Estimating extreme snow avalanche runout for the Columbia Mountains, British Columbia, Canada

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ABSTRACT
Extreme avalanche runout is typically estimated using a combination of historical and vegetation records as well as statistical and dynamic models. The two main classes of statistical models (*α – β* and *runout ratio*) are based on estimating runout distance past the β-point, which is generally defined as the point where the slope incline first decreases to 10° while descending the slope. Using a dataset of 31 avalanche paths we calculated α – β and runout ratio parameters unique to the Columbia Mountains.

RÉSUMÉ
Longeur d'ecoulement d'avalanche extreme est estimé en croisant les faits historiques avec les relevés de la faune locale, en utilisant des modèles statistiques et dynamiques. Les principales classes de modèles statistiques (*α – β* en *rapport de longeur d'ecoulement*) sont basés sur la prévision de la chute après le point ß, qui est généralement défini comme le point ou la pente diminue de 10° dans le sens de la descente pour la première fois. En analysant les données de 33 chemins d'avalanches nous avons développé des modèles de ratios α – β ainsi que des modèles de risque de chute spécifiques aux massifs de Colombie-Britannique.

1 INTRODUCTION

In Canada, the snow avalanche hazard to structures and utilities is commonly mitigated by identifying and avoiding areas threatened by avalanches. Avalanche hazard mapping professionals commonly use a combination of field studies, terrain analysis, and research of historical records along with statistical and dynamic models to define extreme avalanche runout positions. When reliable field observations (vegetative damage) are available, they are often compared to the extreme runout point estimated by statistical and dynamic models to provide the mapper with a higher degree of confidence in their estimates (Jamieson et al., 2008). There are two classes of statistical models which are commonly used in Canada: the *α – β* (Lied and Bakkehöi, 1980) and *runout ratio models* (McClung et al., 1989). Both models are based on estimating avalanche runout past the β point, which is generally defined as the point where the slope incline first decreases to 10° while descending the slope (Figure 1).

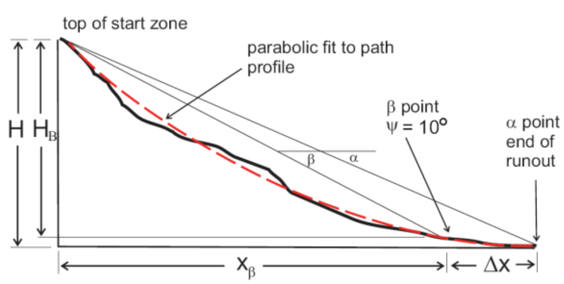

Figure 1. Geometry and parameters used to derive the α – β and runout ratio models (after Canadian Avalanche Association, 2002)

The α – β model was first developed by Lied and Bakkehöi (1980), using data from 192 Norwegian avalanche paths with well defined extreme runout positions. They examined a range of physical parameters, and found that β was the only significant predictor. Since then, α – β models have been developed for other mountain ranges in Europe and North America.

The runout ratio model was first developed by McClung et al. (1989) by applying extreme value statistics to avalanche runout data. McClung et al. (1989) found that the runout ratio for extreme events obeyed an extreme value type 1 (EV1 or Gumbel) distribution, and that the Gumbel parameters *u* and *b* could be used to estimate extreme runout for specific non-exceedence probabilities in a given path. $X_β$ (Figure 1) is defined as the horizontal distance from the avalanche path starting position to the β point position. The non-exceedence probability, *P*, is defined as the fraction of avalanche paths in a particular mountain range that do not exceed a specific runout ratio. The runout ratio relates the horizontal runout distances to the avalanche path slope angles *α*, β and *δ* by the following formula:

$$\frac{\Delta x}{X_\beta} = \frac{\tan\beta - \tan\alpha}{\tan\alpha - \tan\delta} \quad [1]$$

In Canada, α – β and runout ratio model parameters have been developed based on paths located within large geographical areas: the Coast Mountains (Nixon and McClung, 1993) and the combined Rocky/Purcell Mountains (McClung et al., 1989). Jones and Jamieson (2001) developed a Canada-wide short slope model for avalanche slopes with a vertical drop less than 350 m. Delparte et al. (2008) developed α – β models for the Columbia Mountains using topographical data from high

(5 m) and low (25 m) resolution digital elevation models (DEMs). The runout positions used to develop these models were based on observed avalanche runout to the Trans-Canada Highway through the Rogers Pass corridor during a 40 year observation period. Avalanche runout during this 40 year observation period may not accurately represent extreme avalanche runout for all paths, which is generally defined in Canada as the avalanche with a 30 to 100 year return period. The extreme runout positions likely exceed the runout positions observed during this 40-year period.

Within the Columbia Mountains, there is substantial residential, industrial and recreational development within avalanche terrain that may require identification of avalanche hazards. The objective of this study is to develop α – β and runout ratio model parameters which can be used to assist with estimating extreme avalanche runout for tall avalanche paths ($H > 350$ m) in the Columbia Mountains.

2 METHODS

2.1 Study Area and Avalanche Path Site Selection

An avalanche path can generally be divided into three portions: the starting zone, track and runout zone. The avalanche track is the portion of the path where large avalanches typically reach maximum velocity and where the slope incline typically ranges from 30 to 15° (McClung and Schaerer, 2008).

The avalanche paths surveyed as part of this study included paths with little to no uphill (i.e. cross-valley) runout and paths that are not confined or channelized in the track and runout zone. These types of paths are typically better represented by statistical runout models. The surveyed paths were also chosen based on ease of access (road or trail access) and because they had a mature vegetation record of avalanche impacts in the runout zone (minimal logging or fire in the runout zone). To the extent possible, we attempted to choose paths from a variety of aspects and elevations within the Columbia Mountains.

The Columbia Mountains include the Monashee, Cariboo, Selkirk and Purcell sub-ranges (Figure 2). The Columbia Mountains encompass an area of approximately 135,000 km^2, with elevations ranging from valley bottoms near 500 m up to 3519 m at the highest point (Mt. Sir Sandford).

Figure 2. Map of the Columbia Mountains, British Columbia, Canada. Black dots show the locations of the surveyed avalanche paths.

2.2 Field Methods

Based on the avalanche path characteristics described above, avalanche paths were initially identified using digital imagery from Google Earth (Version 5.1, 2010). Terrain Resource Inventory Maps (British Columbia Government, 2010) topographic maps (1:20,000) with 20 m contour intervals were used to estimate the initial boundaries of the avalanche paths and to calculate slope inclines and slope segment lengths from the top of the starting zone to a position located downslope of the extreme runout position based on vegetative damage. Prior to the field survey, the approximate location of the beta point was identified from the topographic maps to help facilitate the starting point of the detailed field survey.

The field surveys were conducted during July and August 2010. During the surveys, slope angles and slope segment lengths were measured starting from a point located above the β point to a location approximately 50+ m beyond the extreme runout position (α point). A clinometer was used to measure the slope segment angles to an accuracy of ±0.5° and a laser rangefinder (accuracy ±1 m) or hip chain (accuracy ± 0.2%) to measure the slope distances. A GPS was used to collect waypoints with a horizontal accuracy ranging from ±3 to ±15 m (average ±7 m) and an altimeter was used to collect elevation at the waypoints with an accuracy of ±5 m. Laser rangefinder and hip chain data were used as the primary measurement of slope segment length – when these were not available, GPS waypoints were substituted. The alpha point was identified in the field by observing patterns of vegetative growth and damage in the runout zone. To the extent possible, this vegetative damage is assumed to represent damage from the dense flow component of the avalanche, but where it was difficult to differentiate between the damage from the dense flow and from the powder component, the later likely influenced identification of the α point by favouring a longer runout or smaller α angle. The α angle was measured in the field where possible, and calculated from the topographic slope profile where vegetation, terrain and/or weather prevented taking a field measurement.

The intent of the runout survey was to identify the runout position of the 100 year avalanche event; however, the average return period associated with a runout position identified from observations of vegetative damage is likely on the order of 50 – 300 years (McClung and Mears, 1991), introducing unavoidable random error into the analysis.

3 DATA

In total, 31 avalanche paths were analyzed including 14 paths from the Monashees, 11 paths from the Selkirks, and 6 paths from the Cariboo Mountains. The locations of these avalanche paths along with the physiographic boundary of the Columbia Mountains are shown in Figure 2. Descriptive statistics for the Columbia Mountain avalanche paths are summarized in Table 1.

Table 1. Descriptive Statistics for Columbia Mountain Data.

	Mean	Standard Deviation	Range of Values	
			Minimum	Maximum
α (°)	26.9	4.4	19.4	37.2
β (°)	29.0	4.6	21.4	41.0
δ (°)	7.2	9.3	-12.9	25.7
y” (m^{-1})	1.8 x 10^{-4}	1.0 x 10^{-4}	3.1 x 10^{-4}	4.1 x 10^{-4}
H (m)	940	430	447	2045
∆x (m)	223	158	56	720

For comparison, the mean α angles for the Canadian Rockies/Purcells and the British Columbia Coast Mountains are summarized in Table 2.

Table 2. Mean alpha angles (α) and the number (n) of paths for three Canadian mountain ranges

Range	Mean α (°)	n	Reference
Rocky and Purcell Mountains	27.8	125	McClung et al., 1989
Coast Mountains	26.8	31	Nixon and McClung, 1993
Columbia Mountains	26.9	31	this study

The minimum runout zone angle of -12.9° was obtained from a path in the Selkirk mountains with an α point located at the top of a steep creek cutbank.

Since lower α angles imply longer runout distances relative to vertical fall height, the mean α angle of 27.0° for the Columbia Mountains indicates that avalanche paths in our Columbia mountain dataset tend to run relatively farther than those in the dataset for the Rocky and Purcell Mountains which have a mean alpha angle of 27.8°.

4 ANALYSIS AND RESULTS

4.1 Alpha – Beta Runout Model

Lied and Bakkehöi (1980) and McClung and Mears (1991) found that β was the only significant predictor variable for paths with over 300 m vertical fall height. Under this assumption, the avalanche path data from the Columbia Mountains was analyzed using the least squares regression method to obtain a model of the form:

$$\alpha = C_o\beta + C_1 \quad [2]$$

with α and β in degrees and the coefficients C_o and C_1 obtained by regressing α on β. Results are shown Figure 3 and summarized along with the model parameters for other Canadian Mountain ranges in Table 3.

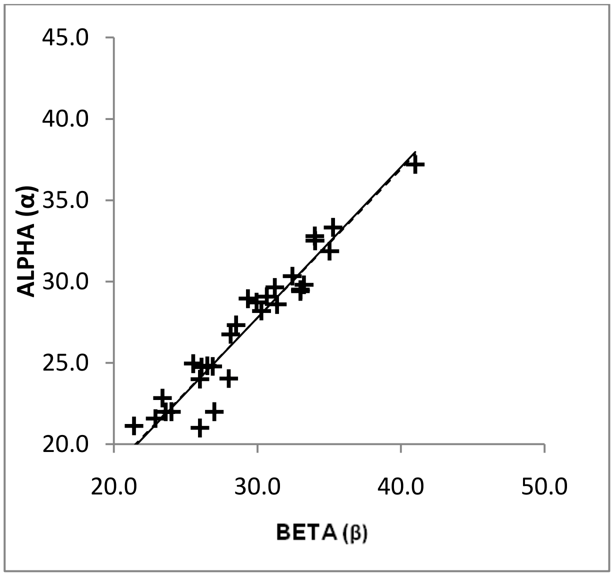

Figure 3. Linear regression following Equation 2 using alpha and beta points measured from 31 avalanche paths located in the Columbia Mountains, British Columbia, Canada.

The resulting formula is shown below:

$$\alpha = 0.91\beta^\circ + 0.34 \ (n = 31, R^2 = 0.92, s = 1.2^\circ) \qquad [3]$$

Where R^2 is the coefficient of determination and s is the standard error of estimation. If we force the regression model through the origin ($C_1 = 0$), we obtain the following simplified formula:

$$\alpha = 0.92\beta^\circ \ (n = 31, R^2 = 0.92, s = 1.2^\circ) \qquad [4]$$

Table 3. Summary of Statistical Model Parameters for Canadian Mountain Ranges.

Area	Alpha Beta					Runout Ratio					Reference
	C_0	C_1	R^2	SE °	n	u	b	R^2	SE	n	
Columbia Mountains (uncensored)	0.91	0.34	0.92	1.2	31	0.113	0.010	0.97	0.016	31	this study
Columbia Mountains (runout ratio censored, C_1 = 0)	0.92	-	0.92	1.2	31	0.048	0.177	0.87	0.016	19	this study
Coast Mountains	0.90	-	0.74	1.70	31	0.096	0.092	0.96	0.021	20	Nixon and McClung, 1993
Rocky and Purcell Mountains (uncensored)	0.93	-	0.75	1.75	126	0.079	0.070	0.98	0.012		McClung and Mears, 1991
Rocky and Purcell Mountains (runout ratio censored)	-	-	-	-	-	0.092	0.065	0.97	0.012	53	McClung et al., 1989
Columbia Mountains	0.93	-	0.89	1.10	35	-	-	-	-	-	Delparte et al., 2008
Canadian Short Slopes (*H* < 350 m)	-	-	-	-	-	0.494	0.441	0.98	0.080	46	Jones and Jamieson, 2004

4.2 Runout Ratio Model

To derive parameters for the runout ratio method, the data from the Columbia Mountains were analyzed using extreme values statistics by fitting a dimensionless runout ratio ($\Delta x/X_\beta$) to a Gumbel distribution after McClung and Mears (1991). The least-squares fit to the data takes the form:

$$x_p = u + b(-\ln(-\ln(P)) \quad [5]$$

In the above equation, –ln(-ln(P)) is the "reduced variate", u and b are location and scale parameters, and P is a chosen non-exceedence probability between 0 and 1, which represents the proportion of paths in the dataset with runout ratios not exceeding x_p . A fit of the runout ratio to the Gumbel distribution for the 31 avalanche paths in the Columbia Mountains is shown in Figure 4 and included below:

X_p=0.113+0.100(-ln(-ln(P)) (R^2=0.97,s=0.014,n=31) [6]

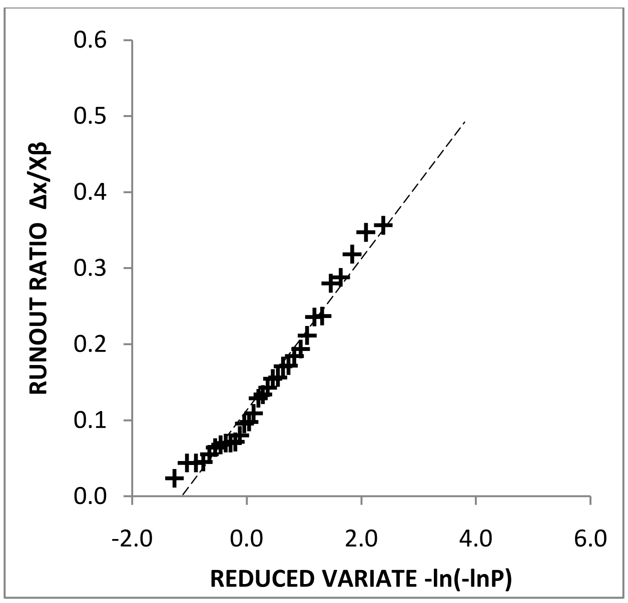

Figure 4. Runout Ratio (Gumbel) Distribution for Columbia Mountains (uncensored, n = 31).

If we censor the dataset as shown on Figure 5 to exclude values below P = e^{-1} we get slightly different parameters:

X_p=0.097+0.115(-ln(-ln(P)) (R^2=0.99,s=0.014,n=19) [7]

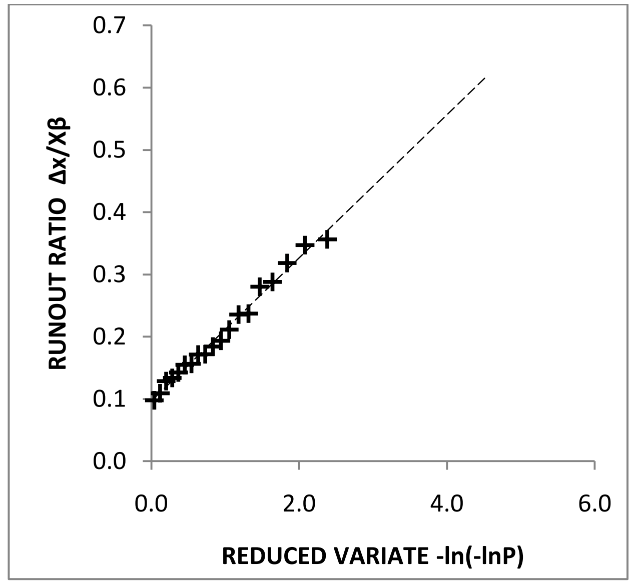

Figure 5. Runout Ratio (Gumbel) Distribution for Columbia Mountains (censored below P = e^{-1}, n = 19).

Censoring the dataset below P = e^{-1} effectively removes the shorter running avalanches from the dataset and provides a better fit to the higher values of the runout ratio, building additional conservatism into the estimated runout. Although the censored sample size of n=19 is less than n=30 which is typically considered a representative sample size for developing these models, this censored dataset may still provide a useful comparison for estimating extreme runout positions since the influence of long running paths is increased.

5 DISCUSSION

In the previous section, avalanche runout models were developed using two different methods: the α– β regression and runout ratio method. These parameters can be used for estimating extreme avalanche runout in the Columbia Mountains.

The simplified α – β method yields a good fit to the avalanche path data for the Columbia Mountains and can be used to estimate extreme avalanche runout for typical avalanche paths in this range with unknown extreme runout (α) points. The α - β method is known to be more sensitive to δ which is the average slope in the runout zone between the β-point and the α-point. The runout ratio method is generally more suited to paths with a component of uphill runout since it estimates extreme avalanche runout independent of the runout zone slope angle.

Delparte et al. (2008) developed an α – β model for the Columbia mountains using avalanche path profiles obtained from high and low resolution digital elevations models (DEMs) along with avalanche runout observations recorded during a 40 year period in Glacier National Park. Comparing the models developed by Delparte et al. (2008) to the models derived from our dataset (Table 3) shows that α angles calculated using the α – β relationships presented in this study are smaller than the α angles calculated using the results of Delparte et al. (2008). The smaller α angle calculated from our results will result in a longer runout distance than the formula presented by Delparte et al. (2008). This is consistent with the fact that Delparte et al. (2008) used avalanche runout observed during a 40 year observation period, while the runout positions typically identified from observations of vegetative damage in western Canada are on the order of 50 – 300 years (McClung and Mears 1991).

The models presented in this paper were developed using "typical" avalanche paths from the Columbia Mountains. This excluded paths with significant uphill runout (such as those found in very narrow valleys) or paths with a high degree of channelization in the track and/or runout zone and included paths which were not significantly channelized or without significant uphill runout. Paths with uphill runout will usually have a smaller Δx than paths with no uphill runout, and paths which are channelized in the track or runout zone will typically run further than paths without confinement. Caution must be exercised when applying these runout models to atypical paths.

6 CONCLUSIONS

This paper presents α – β and runout ratio model parameters specific to avalanche paths in the Canadian Columbia Mountains which were developed using a dataset of 31 avalanche paths from the Monashee, Cariboo and Selkirk Mountains. Runout ratio parameters were derived for the full dataset and also for a censored dataset. The censored runout ratio parameters were derived using the data from the longer running avalanches in the Columbia Mountains which builds some conservatism into runout estimates obtained using these models. With careful consideration of the limitations of this study and of statistical runout estimation, these parameters can be used by experienced avalanche mapping professionals to estimate extreme avalanche runout for typical avalanche paths in this mountain range with vertical drops over 350 m. Future work on this project will involve incorporating precipitation data into this analysis to explore the relationship between extreme avalanche runout and snowfall.

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