A SYSTEMATIC APPROACH TO ESTIMATING THE 300-YEAR RUNOUT FOR DENSE SNOW AVALANCHES

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Abstract: For residential zoning near a snow avalanche path in Canada, three zones are usually identified: Red (no new construction), Blue (restricted development) and White (unrestricted development). The Red-Blue boundary depends partly on the runout from a 300-year dense snow avalanche. This runout is estimated along the centerline of the path using up to four sources: historical records, trim lines in vegetation, statistical runout models, and dynamic runout models. The confidence in the estimated runout distance and return period for these sources vary. For example, the extreme runout position in a forested path can often be identified with high confidence based on obvious trim lines, however, even if the date of the last extreme event was known (e.g. 60 – 63 years ago), the confidence in the return period is low when it is based on a single event only. Traditionally, these estimates with different levels of confidence and return periods are combined with the consultant's expert knowledge. In the proposed approach McClung's (2000) recently validated Space-Time model is used to adjust the statistical runout estimate to a 300-year runout. The other runout estimates are extrapolated to 300-years with expert knowledge. The 300-year runout for a dense flow avalanche is then calculated as a confidence-weighted average. To compensate for high uncertainty, sometimes because runout estimates from less than four sources are available, the red-blue boundary can be extended down the path. An example is presented to illustrate the proposed method.

1 INTRODUCTION

Snow avalanches can threaten people and property wherever there are sufficient snow and slopes. For recreation and some worksites, the short term hazard or risk is often mitigated with operational measures (e.g. McClung and Schaerer 2006). The long term hazard or risk is often identified on maps, and mitigated with a variety of operational measures such as explosive triggering, as well as static measures including prescriptive zoning and earthworks.

There are various applications for snow avalanche hazard zoning, including residential areas (e.g. McClung and Schaerer 2006). In Switzerland, Canada and some other countries, hazard zones from snow avalanches are defined in terms of impact pressure and return period (Bründl and Margreth 2015). While Switzerland has four residential zones, labelled Red, Blue, Yellow and White, the Canadian Avalanche Association (2002) guidelines specify three zones for residential areas: Red (no new construction), Blue (restricted development) and White (unrestricted development) (Figures 1 and 2).

The Red-Blue line in Figure 2 represents varying combinations of return period and impact pressure. In practice the following three scenarios, marked as [1], [2] and [3] in Figure 2, are considered:

1. Any avalanche with a 30-year return period, regardless of its impact pressure
2. A 100-year avalanche with an impact pressure of 10 kPa
3. A 300-year avalanche with an impact pressure of 30 kPa.

While Figure 2 shows a continuous Red-Blue criterion for return periods between 30 and 300 years, Mears (1992, p. 38) points out that, in practice, only a 100 year avalanche scenario can be distinguished within this range.

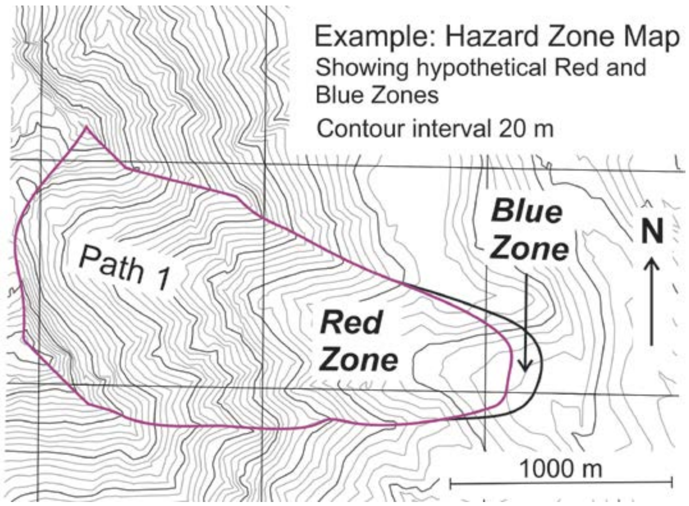

Figure 1: Example of a hazard map for occupied structures. Modified from Canadian Avalanche Association (2002) with permission.

The first and third scenarios are the same in the Canadian (CAA 2002) and Swiss Guidelines (BFF and SLF, 1984). The most conservative scenario (farthest downslope) of the three determines the Red-Blue boundary in a particular avalanche path. In many paths, the third scenario — 300-year impact pressure of 30 kPa — determines the boundary. Since dry snow avalanches typically run farther than wet avalanches, the 300-year dry snow avalanche is frequently the design avalanche for residential zoning. The point at which the impact pressure of the design avalanche is reduced to 30 kPa is obtained from a dynamic model of avalanche motion (e.g. Christen et al. 2002, ramms.slf.ch).

In North America, the dynamic model of the design avalanche is fitted to the 300-year runout, which is based on four sources/methods (e.g. CAA 2002, Bründl and Margreth 2015):

1. Vegetation damage identified in historical air photos, satellite imagery and field studies. Where avalanches run out in forests, the trim line farthest down the path typically represents an extreme avalanche within the previous 80 years (e.g. Mears 1992, Reardon et al. 2008, Luckman 2010)
2. Human records of long running avalanches
3. Statistical models of extreme runout based on paths in the same range (e.g. Lied and Bakkehøi 1980, McClung et al. 1989)
4. Dynamic models of extreme avalanches (e.g. Christen et al. 2002, Jamieson et al. 2008, ramms.slf.ch).

The typical confidence in the runout from these sources or methods varies between North America and Western Europe as shown in Table 1. The human records of extreme runout are often very good in the populated mountain valleys of Western Europe and very limited in the areas proposed for development in Canada. The runout predicted by dynamic models depends strongly on the release mass and friction coefficients. In Europe, slab depth has been calibrated by region and return period (SLF, 2005), and for the RAMMS model the friction coefficients have been well calibrated based on elevation, slope angle, slope curvature, flow volume and return period (SLF, 2013). In North America, given the sparse data over large and varied geography, the calibration of friction coefficients by such factors is usually lacking and hence confidence in extreme runout predicted by dynamic models is poor. Table 1 summarizes the typical return periods (T) and confidence associated with the four methods in Western Europe and North America.

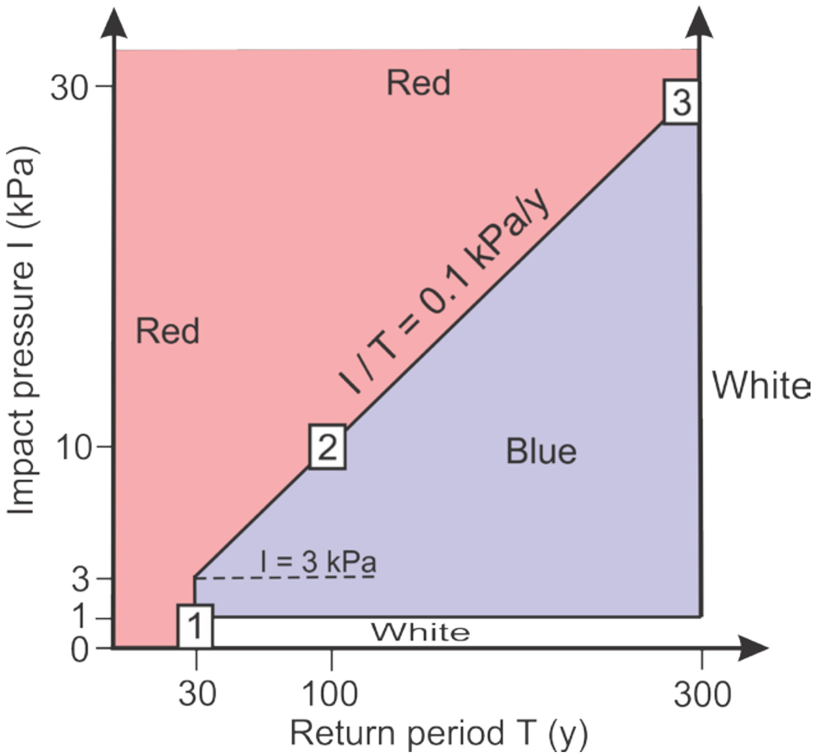

Figure 2: Snow avalanche hazard zoning for occupied structures as recommended by Canadian Avalanche Association (2002). Reproduced with permission of the Canadian Avalanche Association. Avalanches contained in the red zone include: i) any avalanche with a return period of less than 30 years [as marked by box 1]; ii) any avalanche with a return period (years) of less than 10 times the impact pressure (kPa) [box 2]; or iii) any avalanche with impact pressure of greater than 30 kPa and return period less than 300 years [box 3].

The general ratings of confidence (good, fair, poor) in Table 1 often do not apply to specific paths. For example, where avalanche paths runout onto land that was cleared for grazing or agriculture many decades previously, the confidence in the runout based on vegetation damage is poor at best. Also, north of the treeline in Canada, vegetation records of avalanches do not exist and statistical models are limited to Jones and Jamieson (2004), which only applies to short slopes and was not validated for paths north of the treeline. Further, when a path differs from those used to calibrate a statistical or dynamic model, uncertainty in the predicted runout increases and confidence decreases (Margreth 2014).

For each of the four methods in Table 1, Figure 3 shows the runout estimates along the centerline of a hypothetical path. Runout estimates from more than one dynamic model and more than one statistical model can be applied. In this example, one estimate from a dynamic model and two from statistical models are shown. For statistical runout models, the α–β model (e.g. Lied and Bakkehøi 1980) and runout ratio models (e.g. McClung et al. 1989) are in common use in North America. Both these statistical runout models estimate an extreme runout past the β point, which is where the slope decreases to 10° while descending along the centerline of a path.

Table 1: Typical time scale and confidence for various methods used to estimate extreme runout

Method	Western Europe		North America	
	Confidence in runout	Time scale	Confidence in runout	Time scale
Human records	Good	T ~ 50 to 300 years	Poor	< 30 years previous [a, b]
Vegetation damage (trim line farthest down the path)	Good	< 100 years previous	Good	< 100 years previous [b]
Statistical models	Poor	T ~ 30 to 100 years	Fair	T ~ 30 to 100 years
Dynamic models	Fair	T ~ 100 to 300 years	Poor	T ~100 years

[a] Hazard mapping is often required where human records or extreme avalanche runout are limited or absent.
[b] In North America, a large avalanche near a developed area in the previous year has often prompted hazard zoning.

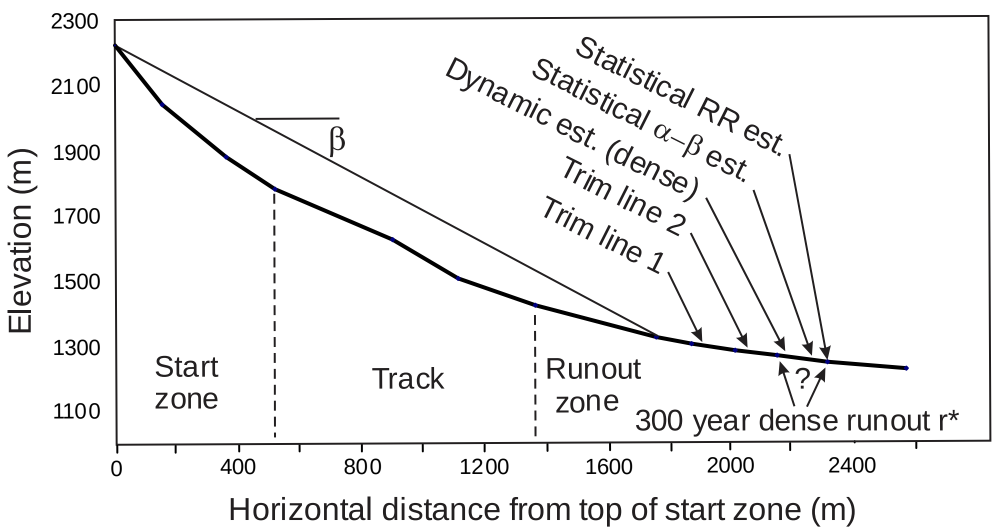

Figure 3: Hypothetical example of runout estimates from three different methods along the centreline of an avalanche path: vegetation damage, dynamic models and statistical models for dense flow avalanches. These estimates must be combined to estimate the 300-year runout from a dense flow avalanche r*, as indicated by the question mark.

Traditionally, the runout estimates from the methods listed in Table 1 and presented as an example in Figure 3 have been combined based on the consultant's expert knowledge (e.g. Margreth and Gruber 1998, CAA 2002; Rudolf-Miklau et al. 2015). Barbolini and Keylock (2002) proposed a method for combining statistical and dynamic models. We are unaware of any published method of combining the estimates from the different methods, including trim lines in vegetation and historical records, to determine the 300-year dense flow runout, r*. However, some consultants have stated that they consider the confidence in the various estimates, and Jamieson (2001, unpublished) proposed a table in which confidence in each method is explicitly stated. A simplified version of this table including only methods appropriate to dense flow runout is shown in Table 2. Note that the confidence ratings in Table 2 are for a specific path, whereas Table 1 shows typical confidence ratings for Western Europe or North America.

Table 2: Confidence in runout estimates along centre-of-flow of Path A

Estimation method	Horizontal distance past β point (m) [a]	Confidence in runout	Time scale: Return period or time elapsed (years)	Confidence in time scale
Historical record				
Forest damage from field survey and air photos				
Statistical α–β model [b]				
Statistical Runout Ratio model [b]				
Dynamic model for dense flow with friction coefficients				
Combined result				
300-year dense flow runout	r*	good	300 y	good

[a] Any reference point near the runout zone can be used. The β-point where the slope angle decreases to 10° while descending the path (e.g. Lied and Bakkehøi 1980), is often suitable.
[b] to be conservative, especially for paths expected to run relatively longer than other paths used to calibrate the model parameters, a non-exceedance probability > 0.5 can be applied.

While Table 2 has the advantage of requiring the user to explicitly rate confidence (or conversely, rate uncertainty), it does not outline

1. how the runout estimates are to be combined based on levels of confidence
2. how runout estimates with different return periods or time scales are to be combined. Note that the time scales for a specific path (e.g. Table 2) are much more variable than the typical values in Table 1.

In this paper, we describe a more systematic and more transparent approach to combining the runout estimates from different methods. First, each runout estimate is extrapolated to a 300-year runout. This is done based on expert knowledge (e.g. Peck 1980), except for the statistical runout-ratio estimate, which is extrapolated based on McClung's (2000) Space-Time model. Second, a numerical weight is assigned to each estimate according to the confidence in the estimate, and a confidence-weighted average runout is calculated.

2 SPACE-TIME MODEL

McClung (2000) developed the Space-Time model for extreme avalanche runout, which can calculate the runout for a specified return period, or the return period for a specified runout. The runout is described by a dimensionless runout ratio, rr, given by the ratio of the horizontal runout past the β point, ΔX, to the horizontal distance from the top of the start zone to the β point, X_β (e.g. McClung et al. 1989). The model uses Gumbel parameters from the mountain range to relate runout to return periods within a specific path. The model requires that the return period, T_0, be known at a reference point in the path, where T_0 is the reciprocal of the Poisson mean annual arrival rate at the reference point. Following

McClung (2000), the non-exceedance probability at a point with runout ratio, rr_1, given the arrival rate $1/T_0$ at the reference point, is

[1] $$P(rr \leq rr_1 | \mu = 1/T_0) = \exp\left\{\left[\left(\exp\left(-\exp\left(\frac{u - rr_1}{b}\right)\right)\right) - 1\right] / T_0\right\}$$

where *u* and *b* are the Gumbel parameters for the range (e.g. McClung et al. 1989). In Eq. 1, the reference point is the β point. McClung (2000) and Sinickas (2013) show how to apply Eq. 1 where the return period is known at a reference point other than the β point.

The return interval, T_1, at a point with known runout ratio, rr_1, is the reciprocal of the arrival rate (exceedance probability), which is the complement of the non-exceedance probability on the left hand side of Eq. 1.

Solving Eq. 1 for rr_1 yields

[2] $$rr_1 = u - b\ \ln[-\ln(T_0 \ln(1 - 1/T_1) + 1)]$$

Using T_1 = 300 y, Eq. 2 yields the 300-year runout ratio given the return period, T_0, at the β point.

McClung (2000) validated the model for one Norwegian path in which the 1000-year runout was known. Sinickas (2013) validated the model using 34 paths in western Canada where the runout was estimated based on vegetative damage for return periods mostly between 5 and 300 years. For these paths and return periods, Sinickas (2013) found the model tended to overestimate runout.

3 CONFIDENCE-WEIGHTED AVERAGING OF EXTREME AVALANCHE RUNOUT

A weight, w_i, for each estimate i ≥ 1 such that $\sum w_i = 1$, are assigned based on the hazard mapper's confidence in each runout estimate (after adjusting to 300-year return periods), r_i. These are then combined to yield the confidence-weighted average runout, r*.

[3] $$r^* = \sum_i w_i r_i$$

4 WORKED EXAMPLE

For hypothetical Path A, horizontal runout estimates for each method based on Figure 2 are shown in Table 3 Column 2 along with the associated time scale (Column 4), which is either the return period for the model estimates, or commonly, the elapsed time for the historical record. The confidence levels associated with the runout (Column 3), and with the time scale (Column 5) are also shown.

The 300-year runouts in Column 6 are estimated as follows:

- For the Runout Ratio model, the 300-year runout is estimated with Eq. 2. In this example, the 300-y runout estimate is 30 m past the unadjusted estimate. (As mentioned in Section 1, statistical model estimates may include non-exceedance probabilities > 0.5.)
- For the dynamic model, the initial estimate may be extrapolated for a 300-year runout. Or the release area and friction coefficient parameters may be chosen conservatively to favour extreme runout distances.

- For the other methods, the 300-year runouts are estimated based on Columns 2 to 5 using expert knowledge.

The conservativeness of the chosen parameters and non-exceedance probability will influence the associated confidence in runout estimates and in the weights.

Table 3: Runout estimates along centreline of Path A and confidence levels

1	2	3	4	5	6	7
Estimation method	Horizontal distance past β point (m) [a]	Confi-dence in runout	Time scale: Return period or time elapsed (years)	Confi-dence in time scale	Horizontal distance past β point (m) (300-year)	Weight w_i
Historical record	~	none	~	none	~	0
Forest damage from field survey and air photos	145 (Trim Line 1)	Good	47-31	Good	450	0.45
	380 (Trim Line 2)	Good	67-80	Good		
Statistical α–β model [b]	490	Fair	30 to 100	Good	520	0.20
Statistical Runout Ratio model [b]	515	Fair	30 to 100	Good	550	0.20
Dynamic model for dense flow with friction coefficients	410	Poor	~100	Fair	440	0.15
Weighted average 300-year dense flow runout					483	1

[a] Any reference point near the runout zone can be used. The β-point (e.g. Lied and Bakkehøi 1980), where the slope angle decreases to 10°, is often suitable.
[b] to be conservative, especially for paths expected to run relatively longer than other paths used to calibrate the model parameters, a non-exceedance probability > 0.5 can be applied.

In Column 7, numerical weights for the 300-year runout estimates are assigned based primarily on the confidence ratings in Columns 3 and 5. The weight for the two statistical runout estimates, each with fair confidence in the runout, is divided between the two estimates. Using Eq. 3, the weighted average 300-year runout for dense flow avalanches, r*, is calculated to be 483 m past the β point.

This confidence-weighted runout estimate is for the 300-year dense flow avalanche, which influences the Red-Blue Hazard Line as explained in Section 1. Potentially, the Red-Blue Line may be upslope of the 300-year dense flow runout to allow for deceleration below 30 kPa. However, the Red-Blue Hazard Line may also be past the 300-year dense flow runout to allow for limited confidence in the various estimates, especially when only one or two method-based estimates are available.

5 SUMMARY

In Canada and some other countries, the 300-year runout from dense flow avalanches influences the Red-Blue hazard line for occupied structures. This 300-year runout is typically based on estimates from four distinct methods: human records, vegetation damage, statistical models and dynamic models. We have proposed a systematic approach for combining the estimates, in which the statistical runout is extrapolated to a 300-year return period with McClung's (2000) Space-Time model. The other estimates are extrapolated to the same return period using expert knowledge. Numerical weights based on confidence are assigned to each of the 300-year runout estimates and a confidence weighted average for the 300-year dense flow runout is calculated. Factors that commonly influence the confidence levels are briefly reviewed.

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