TOWARDS AN OPERATIONAL AVALANCHE FORECASTING TOOL USING RAMMS::EXTENDED

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ABSTRACT: Recent advances in remote sensing enable real-time estimation of snow depth in avalanche starting zones. An emerging opportunity for avalanche forecasting is the incorporation of these data with avalanche simulations to estimate the potential avalanche runout distance for a given release volume. This could help predict whether it is possible for avalanches to reach a specific element at risk with the current conditions. Recent studies have explored the potential for RAMMS::Extended simulations, initialized with measured or modelled snowpack and weather data, to forecast avalanche runout distances. While these approaches are promising, they require further research into the appropriate model parametrization to accurately simulate non-extreme events before they can be broadly implemented as a predictive tool.

Avalanche Path 51 is located on Highway 99 (i.e., Duffey Lake Road), approximately 85 km northeast of Whistler, Canada, in the Coast Mountains of southwestern British Columbia. It is the most active avalanche path along this corridor with an average of three events per year reaching the road. It has a highly channelized 1100 m long track that results in unique avalanche dynamics, with relatively low release volumes of often less than 5000 m^3 running the full length of the path. Combined with a 46-year record of approximately 1500 avalanche observations, these physical characteristics make Path 51 a strong candidate for exploring RAMMS::Extended parameterization for non-extreme event simulation.

This paper provides some promising initial results from fitting RAMMS::Extended simulations to observed late-season low-volume avalanches in Path 51. The results are intended to support the development of a forecasting tool that estimates runout distances based on measurable parameters such as release volume, snow temperature, and air temperature.

KEYWORDS: Release volume; runout distance; RAMMS::Extended; model parameters; avalanche forecasting

1 INTRODUCTION

Determining the end of avalanche season is often a difficult decision that avalanche forecasters face. These decisions typically hinge on estimations of potential avalanche runout extent given the amount and structure of snow in the starting zones (i.e., potential release volume), the condition of the track (e.g., smooth or rough), and the avalanche flow regime (e.g., dry or wet).

Dynamic numerical avalanche simulations, such as RAMMS (Rapid Mass Movement Simulation; Christen et al., 2010) are commonly used in planning stage risk assessments to model extreme magnitudes for long return-period avalanches (Canadian Avalanche Association, 2016). However, these models have seen limited use as a predictive tool for operational risk assessments. This limitation stems from model sensitivity to input variations, which have historically been calibrated against extreme avalanche events (Buser & Frutiger, 1980); the use of snow-free topography as a sliding surface (Bühler et al., 2011); and challenges in accurately initializing simulations because release volume, entrainment, and snow temperature all affect runout extent (Vera Valero et al., 2015).

For this study, we use RAMMS::Extended (Bartelt & Christen, 2025) to perform a sensitivity analysis of measurable flow regime parameters (e.g., snow temperature, air temperature, erodible snow depth, and water content) to explain variations in runout extent for a given release volume in an avalanche path with smooth track conditions.

1.1 Study Site

Path 51 is the most active path on Highway 99 in the Coast Mountains of British Columbia, Canada (Figure 1), with an average of three avalanches reaching the highway annually over the past 47 years of record keeping (i.e., 1979-2026). It's broad alpine starting zone (1700–2300 m elevation; Figure 2) feeds into a highly channelized (20-50 m wide) 1000 m long track that descends to Duffey Lake at 1000 m (Figure 3). The highway intersects the path near the middle of the of the

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runout zone approximately 75 m below the 10° beta-point (Figures 1 & 4).

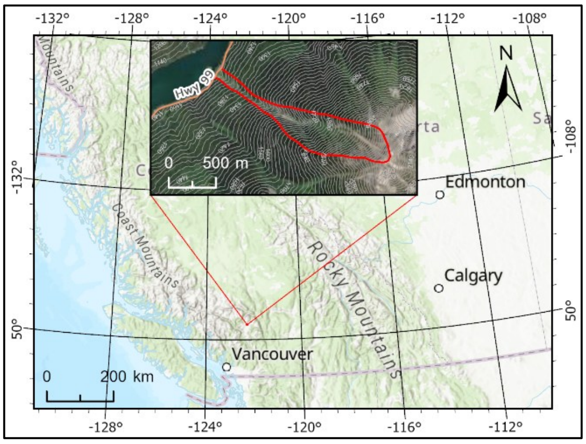


Figure 1: Path 51 is located approximately 150 km northeast of Vancouver in southwestern British Columbia.

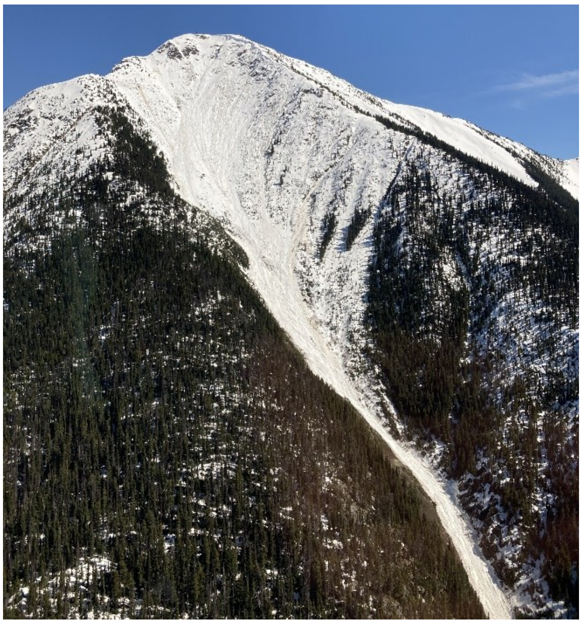
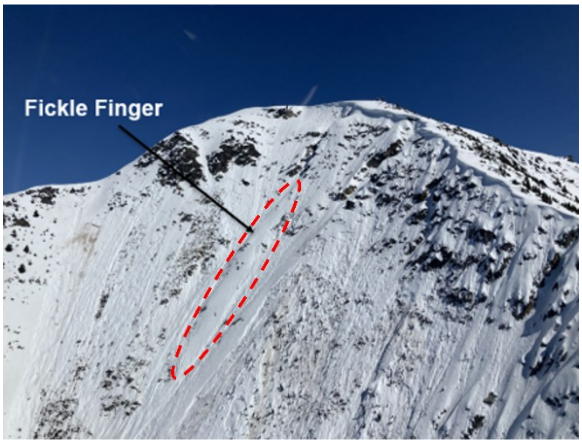


Figure 2: Photo of Path 51 showing the large alpine starting zone that funnels into a long and narrow track (Photo credit: MoTT).

Figure 3: Photograph of the track showing a deeply incised gully with bedrock-lined walls and ~1000 m of vertical relief to Duffey Lake below (Photo credit: MoTT).

Figure 4: Photo of avalanche deposit in the runout zone of Path 51 and highway (black dashed line) in the runout zone (Photo credit: MoTT).

The path is monitored and controlled by full-time Ministry of Transportation and Transit (MoTT) avalanche forecasters with the aid of a GazEx system installed in 1992. “Fickle Finger” is an aptly named release area in the lower starting zone that typically does not release with avalanches flowing from above and has a history of producing post-control natural avalanches that reach the highway (Figure 4). It is a relatively small release area (< 5000 m^2) compared to the ~100,000 m^2 starting zone area.



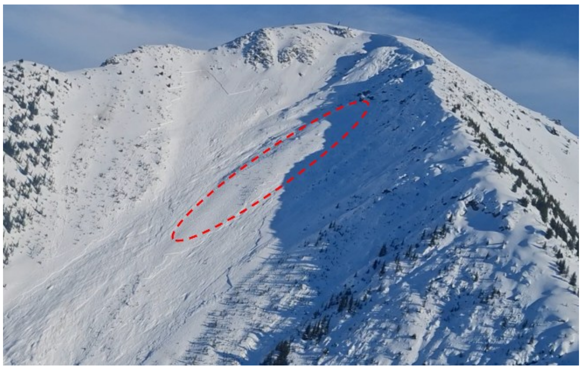


Figure 5: Photos of the Path 51 starting zone after two different explosives-control missions, showing the Fickle Finger release area (red outlined area) that did not release (Photo credit: MoTT).

1.2 Previous Research

Several studies (e.g., Dillon & Hammonds, 2021; Glaus et al., 2025; Stoffel et al., 2018; Vera Valero et al., 2016, 2018) have demonstrated that RAMMS::Extended, when initialized with measured or modelled snowpack and weather data, can capture runout distances under varying flow regimes. While these approaches are promising, they require further research into the appropriate model parametrization to accurately simulate non-extreme events before they can be broadly implemented as a predictive tool.

Campbell et al. (2024) found a weak correlation between release volume and runout distance for Path 51, with relatively low release volumes of less than 5000 m^3 often reaching the highway. They examined dynamic friction parameters to explain variations in the relationship between release volume and runout distance for low-volume end-of-season avalanches and found that friction coefficients (μ) ranging from 0.100 to 0.430, corresponding to different track conditions, can explain these variations. However, discussions with MoTT avalanche forecasters indicated that avalanche flow regime also plays a critical role in whether low-volume late-season avalanches reach the road. These avalanches have a dense, wet snow, plug-like flow, with little volume increase in the track (i.e., smooth icy track), similar to those analyzed by Vera Valero et al. (2016).

Building on this work, this study examines how erosion depth, snow temperature, air temperature, and water content affect simulated runout in Path 51, to evaluate their potential as forecasting parameters.

2 METHODS

In keeping with previous studies (e.g., Glaus et al., 2024), we started with a sensitivity analysis of RAMMS input parameters with a constant release volume. We ran 224 RAMMS::Extended simulations for Path 51 to test the sensitivity of runout distance to measurable flow parameters. We chose to vary parameters that can be either measured, or reasonably estimated in real-time, and that can be associated with wet spring avalanches. The range of values were chosen based on the local snow climate and resulting simulated runouts coming within the vicinity of the road.

Simulations were initialized with release conditions based on observed Fickle Finger avalanches and use a snow-covered 2 m DEM acquired in mid-April, 2025. Erosion depth, snow temperature, snow temperature gradient, water content gradient, and air temperature were varied in stepwise fashion across realistic ranges as specified in Table 1. All other model inputs were based on observations of avalanches releasing from Fickle Finger and followed Bartelt & Christen (2025) recommendations and prior studies (e.g., Vera Valero et al., 2016, 2018) as specified in Table 2. The resulting runout distance was calculated relative to the highway, with negative values indicating simulations that stopped above the road.

Table 1: RAMMS::Extended parameters with range of values used for the sensitivity analysis.

Parameter	***Values Used***
Erosion depth - d_0* (m)	0 to 1
Snow temperature (°C)	0 to -4
Snow temperature gradient - ΔT (°C/100 m)	0 to 0.4
Water content gradient - ΔW (%/100 m)	0.04 to 0.52
Air temperature (°C)	5 or 10

Table 2: Fixed RAMMS::Extended parameters used for the sensitivity analysis.

Parameter	*Value Used*	*Comments*
Release Area (m^2)	3791	From occurrence records of late-season avalanches from Fickle Finger.
Release Depth – d_0 (m)	1.9	From occurrence records of late-season avalanches from Fickle Finger.
Return Period (years)	10	Friction parameters associated with the lowest return period simulation possible with RAMMS::Extended
Size	S	Default RAMMS::Extended size classification based on release volume.
Curvature	On	As per Bartelt & Christen (2025)
Erosion Depth Gradient - Δd_0* (m/100m)	0.03	As per Bartelt & Christen (2025)
Water Content (%)	0	Assumed based on initial snow temperature
Release Density (kg/m^3)	250	Based on regional snow survey data.
Deposit Density (kg/m^3)	450	Assumed based on experience
Front Splash	0.2	As per Bartelt & Christen (2025)
Yield Stress (Pa)	300	Recommended value as per Bartelt & Christen (2025)
Erosion Density (kg/m^3)	200	Assumed based on experience with local snowpack properties.
3-day/Variable/Constant	Var	As per Bartelt & Christen (2025)
Type	Flowing	As per late season moist-wet avalanches
Generate (%)	5	As per Bartelt & Christen (2025)
μ (Mu wet)	0.12	As per Vera Valero et al. (2016)
Dry-wet Transition (mm)	100	As per Bartelt & Christen (2025)

3 RESULTS AND DISCUSSION

First, it must be acknowledged that RAMMS was developed as a planning tool to simulate extreme avalanches with longer return periods, but using it to simulate annual, or more frequent avalanche events, for operational forecasting is not a new concept. It’s also important to note that RAMMS::Extended was originally designed for cold-temperature, powder avalanche simulations. It has been adapted to wet-snow and water content, but calibration data are still sparse. With that in mind, we present the following preliminary results that show important trends for simulated avalanches that run out within 25 m of the road.

We also present our physical understanding of the effect of the tested parameters on the runout extent of simulated avalanches. However, in most cases there are likely competing processes that contribute to the simulation results, which have not been studied in isolation.

3.1 Erosion Depth

Erosion depth emerged as the most dominant parameter affecting runout distance. Figure 6 shows runout distance ranging from -23 m to 16 m for an erosion depth ranging from 0.6 to 1.0. Runout distance increases with erosion depth due to the additional entrained mass added to the avalanche flow width. Furthermore, simulations initiated with erosion depths shallower than 0.4 m consistently stopped well above the highway with any realistic water content gradient. However, future studies will focus on simulations with less erodible snow but higher initial water contents to test the scenario with a smooth icy track.

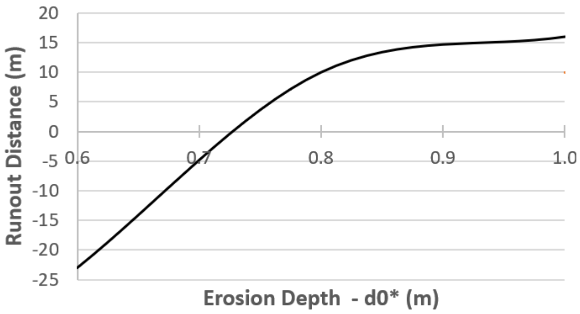


Figure 6: Runout distance relative to the road (i.e., negative values are above the road) versus erosion depth for a snow temperature of -4 °C, a snow temperature gradient of 0 °C/100 m, a water content gradient of 0.1 %/100m, and an air temperature of 10 °C.

3.2 Snow Temperature and Gradient

Initial snow temperature also had a significant effect on runout distance. Figure 7 shows runout distance ranging from -10 m to 10 m for initial snow temperatures ranging from -4 °C to 0 °C. Runout distance decreased significantly with an increase in initial snow temperature from -4 °C to -2 °C, only to increase slightly as the initial snow temperature warmed from -2 °C to 0 °C. We understand that this is because there is some water being generated with snow temperatures between −4 °C and −2 °C, but not enough to offset the increase in “stickiness” represented by decreasing turbulence. Between −2 °C and 0 °C, however, the system flips: water production becomes significant, basal friction drops, and runouts lengthen. Although this is a consistent model result, we can’t say with confidence whether it matches reality since there is a lack of field data to support this. However, snow temperature is a critical factor in the formation of snow granules during avalanches and -1 °C is an important threshold for granule formation (Steinkogler et al., 2015).

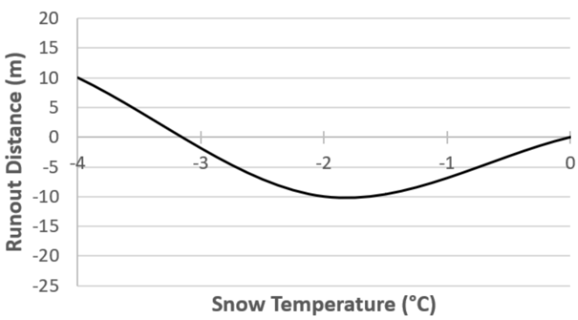


Figure 7: Runout distance relative to the road versus initial snow temperature for an erosion depth of 0.8 m, a snow temperature gradient of 0 °C/100 m, a water content gradient of 0.1%/100 m, and an air temperature of 10 °C.

Runout distance decreased with increasing snow temperature gradient for simulations initiated with a snow temperature of –4 °C. Figure 8 shows runout distance decreasing from 4 m to -4 m (i.e., stopping above the road) for an increase in snow temperature gradient from 0 °C/100 m (i.e., no gradient) to 0.4 °C/100 m (i.e., snow temperature reaches 0 °C in the runout zone of the 1000 m path). This effect is likely caused by similar mechanisms to what was observed for cooler initial snow temperatures.

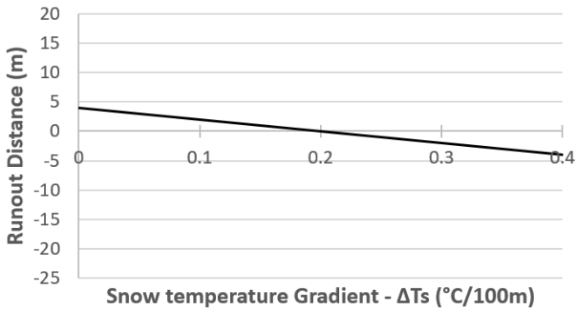


Figure 8: Runout distance relative to the road versus snow temperature gradient with elevation for an initial snow temperature of -4 °C, an erosion depth of 0.6 m, a water content gradient of 0.16 %/100 m, and an air temperature of 10 °C.

3.3 Water Content Gradient

The dependency of runout distance on water content gradient proved to be one of the more interesting results of this study. Figures 9 and 10 show increasing runout distance with increasing water content gradient. Our understanding is that this is due to decreased basal friction with increased water content, which starts with a sharp reduction in friction with the introduction of water, then the effect tapers as the flow becomes wetter, eventually saturating at the specified wet basal friction input parameter (i.e., 0.12). The turbulence coefficient also decreases with water content which contributes to longer runouts for wetter snow, even if velocities are reduced.

However, the water content gradient required for simulated avalanches to run out within 25 m of the road depends heavily on erosion depth. Figure 9 shows that for an erosion depth of 1.0 m, runout distance increases from -13 m to 15 m as water content gradient increases from 0.04 %/100 m to 0.10 %/100 m. While Figure 10 shows that for a much shallower erosion depth of 0.4 m, runout distance increases from -15 m to 2 m as water content gradient increases from 0.4 %/100 m to 0.52 %/100 m (which results in quite a high water content).

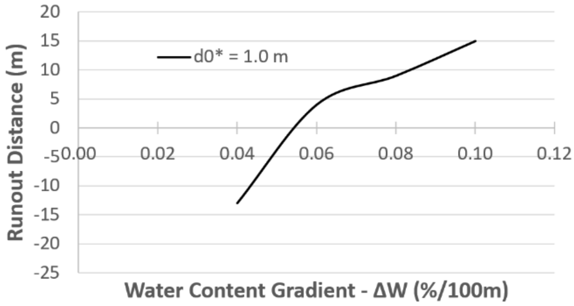


Figure 9: Runout distance relative to the road versus water content gradient for an erosion depth (d0*) of 1.0 m, an initial snow temperature of -4 °C, a snow temperature gradient of 0.4 °C/100 m, and an air temperature of 10 °C.

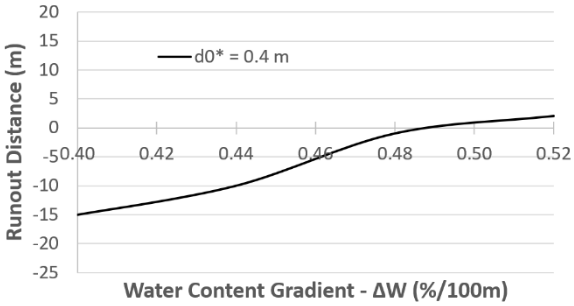


Figure 10: Runout distance relative to the road versus water content gradient for an erosion depth (d0*) of 0.4 m, an initial snow temperature of -4 °C, a snow temperature gradient of 0.4 °C/100 m, and an air temperature of 10 °C.

3.4 Air Temperature

Air temperature for the values analyzed (i.e., 5 or 10 °C) had little effect on runout distance under any combination of other parameters. We understand that this parameter was mainly included in RAMMS::Extended to handle very cold powder avalanches, where heat exchange with the air plays an important role.

4 CONCLUSIONS

This study explored measurable (or reasonably estimated) parameters that affect runout distance in RAMMS::Extended simulations for low-volume, late-season avalanches in an avalanche path with a highly channelized track. Erosion depth, snow temperature, and water-content gradient with elevation were the most influential factors, with snow temperature gradient playing a secondary role, while air temperature had little effect. Because they can be observed or estimated in real time, these parameters could be incorporated into operational forecasts.

Ultimately, the idea is to develop a forecasting tool that helps to predict whether an avalanche from a specific release area with a given slab depth will reach the road. With strategically placed remote weather stations that have snow temperature sensors and moisture probes, and regular drone surveys of the release areas (Figure 11), such a tool could prove to be very powerful. Path 51 poses a specific challenge in forecasting late-season avalanches due to the relatively low release volumes that can produce avalanches which reach the highway. That is why a tool like this could be particularly valuable in the spring, when it comes time to make the decision whether or not avalanche season has come to an end.

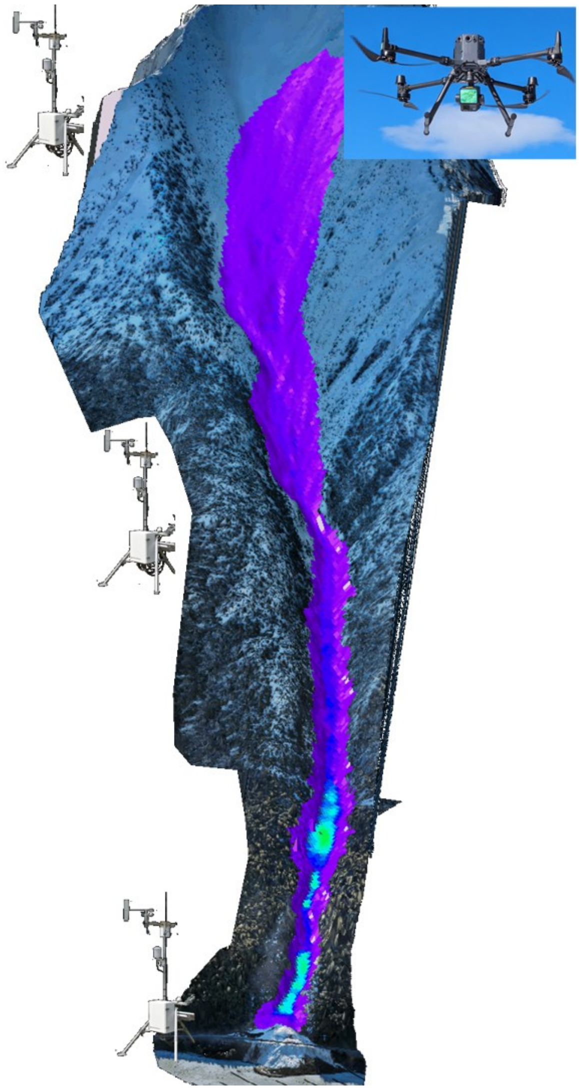


Figure 11: Conceptual diagram of Path 51 showing strategically placed weather stations, drone-based LiDAR survey, and RAMMS::Extended simulation results.

Future efforts will examine the sensitivity of runout extent to initial water content and release volume supported by drone surveys and SNOWPACK modelling (Lehning et al., 1999) to define realistic parameter ranges. Ultimately, the goal is to develop a tool that estimates the potential for late-season avalanches to reach the highway based on lidar measurements of release volume and measured or modelled flow regime parameters.

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