LIMITATIONS OF RAMMS:DEBRISFLOW AS A SLUSHFLOW SIMULATION TOOL

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ABSTRACT: Slushflows are defined as water-saturated snow (slush), that moves rapidly downslope as a gravitational mass flow. The high-water content of the flow results in a high density, posing a significant danger to construction, infrastructure and people in its path. To reduce this danger, it is important to predict where slushflows may initiate and travel in the terrain. Numerical modelling of the runout process is a valuable tool for both hazard mapping as part of the spatial planning process, and to identify areas that may require early warning systems or mitigation. RAMMS:Debrisflow is a gravitational mass flow runout simulation tool that has been parameterized for debris flows. To use RAMMS:Debrisflow to simulate slushflows the assumptions made in simulation must be checked and the parameterization must be adapted. The parameterization must be adapted from the friction and density of sediments to slush material. To establish a parameter set for slushflows a catalog of slushflow events are needed for model calibration and validation. Several parameter sets have been proposed already for slushflow simulations with RAMMS:Debrisflow, however these were only built on a few events, so further validation is needed. To this end, three events from winter/spring 2023 in Northen Norway were digitized for simulation of the runout. While the parameters represent slushflow runout to some extent, a shortcoming is the simulated runouts are sensitive to the input data. The slushflows released in gentle slopes, however, the model cannot replicate these starting conditions. The solution was to create release areas for events in the part of the slushflow where it rolled over into steeper terrain. To analyze the sensitivity of the flow path to different release conditions we simulated the known slushflow events with varying slope gradients, surface areas and fracture depth. We conclude that input parameters (release areas and release volume) are too sensitive to truly test the capabilities of RAMMS:Debrisflow to simulate slushflows. There must be more work done to standardize the method to delineate the release areas.

KEYWORDS: Slushflow, simulation, spatial planning, RAMMS.

1. INTRODUCTION

Slushflow hazards occurs on a global scale in areas with a seasonal snow cover (Onesti and Hestnes, 1989). Particularly, slushflows have posed a significant risks to maritime mountainous communities worldwide for centuries, including the Pacific Northwest of the United States, New Zealand, and Scandinavia (Relf et al., 2015). The atmospheric and hydraulic boundary conditions in the polar and sub-polar regions, fulfil the conditions for slush flow initiation and make slushflows relatively common in these areas (Scherer et al., 1998).

In Norway, all types of rapid mass movements must be considered in hazard assessments. This includes the slushflow danger (Hestnes and Lied, 1980). Slushflows are gravitational mass flows that initiate when water saturates the snowpack. A slushflow event occurs when the snowpack losses its cohesion and rapidly moves downslope like a fluid (Jaedicke et al., 2022). The high-density water-snow mixture has the potential to entrain slush, water, debris and organic material along the path (Hestnes and Jaedicke, 2018). The definition of slushflows covers a range of water-snow ratios, leading to various characterizations of occurrence, mobility and runout (Hestnes et al., 2017; Jaedicke et al., 2022). Because of the wide range of water-snow ratio the distinction between river breakup and slushflows is not as clearly defined. One specific type of slushflow could occur as a type of spring river breakout (Nyberg, 1989).

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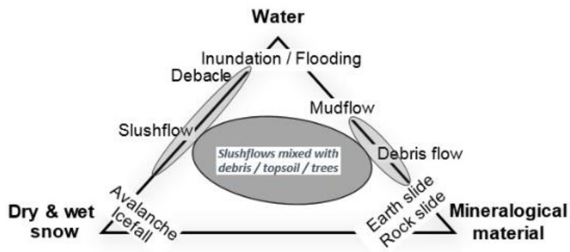

Figure 1: Classification system for rapid mass movements developed by Hestnes et al. (2017) including slushflows.

Hestnes et al. (2017) created a classification system for slushflows, describing the complexity of difference in components of water, slush and entrained sediments (Fig. 1). Even though this classification covers the complexity of these rapid mass flow events the need for a more complete classification system is outlined in our concurrent contribution (D'Amboise et. al., 2024).

Due to the water-saturated snow and added water in the flow, these high-density events have the potential to damage everything in their path (Washburn and Goldthwait, 1958; Jaedicke et al., 2022). Given the significant threat slushflows pose to society, there is a need for tools to assess this hazard with minimal uncertainties. The most effective way to avoid any fatal consequences of a slushflow event is to limit the exposure of the hazard. This require a need of objective criteria to enable identification of slushflow hazard and methods for slushflow prediction and control (Hestnes, 1985; Hestnes and Bakkehoi, 1995).

Numerical modelling is a tool widely used in spatial planning and the construction of mitigation measures, both concerning the debris flow and snow avalanches danger (Christen et al., 2010). Yet, no model is developed to exclusively simulate slushflow runouts (Jaedicke et al., 2022). One software that has been used as a tool in hazard assessments to simulate this flow process is RAMMS:Debrisflow. To cover the complexity of different debris flow scenarios, the software allows a wide range of different input values and friction parameter calibration. This flexibility allows the model to be calibrated to simulate the high-water content flow (Christen et al., 2012).

The quality of the result is determined by the input values. A necessary input variables includes friction parameters describing the flow dynamic (Christen et al., 2010) . The software uses the two-parameters, Voellmy-Slam friction model (Zhang, 2019). This model splits the friction into the total basal friction (coefficient μ [-]) and a velocity depended "viscous" or "turbulent" friction (ξ [m/s^2]) (Salm, 1993). Since slushflows have a significantly different mobility compared to debris flows it requires a calibration of the friction parameters. Kronholm (2021) suggested combinations of these two parameters for simulating slushflows runouts for different hazard scenarios with return periods of 1/100, 1/1000 and 1/5000, according to the Norwegian regulations for spatial planning (TEK 17, § 7-3).

Since slushflows pose a significant danger to humans, constructions, and infrastructure, the limitation of the methods used in the numerical modelling of slushflow runouts needs to be evaluated, to reduce the risk in future spatial planning. Improving these methods would not only affect spatial planning but also limit areas for early warning and strengthen the foundation in the development of mitigation measures. The friction parameter set used to simulate these runouts in the RAMMS:Debrisflow model is currently based on a few well-documented events, and the suggested parameters are therefore just a combination of the two parameters, and needs to be further validated and tested on other high quality documented events (Kronholm, 2021).

To evaluate the credibility of using RAMMS: Debrisflow as a tool in hazard assessment, the method and calibrated parameterization are tested on three events occurring in the winter and spring of 2023. Because of assumptions made in the model design for replicating debris flow events, the sensitivity of the release area is also tested here, including release volume and source location.

2. METHODS

2.1 Dataset

The method and parameterization used to generate slushflow runouts with RAMMS: Debrisflow for hazard assessment (Kronholm, 2021) were tested on three events. In the process of back-calculating these three events a comprehensive field documentation of three slushflow events was undertaken. This included gathering information about the full extent of the release area and runout.

The events were released in Northern Norway during the winter and spring of 2023. Coordination with Troms and Finnmark County (TFFK) was crucial for conducting field documentation from the events, including drone videos and photos from all the events.

February 17, 2023, a small slushflow displaced three vehicles from the road, County Road (Fv) 889, in Bakfjorddalen, Måsøy. This event released a channel steeper than 30° which is considered steep for slushflows. Two small events were triggered in this field site within a short period of time.

On April 24, 2023, a slushflow event closed Fv 7962 in Nålelva, Burfjord, Kvænangen. The slushflow event initiated in flatter terrain with water overflowing the snowpack. As the flow moved downslope, following a small stream entering steeper parts of the terrain, the flow entrained both snow and sediments, resulting in a long runout, stopping at sea level. The event extent was documented with drone videos and photos, followed by a helicopter survey the next day. The release area was investigated from the air, and surrounding areas with water saturated snow were observed. Fieldwork also involved on-foot investigations of the deposit, analysing differences in deposition composition, and gathering of information about both the horizontal and vertical extent of the deposit.

May 15, 2023, a slushflow deposited a large amount of slush and ice closing European road (E) 6 in Leirbotnvannet, Alta. This mass movement travelled a long distance in low gradient terrain because of almost unlimited access to free-flowing water and would fall under the river breakout categorized slushflow.

The release areas were digitized based on the field observations, and the full extent of the event was digitized in GIS to compare the simulation outputs with the reality of the event. This was done mainly by comparing recognizable terrain features from the documentation with high resolution digital terrain models (DTM) (Table 1) from LiDAR Data. The Esri GIS plug-in tool "georeferencing", was used to linked air photos from the field to their corresponding location on the map, which made it possible to digitise the event with a reasonably high degree of accuracy.

Table 1: Overview of Digital terrain models (DTM)

Events	**DTM**	**Horizontal resolution**	**Sim reso-lution**
Bakfjord-dalen	National terrain model UTM33	1 m	2 m
Leirbotn-vannet	National terrain model UTM33	1 m	2 m
Nålelva	"NDH Kvænan gen 2pkt 2016"	0.5 m	2 m
Source of data:	https://hoydedata.no/LaserInnsyn2/		

2.2 *Input sensitivity analysis*

The RAMMS:Debrisflow model (WLS, 2024) was employed to simulate slushflow runouts. To evaluate the sensitivity of the input variables, a series of tests were conducted, varying both the parameterization and the release area.

Initially, the events analyzed by Kronholm (2021) were replicated using the same method and input files, provided by Kronholm. The original simulations conducted by the author, were generated using RAMMS:Debrisflow version 1.7.20. However, this project employs version 1.8.0 to regenerate the simulations. Notable differences between these versions have impacted the simulation outputs.

To evaluate the efficiency of this method, the three digitized events were used to determine whether realistic results could be generated using the same parameterization. A 2 m resolution ascii was used as the DTM for all simulations. Different combinations of the basal friction (μ) and the internal friction (ξ) (Table 2) were tested on the events.

Table 2: Calibrated friction parameters (Kronholm, 2021)

Frequency	**Erosion**	**μ (-)**	**ξ (m/s^2)**
1/100	No	0.08	2000
	Yes	0.08	3000
1/1000	No	0.05	3000
	Yes	0.05	4000
1/5000	No	0.04	4000
	Yes	0.04	5000

The friction forces are also affected by the slope angle (ϕ) and the density of the moving material (ρ). To reflect the high water-content in the saturated snowpack the density of the material was set to 1000 kg/m^3 for all simulations, to exactly replicate the method (Kronholm, 2021). The simulations were set to stop when the total momentum reduced to 5% of the initial value. The end time for all simulations was set to 1000 seconds, with output data recorded at 2 second intervals. For defining the release depth in this project, we utilized interpolated snow depth data from the Norwegian Water Resources and Energy Directorate (NVE) database, Xgeo (Geodata, 2024).

The Bakfjorddalen event initiated in steeper terrain, the original release area location was used for generating slushflow runouts. Due to model assumptions that limit replicating slushflow runout simulation initiating in slopes gentler than 10°, as noted by Kronholm (2021), it was necessary to define the release area in steeper parts of the subsequent slushflow path specifically for the Nålelva event. In contrast, the Leirbotnvannet event never transitioned into terrain steeper than 10°, and using this method it is not possible to work around this assumption in the model by changing the release area location.

The release areas were defined using a slope map generated with GIS based on DTM used for the simulation (Table 1). For the Nålelva event, different segments of the slushflow path with an average slope angle exceeding 10°, were selected and tested. Since the frictional forces are affected by the slope angle a sensitivity analysis of the location was conducted by changing the location whilst maintaining the volume of the release and keeping the other parameters constant. One release area was defined close to the original initiation with a slope angle around 11° and one closer to the road with a slope angle of 20°. To identify the effect of delineated release areas other simulations were generated changing the volume by either change the spatial extent or release depth, and keep the other parameters constant.

3. RESULTS

3.1 Simulation setup

The replicated events from Kronholm's study (2021) reveals minor deviations from the original simulations. The main discrepancy observed between the simulations was in the spatial extent of the runout, particularly in the low-velocity and shallow-flow height deposits (Fig. 2). This could be seen by comparing Kronholm's simulation made with RAMMS:Debrisflow version 1.7.20 (the black outline in Fig. 2) to the simulations made with version 1.8.0 (blue shaded region).

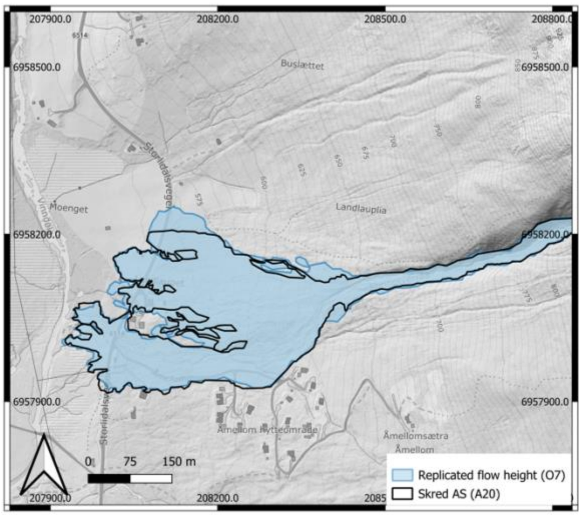

Figure 2: Spatial deviations between the maximum flow height from the replicated event and the original event (Kronholm, 2021). The blue polygon represents the output from the current project's simulation, while the black outline shows the original simulation's results. The basemap consists of a hillshade generated from the DTM and the "topografisk Norgeskart gråtone" from Kartverket.

The success of the simulations in back-calculating the digitized release areas for the documented events at Bakfjorddalen, Nålelva, and Leirbotnvannet varied, primarily due to differences in terrain profiles. In Bakfjorddalen, the simulations of the two slushflow events generally aligned with the observed runout extents and accurately captured the overall spatial distribution of the flows (Fig. 3). However, the deposition outputs, generated using the different friction parameter combinations (Table 2), resulted in slightly longer runout distances compared to field observations. The simulations also showed a wider flow spread than what was observed during the actual events. The best deposition output was achieved with the parameter combinations developed for 1/100-year slushflow frequencies, specifically the highest μ value of 0.08 and the lowest ξ value of 2000 m/s² (Fig. 3).

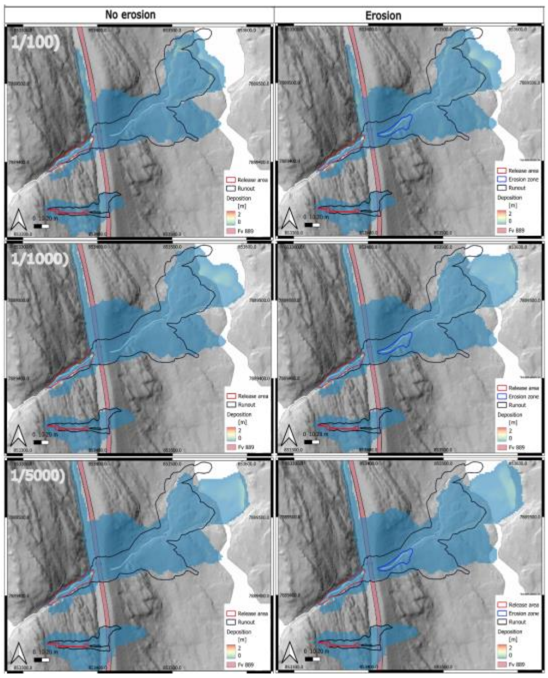

Figure 3: The digitized Bakfjorddalen event with release area (red), erosion zone (blue) and full runout (black). The friction parameter set (Table 2) is tested for both with and without erosion with an initial release volume of V=377 m^3 and V=90 m^3 for the two events.

In the Bakfjorddalen simulations, the impact pressure was in a plausible range to displace two vehicles. The maximum pressure output, using friction parameters for a 1/100 return period (Fig. 4), was approximately 250 kPa. This value aligns with the pressure required to displace vehicles positioned where the slushflow path crosses the road. This can be seen in Figure 4 by comparing the displacement position of the vehicles (indicated with red points) with the pressure color scale.

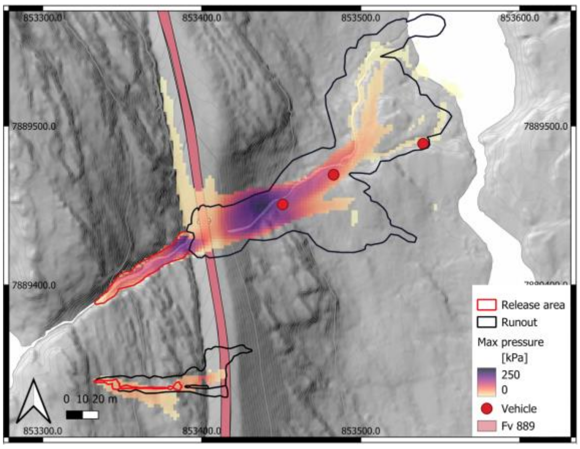

Figure 4: The maximum pressure for the Bakfjorddalen event for simulations generated with V = 377 m^3, μ = 0,08 and ξ =2000 m/s^2. Red points illustrate vehicles displaced from the road.

For the Nålelva and Leirbotnvannet events, simulations using simulated snow depth data (Xgeo, 2024) and the observed release areas were generated. The release area at Nålelva has an average slope of 3.5° where Leirbotnvannet has an average slope angle of 1.3°. For these two events RAMMS:Debrisflow was unable to accurately replicate the observed runouts using the low angle release areas. The simulated runout lengths were significantly shorter than those observed in these events (Fig. 5).

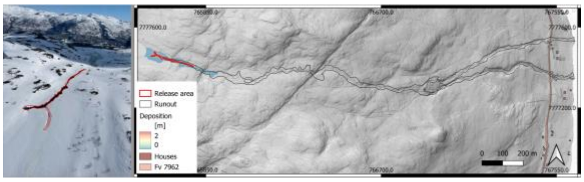

Figure 5: Simulation of the mapped release area for the Nålelva event compared with the runout observed in field (black). Initial release volume (red) V= 762 m^3, μ = 0,08 and ξ =2000 m/s^2.

The terrain at Nålelva featured a combination of steep and gentle sections along the slushflow path, making it an ideal test case for the model. By adjusting the model to define the release area in sections of the path that transitioned into steeper terrain, the simulations resulted in longer, more realistic runouts. However, RAMMS: Debrisflow struggled to accurately reproduce the Leirbotnvannet event due to the low slope gradient (below 10°), which made it impossible to work around this assumption.

3.2 <u>Model sensitivity</u>

The Nålelva event demonstrated significant differences in runout extents and impact pressures when different snow depths, release area sizes and locations were used. The simulations revealed that placing the release area further down the path, within a steeper segment of the terrain (20°), resulted in a markedly higher impact pressure at the road crossing compared to when the release area was positioned closer to the true initiation point in a less steep segment (11°). This trend was also evident in the maximum flow height measurements. Specifically, simulations with the release area located further down the path produced results that more closely matched the observed maximum flow height of 2 m, as indicated by the red point in Figure 6d. In contrast, the analysis of deposition patterns showed that a release area positioned further upstream more closely aligned with the observed spatial extent of the deposition.

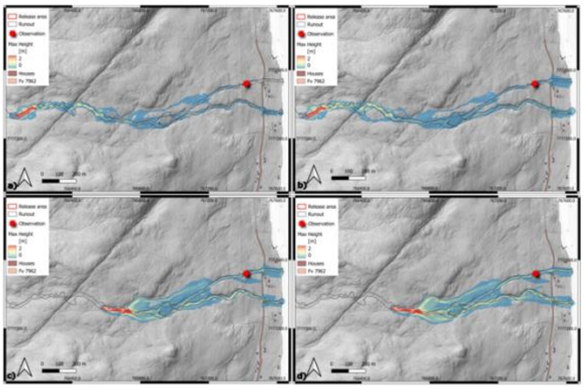

Figure 6: The mapped Nålelva event with release area (red outline) and runout (black outline) compared with simulations with different input variables. All four simulations are simulated with a volume 3400m^3. a) and c) are generated with the friction parameter for return periods 1/100, while b) and d) uses the friction parameters for return periods 1/1000. The red point illustrates observations of a 2 m flow height.

The Nålelva event shows that the friction parameter is a sensitive variable with regards to runout distance and impact pressures. The 100-year parameterization exhibited a considerably shorter runout, for the highest placed release area (Fig. 6a), compared to the 1000-year parameterization (Fig. 6b). The lowest values for μ of 0.05 and highest value of internal friction ξ of 3000 m/s^2 gave the best match The choice of defining release area in the different segments of the slushflow path would have a larger impact generated simulation output than changing the friction parameter combinations.

4. DISCUSSION

4.1 Release area delineation

Release area delineation including the size, shape, location and snow depth of release areas are sensitive variables. This can be seen in the results where event Nålelva had dramatically different runout lengths when the release area was changed from the observered starting zone to steeper parts in the slushflow path. The result of testing the location of the release area, gave more realistic results for the release area located closer to the area of impact in the steeper parts of the slushflow path (Fig. 6).

The choice of release area location and size are very important to successfully reproducing realistic runout areas and impact pressures. Much of the simulations outcome is dependent on user expertise because there are not well-defined systems for choosing the release areas location and size. Kronholm (2021) noted that in previous simulations, release areas were estimated differently for each event. To achieve consistent and objective hazard assessments, standardized guidelines for defining the spatial extent, release depth, and location, of the release areas in the steeper areas of slushflow path, are necessary.

Reproducing an event is possible with careful choice of the release area. However, it would be exceedingly difficult to use this tool for hazard assessment for slushflows staring on open slopes or other slushflows that do not have a well define path or release area.

4.2 Model credibility

RAMMS: Debrisflow is a useful tool for identifying areas susceptible for a particular type of slushflows. The model is an effective tool to see the spatial extent and impact pressures of slushflows in the terrain. However, the current friction parameterizations assume homogeneous flow conditions (Kronholm, 2021), but field observations reveal significant variability in slushflow behavior due to factors like water availability and material composition, presenting challenges in accurately simulating the diverse range of slushflow events. As noted in the slushflow classification by Hestnes et al. (2017), the complexity of slushflows, due to varying compositions of water, slush, and entrained sediments, leads to a wide spectrum of event types. These three events show how diverse the flow behavior can be for slushflows. Bakfjorddalen and Nålelva event showed a more turbulent type of flow behavior where Leirbotnvannet event had a more laminar flow type due to the high amounts of liquid water. To enhance the model's accuracy and reliability, it is crucial to develop guidelines for classifying slushflow types and behaviors (D'Amboise et. al., 2024). This will help refine parameter accuracy, release area delineation, initiation and volume which can help justify what simulation tool and parameters to use for hazard assessments.

For slushflows that demonstrate a more laminar flow a different simulation tool should be used. The Leirbotnvannet event showed the limitation of RAMMS:Debrisflow for low gradient terrain slushflows. This is expected as RAMMS: Debrisflow is a simulation tool developed for turbulent flows while the Leirbotnvannet event is more of a river process with laminar flow.

RAMMS:Debrisflow is well suited for simulating slushflows with steeper release areas, however it has major limitations when it comes to flatter release areas. One approach is to define the release areas in parts of the slushflow path where it rolls over into steeper terrain. This method generated realistic results; however, it is more of a workaround than a reliable method. A different simulation tool that is less restrictive in flatter terrain would be a better choice for the Nålelva event.

The terrain at the Bakfjorddalen field site is characterized by relatively steep slopes, which is consistent with the formation of debris flow. Therefore, the event at Bakfjorddalen yield realistic simulations using the observed release area location. However, some deviations were noted between the observed deposits and the simulated results across the three parameter sets (Fig. 3). The simulations for both Bakfjorddalen and Nåleleva resulted in increased impact of the event by reducing the basal friction parameter μ and increase the internal friction parameter ξ. This is suggested in the three parameter sets for 100-, 1000- and 5000-year return periods (Kronholm, 2021). Based on the results from the sensitivity analysis of the Nålelva event (Fig. 6) the release area is a more sensitive variable than the friction parameters. Because reproducing a slushflow event with RAMMS.Debrisflow is highly sensitive to the correct delineation of the release areas it is not possible to validate the friction parameters of these events.

The slightly different spatial extent between simulations made with RAMMS:Debrisflow version 1.8.0 (presented in this work) and version 1.7.20 presented in Kronholm (2021), shows that the version of the software will bring minor changes to the runout extent. However, both versions' simulations are consistent in higher impact areas. Therefore, the model remains reliable for predicting critical aspects of slushflow behavior with the new version of the software.

5. CONCLUSION

The three field sites show that RAMMS: Debrisflow, with the suggested parameterisations for slushflows, can fit the observed runout to some extent. The three slushflow events had differences in the initiation, mass entrainment and water content which resulted in different flow behaviours. The model will reproduce events relatively well for slushflows that either initiate in steeper slopes or ones that roll into steeper terrain in the slushflow path. RAMMS:Debrisflow cannot simulated slushflows paths with terrain profiles under 10°. The Leirbotnvannet slushflow path does not transition into steeper terrain, and therefore, this model is not well-suited to accurately simulate this slushflow type. To be able to cover these types of events a different simulation tool should be used for more laminar type flow.

Another shortcoming of using the RAMMS: Debrisflow is that the runout is sensitive to the snow depth, release area shape, size and location. The most effective way to make the simulation match an observed event is to either change the location or volume of the release area. This project highlights that the variable of the release area is too sensitive to validate the established friction parameter set developed for slushflows. To truly test the capability of RAMMS:Debrisflow to simulate realistic runouts for spatial planning more event data is needed. There is the pressing need to develop a standardised method to delineate release areas, even though robust spatial data on slushflow events is rarely recorded currently.

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