind Index appears as significant in some of the correlations and regressions described, it may have limited usefulness in applications. The Wind Index, as defined, mixes terrain aspect and snow supply within the five levels of its definition so that there is the possibility of redundancy with other variables. Thus, for example, it cannot be concluded that correlation of Wind Index with avalanche size is related directly to snow supply.

Acknowledgments

This research was funded by Forest Renewal BC, Canadian Mountain Holidays, the Natural Sciences and Engineering Research Council of Canada, the Vice President Research at the University of British Columbia, and the Peter Wall Institute of Advanced Studies at the University of British Columbia. I am very grateful for these sources of support. Doug Sandilands and Peter Weisinger of the Department of Geography at the University of British Columbia provided invaluable assistance with assembling the data. Ted Weick of the B.C. Ministry of Transportation and Highways graciously provided frequency and size data for Kootenay Pass, Three Valley Gap, and Bear Pass.

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Ms submitted July 2001

Appendix A: Canadian Avalanche Size Classification

The Canadian avalanche size system is based on estimating the destructive effects of avalanche events. The system is similar in concept to the Mercalli Scale for earthquake intensity and like the Mercalli Scale, it is possible to estimate destructive potential. Guidelines for sizing depend on: (1) avalanche mass, (2) distance moved along the incline, (3) estimated maximum impact pressure, and (4) water content of the debris i.e., dry snow avalanches or wet snow avalanches. The system has been developed from experience and measurements to cover snow avalanche destructive potential for snow avalanches of all known size. The system has 5 classes for which approximately an order of magnitude in destructive potential is estimated for each increase in size. In general, the frequency of avalanches recorded decreases as the size increases. The paper by McClung and Schaerer (1981) contains the theoretical argument and data on which the system is based. It is customary in Canada for avalanche observers to record events using half sizes (e.g., size 2.5). However, due to associated uncertainty, it is recommended to use whole sizes in applications. Table A1 contains descriptions of the size classes.

TABLE A1

Canadian avalanche size classification

Size	Description	Typical Mass	Typical Path Length	Typical Impact Pressures
1	Relatively harmless to people	<10 t	10 m	1 kPa
2	Could bury, injure, or kill a person	10^2 t	100 m	10 kPa
3	Could bury a car, destroy a small building, or break trees	10^3 t	1000 m	100 kPa
4	Could destroy a railway car, large truck, several buildings, or forest with an area up to 4 ha	10^4 t	2000 m	500 kPa
5	Largest snow avalanches known; could destroy a village or forest up to 40 ha	10^5 t	3000 m	1000 kPa