SENSITIVITY ANALYSIS OF THE RAMMS AVALANCHE DYNAMICS MODEL IN A CANADIAN TRANSITIONAL SNOW CLIMATE

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ABSTRACT: The Swiss avalanche dynamics model RAMMS is widely used to simulate avalanche flow for engineering, research, and hazard assessment. Since 2015, RAMMS modelling has been used as part of the Glacier National Park Avalanche Mitigation Project in British Columbia, Canada. Using 51 years of historic occurrence data from Parks Canada and a high resolution digital elevation model, modelled avalanches are calibrated to their predicted runout position.

The sensitivity of the release volume in RAMMS is tested by varying the initially calibrated release volume for four paths and measuring changes to the runout distance and avalanche velocity in the runout zone. For each 10% increase in release volume, the runout distance increased by an average of 9 m and the velocity in the area of the runout zone with a 10-15° slope angle increased by an average of 1.0 m/s.

The sliding and turbulent friction values used in RAMMS are functions of the return period and the avalanche volume classifications. Each of these classifications is tested for their effect on the runout distance and avalanche velocity in the runout zone. Results show that changes in avalanche volume classification have a larger effect on both runout distance and avalanche velocity compared to the return period classification. For each single step increase in volume classification, the runout distance and velocity increased by an average of 49 m and 4.4 m/s, respectively. Comparatively, for each single step increase in return period, the runout distance and velocity increased by an average of 12 m and 0.8 m/s, respectively. These results highlight the importance of choosing appropriate input parameters and testing the sensitivity of the model results to these inputs, especially in North America where limited calibration of the RAMMS model has been completed compared to Europe.

KEYWORDS: Dynamic modelling, RAMMS, sensitivity analysis, avalanche runout.

1. INTRODUCTION

The Swiss avalanche dynamics model RAMMS is becoming increasingly utilized internationally, including use in North America (Honig et al., 2014; Wilbur et al., 2014). The RAMMS numerical model uses the Voellmy avalanche flow equations coupled with the use of three-dimensional digital elevation models (DEM) representing the avalanche terrain (Christen et al., 2010; WSL-SLF, 2017). The model is used in avalanche hazard assessment, engineering, and research. RAMMS was originally calibrated in the continental snow climate of the Swiss Alps, and limited calibration has been completed in other alpine regions, especially in North America.

Glacier National Park (GNP) and the Rogers Pass National Historic Site are located in the Columbia Mountains in British Columbia, Canada, which is classified as a transitional snow climate (Haegeli and McClung, 2003). Forty-four kilometers of the Trans-Canada Highway crosses through GNP and is exposed to 134 avalanche paths. Since the late-1950s, the Avalanche Control Section of Parks Canada (ACS) has operated the avalanche forecast and control program which mitigates the risk to the highway as well as the Canadian Pacific Railway through GNP.

In 2015, Parks Canada commenced the GNP Avalanche Mitigation Project (Argue et al., 2018). The objective of this project includes reducing avalanche risk to the highway, reducing highway closure time, and increasing the operational efficiency of the avalanche control operations. As part of this project, numerous conceptual static avalanche defences were evaluated. Dynamic avalanche modelling was used to determine approach velocities for evaluation of run-up heights and impact pressures on these proposed defences. As part of this project, RAMMS modelling has been applied extensively to at least fifteen avalanche paths in GNP.

2. RAMMS MODEL CALIBRATION

2.1 *Avalanche path selection*

Many of the avalanche paths modelled using RAMMS in GNP were excluded from this sensitivity

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analysis due to substantial run-up of extreme avalanches beyond the valley bottom. Avalanche paths with long runouts and limited or no run-up were selected for sensitivity analysis. Selected avalanche paths also required relatively large release zone areas, capable of producing a release volume of at least 60,000 m³ to meet the volume category of *Large*, as defined within the RAMMS model.

Four avalanche paths were selected for sensitivity analysis from the west side of GNP. This area of the park has a wide valley bottom with relatively limited run-up compared to the east side. Selected avalanche paths have at least 1,000 m vertical fall height. Table 1 lists the selected paths and their terrain characteristics.

Table 1: Characteristics of selected avalanche paths in GNP used for sensitivity analysis and the release volume used for initial calibration.

	Path Height, H_o (m)	Beta angle, β (°)	RAMMS modelled release volume (m³)
Cougar Corner #2	1090	36.5	108,100
Gunners #1	1350	33.1	147,400
Gunners #2	1270	30.2	86,200
Mannix	1360	33.0	73,300

2.2 Extreme runout prediction

Since 1964, detailed avalanche occurrence records have been collected by ACS in GNP. Using 51 years of occurrence records, runout distances and their return period are fit to an extreme value distribution (Figure 1). A logarithmic regression allows estimation of runout distance by return period for each of the selected avalanche paths (Jamieson and Gould, 2018; Rheinberger et al., 2009). The RAMMS model can then be fit to the predicted runout distance for a given return period at each avalanche path.

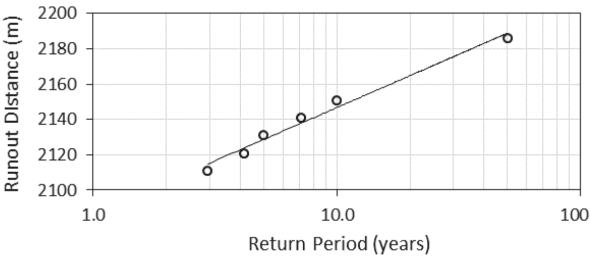

Figure 1: Example of a logarithmic fit of runout distance as a function of return period for Cougar Corner #2 path in GNP ($R^2 = 0.98$).

2.3 Terrain limitations

A limitation of running sensitivity analyses on avalanche paths in GNP is the alterations which have been made to the terrain in the runout zones. The highway and railway both create artificial benches in the terrain which affect modelled avalanche runout distance. Permanent defence structures have also changed the topography in some of the runout zones. The Mannix path has two rows of braking mounds above the highway, and Cougar Corner #2 has a slightly elevated highway grade which creates a small catchment immediately upstream of the highway. The tradeoff for the modifications to the natural topography which are inherent in a transportation corridor is the high quality observation data obtained from the avalanche control program, which allows for high confidence in model calibration.

These localized terrain features in the runout zones affect RAMMS model calibration. A better understanding of the sensitivity of the model with respect to friction values and release volumes, and their effects on runout distance and avalanche velocity should help improve the calibration of the RAMMS model in complex runout zones.

3. SENSITIVITY TESTING

After extensive use of the RAMMS model, it is known that the modelled runout distance and avalanche velocity are substantially influenced by the input friction values and avalanche release volume. This paper seeks to quantify how each of these inputs affects the model results. Two sensitivity analyses were completed to test the effects of varying the input friction parameters and the effects of varying the avalanche release volume. Similar methods were used by Hussin et al. (2012) to test the sensitivity of friction and entrainment inputs in the RAMMS debris flow model.

3.1 RAMMS default friction input parameters

RAMMS has sixteen combinations of default friction input values which vary by return period and by avalanche volume classifications. Each of these combinations of friction inputs has a unique range of sliding and turbulent friction values. Final input values selected from within each range are determined by an algorithm based on terrain characteristics (e.g. open-slope, channelized, gully, or flat) and elevation as represented by a DEM. Table 2 shows each range of friction inputs based on the return period and the avalanche volume classifications.

An important characteristic of the default RAMMS friction inputs is that changing the return period input only affects the sliding friction value, while changing the volume classification input changes both the sliding friction and turbulent friction values.

3.2 Initial RAMMS model calibration

A direct calibration approach modelling was applied using historic avalanche occurrence data (Jamieson et al., 2018). The initial friction inputs were set to *Large, 100-year* for all four paths. The release volume was then adjusted systematically until the modelled avalanche reached the predicted 100-year runout position. The largest observed avalanche occurrence in each path was also used to guide calibration of the model.

The DEM used for RAMMS modelling was created from high resolution LiDAR data and was resampled from 1 m to 5 m resolution for computational efficiency within RAMMS.

Table 2: Summary of RAMMS default friction values for sliding friction (µ) and turbulent friction (ξ) as a function of the return period and volume classifications (WSL-SLF, 2017).

	300-year	100-year	30-year	10-year
Large (>60,000 m^3)	µ: 0.14-0.30 ξ: 1200-4000	µ: 0.15-0.315 ξ: 1200-4000	µ: 0.155-0.33 ξ: 1200-4000	µ: 0.16-0.345 ξ: 1200-4000
Medium (25,000-60,000 m^3)	µ: 0.17-0.36 ξ: 1100-3250	µ: 0.18-0.37 ξ: 1100-3250	µ: 0.19-0.38 ξ: 1100-3250	µ: 0.20-0.39 ξ: 1100-3250
Small (5,000-25,000 m^3)	µ: 0.215-0.40 ξ: 1000-2500	µ: 0.225-0.41 ξ: 1000-2500	µ: 0.23-0.42 ξ: 1000-2500	µ: 0.24-0.43 ξ: 1000-2500
Tiny (<5,000 m^3)	µ: 0.26-0.44 ξ: 900-1750	µ: 0.265-0.45 ξ: 900-1750	µ: 0.27-0.46 ξ: 900-1750	µ: 0.275-0.47 ξ: 900-1750

3.3 Friction inputs sensitivity analysis

For each avalanche path, RAMMS was run for each of the sixteen combinations of default friction inputs in Table 2. The initial release volumes as well as all other RAMMS modelling inputs were fixed for these runs.

3.4 Release volume sensitivity analysis

For each avalanche path, the release volume was varied while fixing the friction inputs and all other RAMMS modelling input variables. The friction inputs were fixed at *Large, 100-yea*r for all the model runs. The release volume then was tested using +/- 10, 20, 30, 40, and 50% of the initial volume. This was done using a consistent release area polygon and varying the release depth.

3.5 Model outputs

Avalanche deposit results in RAMMS are automatically set to exclude results less than 2% of the maximum flow height from being displayed. In order to consistently measure runout distance, the results for all model runs were set to display the final avalanche deposit equal to or greater than 20 cm.

To test changes in velocity, a fixed cross-section was selected in the runout zone of each of the avalanche paths. These cross-sections were selected at the beta point (where the slope angle first decreases to 10°) or immediately upstream of any unnatural alterations to the topography. As a result, the cross-sections represent an average slope angle of 10-15° in the runout zone. The maximum velocity was then extracted from the same cross-section for each model run.

4. RESULTS AND DISCUSSION

4.1 Friction inputs sensitivity analysis

For each avalanche path, sixteen model runs were completed representing each combination of RAMMS default friction inputs in Table 2.

Table 3 shows an example of the runout distance results for the Mannix path and Table 4 shows an example of the avalanche velocity results for the Mannix path, with the sampling cross-section located just upslope of the first row of braking mounds in the runout zone.

Table 3: Example of runout distance sensitivity results for the Mannix path as a function of the default RAMMS friction inputs.

Runout distance (m)	300-year	100-year	30-year	10-year
Large	2230	2209	2200	2189
Medium	2165	2158	2150	2144
Small	2123	2121	2118	2112
Tiny	2108	2100	2094	2088

Table 4: Example of avalanche velocity sensitivity results in the runout zone of the Mannix path as a function of the default RAMMS friction inputs.

Avalanche velocity (m/s)	300-year	100-year	30-year	10-year
Large	25.3	24.4	23.5	22.5
Medium	20.0	18.9	17.8	16.8
Small	14.5	13.8	13.0	12.2
Tiny	10.8	10.2	9.5	8.5

Using the full dataset of results like the examples in Tables 3 and 4, we can independently assess the effects of changing the return period input by assessing the horizontal rows in the table or the effects of changing the volume classification input by assessing the vertical columns. For example, the *Large, 100-year* runout distance in Table 3 is 2209 m. Decreasing the return period input by one step to *30-year* results in a 9 m decrease in the runout distance. Decreasing the volume classification input by one step to *Medium* results in a 51 m decrease in runout distance. This basic method can be used to independently compare all changes to the return period inputs and to the volume classification inputs, and assess the effect of each on runout distance and avalanche velocity in the runout zone.

For all paths used in this analysis, given a fixed volume classification input, the runout distance changes by an average of 12 m for any single step increase (e.g. 30- to 100-year) to the return period input. Conversely, for any fixed return period input, the runout distance changes by an average of 49 m for any single step increase (e.g. medium to large) to the volume classification input. This result shows that the change in runout distance is about four times more sensitive to a single step change in volume classification input compared to a single step change in return period input. Table 5 summarizes the average results for each path.

The same results can be obtained for the avalanche velocity in the runout zone. For any fixed volume classification input, the avalanche velocity in the area of the runout zone with a 10-15° slope angle changes by an average of 0.8 m/s for any single step increase to the return period input (Table 6). Conversely, for any fixed return period input, the avalanche velocity changes by an average of 4.4 m/s for any single step increase to the volume classification input. In this case, changing the volume classification one step results in a 5.5 times larger change in velocity than changing the return period input one step.

Table 5: RAMMS default friction input sensitivity test results for runout distance. The return period classification and the release volume classification components of the default friction inputs are evaluated independently. Standard deviation values are shown in brackets.

Average change in runout distance (m) resulting from a single step change in:	Cougar Corner 2	Mannix	Gunners 1	Gunners 2	All Paths
Return period classification	4.4 (3.6)	9.5 (4.7)	13.2 (4.9)	19.5 (8.3)	11.8 (7.8)
Release volume classification	28.9 (13.2)	38.3 (14.9)	55.2 (20.0)	71.9 (12.6)	47.5 (22.4)

Table 6: RAMMS default friction input sensitivity test results for avalanche velocity in the runout. The return period classification and the release volume classification components of the default friction inputs are evaluated independently. Standard deviation values are shown in brackets.

Average change in runout zone velocity (m/s) resulting from a single step change in:	Cougar Corner 2	Mannix	Gunners 1	Gunners 2	All Paths
Return period classification	0.54 (0.22)	0.88 (0.16)	0.92 (0.11)	0.71 (0.16)	0.76 (0.22)
Release volume classification	3.37 (0.45)	4.73 (0.88)	4.90 (1.21)	4.59 (0.33)	4.40 (0.98)

4.2 Release volume sensitivity analysis

For each avalanche path, eleven model runs were completed with release volumes varying from -50% to +50%, in 10% volume intervals.

Figure 2 shows the change in runout distance as a function of the release volume for each path. Figure 3 shows the change in avalanche velocity in the area of the runout zone with a 10-15° slope angle as a function of the release volume for each path.

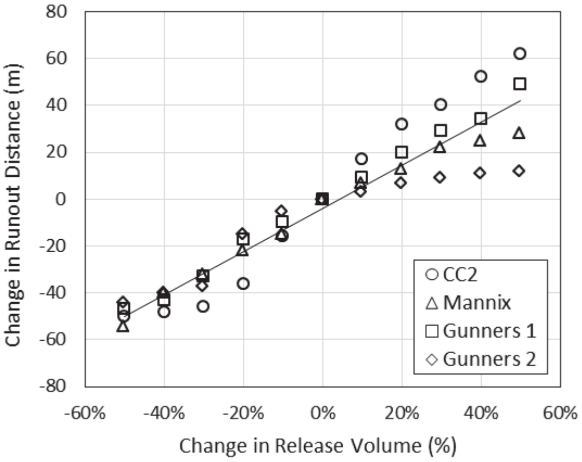

Figure 2: Change in modelled RAMMS runout distance as a function of release volume. A linear fit is applied to the average results of all four paths ($R^2 = 0.99$).

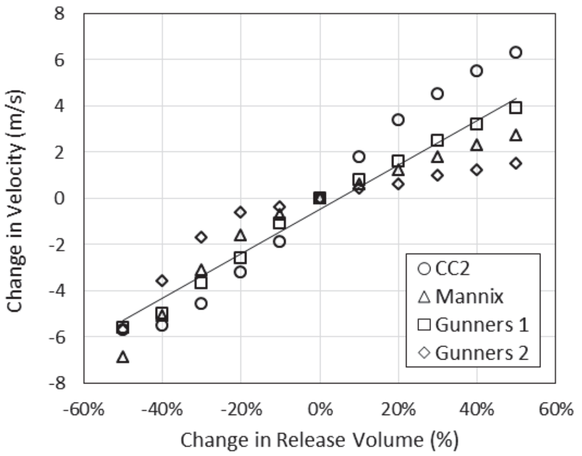

Figure 3: Change in modelled RAMMS avalanche velocity as a function of release volume. A linear fit is applied to the average results of all four paths ($R^2 = 0.98$).

The results in Figures 2 and 3 show a range of values which can be averaged in order to determine the relationship between release volume and the resulting runout distance and avalanche velocity. For each 10% change in release volume, we can expect an average change in runout distance of approximately 9 m. For each 10% change in release volume, we can expect an average change in avalanche velocity in the area of the runout zone with a 10-15° slope angle of approximately 1.0 m/s.

4.3 Effects of terrain on runout distance

The variation in the results for runout distance in both sensitivity analyses (friction input and release volume) are higher than that of the variation in results for avalanche velocity in the runout zone because of the effect of terrain undulations in the bottom of the runout zone where the avalanche is decelerating. The avalanche velocity was sampled above the highway where the terrain is relatively smooth and velocity is higher, thus it is less sensitive to terrain effects.

The two most influential types of terrain in the bottom of the runout zone which affect modelled runout distance calibration appear to be acceleration zones and areas of run-up. The most common cause of an acceleration zone in the runout is a cut slope above a highway or railway grade. Modelled avalanches will not stop on these steeper slopes which causes a concentration of modelled avalanches stopping on the bench below. Terrain run-up is normally expected beyond the valley bottom but can also affect the model calibration within the rest of the runout zone. Common areas of run-up include areas where the highway or railway grade is artificially elevated above the natural terrain or cut into the terrain creating a large lateral trench across the avalanche path. The effects of both acceleration zones and run-up zones on runout distance calibration appear to be most substantial when avalanches are travelling at their slowest during the final deceleration in the runout zone.

5. SUMMARY AND CONCLUSIONS

The objective of this project was to test the sensitivity of the default RAMMS friction inputs and release volume on the resulting runout distance and velocity in the runout zone. This sensitivity analysis was done using four avalanche paths in Glacier National Park, Canada, which is located in a transitional snow climate.

For the default RAMMS friction inputs, changes to the return period and the volume classification inputs were compared. By changing only the return period input by one step, the runout distance changed by an average of 12 m (+/- 8 m) and the avalanche velocity changed by an average of 0.8 m/s (+/- 0.2 m/s) in the area of the runout zone with a 10-15° slope angle.

By changing only the volume classification input by one step, the runout distance changed by an average of 49 m (+/- 22 m) and the avalanche velocity changed by an average of 4.4 m/s (+/- 1.0 m/s) in the area of the runout zone with a 10-15° slope angle. It is clear that RAMMS results are substantially more sensitive to changes in the volume classification input compared to changes in the return period input. This is because changes to the volume classification input causes changes to both the turbulent friction and sliding friction input values while changing the return period input only causes changes to the sliding friction input values, as shown in Table 2.

A linear relationship existed between the avalanche release volume and both the runout distance and the avalanche velocity in the runout zone. For each 10% increase in release volume, the expected average increase in runout distance was 9 m and the expected average increase in avalanche velocity was 1.0 m/s in the area of the runout zone with a 10-15° slope angle.

These results highlight the importance of choosing appropriate input parameters and testing the sensitivity of the model results to these inputs, especially in North America where limited calibration of the RAMMS model has been completed as compared to Europe.

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