MOTIVATION FOR SLUSHFLOW CLASSIFICATION

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ABSTRACT: Slushflows are a type of rapid mass movement where water saturated snow flows downhill. Slushflows come in many different sizes, have different triggering mechanisms, and contain debris ranging from simply snow and ice to soil, rock and vegetation. Slushflows are often misclassified as debris flows, wet snow avalanches or river/stream ice jam processes.

Norway reports 5 to 20 larger slushflows each year which have economic impacts such as damage to infrastructure, road closures, and even fatalities. For improved slushflow hazard assessment a robust classification system must be used to precisely describe what size and type of process is being forecasted, modeled, or investigated. A classification system would be beneficial for both scientific research, data collection, and operational hazard mitigation strategies.

Slushflows have been well defined as a sub-category of mass flows classified by the composition of the mass. However, they have not been systematically broken down into sub-categories that describe the formation, type of movement, size, and quantity of entrained material. These sub-categories are needed because the types of slushflow, the terrain from which they initiate, and the triggering mechanism can differ greatly. Extreme rain on snow or melt events have predictive power for slushflow activity when all slushflow types and sizes are analyzed together. However, many slushflow events occur during periods of moderate rain on snow or melt events, defying forecasts. Weather and snowpack data alone are not able to predict slushflow activity during moderate rates of melt or rain. Some of the nuances of slushflow formation may be uncovered when single slushflow types and/or sizes are investigated independently. Independently investigating slushflow types and sizes will also help define the spatial patterns of slushflow formation.

We propose a classification system which includes some traits of snow avalanche classification, such as size and release mechanisms, and build on this to include other unique traits such as water availability and indication of debris materials. A classification system will allow further research on precise sub-classes of slushflow, because as a whole slushflow behavior is too diverse to describe as a single process.

KEYWORDS: Slushflow, Snow Hydrology

1. INTRODUCTION

Slushflow is a term that is used for mass movements of snow and water that can contain debris and vegetation. Slushflows share some traits with snow avalanches and some with debris flows. There is a diversity in the description of slushflows in the published literature. The term is used to describe events that show a spectrum of behavior regarding the movement, starting conditions and terrain they are associated with. Past work by Hestnes (1985) has categorized slushflow release areas into three types, channel, scar and bowl type release areas. However, there is currently not a robust system to further classify slushflows into sub-categories. This makes it difficult to precisely describe what the term slushflow encompasses and what it doesn't, which has implications on communication of the risk. Forecasts, hazard maps and other risk reduction tools normally mitigate the risk of a subset of slushflows, not the full spectrum.

A number of different processes can contribute to the formation of slushflows. Most types require an input of liquid water to the snowpack. This water typically comes from snow melt or rain (Hestnes and Bakkehøi, 1996). While correlation with extreme rainfall on snow, or intense snow melt, provides some predictive power, this approach is severely lacking due to an absence of causal understanding. With the expectation that winters will become wetter and warmer under a changing climate as stated in the IPCC report (Cissé et al., 2022), we can expect that the formation of slushflows is poised to increase in the coming years for regions that retain a seasonal snowpack (Hestnes and Jaedicke, 2018).

Currently there is an operational slushflow forecast in Norway that gives daily regional warnings on slushflow hazard (Sund et al., 2024). The forecast is built on a ratio of snowpack depth to rain/meltwater, a water input threshold (Jaedicke et al., 2013), and considers the forms of the snow grains. The forecast utilizes weather forecasts, gridded snowpack depth models and the regional snow melt models (HBV and energy balance). The operational slushflow forecast was built as an early warning system for the more turbulent types of slushflows with starting conditions driven by rain on snow or dramatic melt events. Human triggered slushflows and more fluvial low gradient slushflows are not covered by the forecast, however this is not explicitly stated in the forecast due to confusion around what is included in the spectrum of slushflow. Creating subclasses of slushflows will allow for clear language on what type of events are forecast and what are not by these types of tools.

In this work we will describe the motivation for a more robust classification system for slushflows by presenting three events that occurred in Norther Norway in the 2022-2023 winter. These events showcase the diversity in starting conditions, and flow dynamics in which should be the basis of a classifications system. Future work will build upon the motivation laid out in this paper to present a method to classify slushflows. By grouping slushflows into several subclasses, communication of the risk will be improved, as it will trigger a higher level of predicting power for the onset of slushflow conditions and calculations of runout distances.

1.1 Definition of slushflow

There are a number of different descriptions of slushflows published in the last 70 years, some of the definitions are detailed towards a specific type of event and others are more of an umbrella term for the movement of slush. The first definition of slushflows describes them as a mud like flow of water saturated snow moving in a stream channel (Perov, 1998; Washburn and Goldthwait, 1958). Slushflows have been redefined through the years and now may include events not restricted to stream channels (Hestnes, 1996). A definition is presented in Figure 1 that shows slushflows exist between wet snow avalanches and inundation and flooding (Hestnes and Jaedicke, 2018).

The International Classification of Seasonal Snow on the Ground (Fierz et al., 2009) defines slushflows as “A mudflow-like outburst of water-saturated, i.e., soaked snow (see slush, Mfsl), often along a stream course. Commonly occurring after rainfall and/or intense thawing have produced more water than can drain through the snow.”

The commonality between all these definitions is slushflows are a rapid movement of very wet snow. Very wet snow can be defined as snow that has a liquid water content higher than a snow sample of freely drained snow. Wet snow has a residual liquid water content of 3-6% by volume, meaning anything higher than that should lead to percolation of liquid water (Fierz et al., 2009).

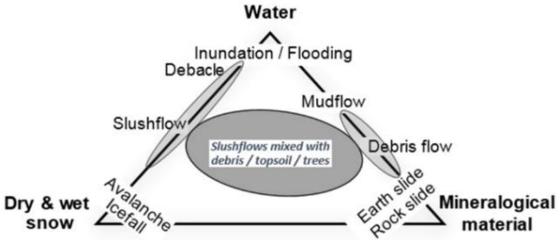

Figure 1: Classification of rapid mass movements that showcases a definition of slushflows as a flow of snow at higher water contents than wet snow avalanches (figure from Hestnes and Jaedicke, 2018).

In most of the definitions of slushflows there is not a criterion to represent flow dynamics (turbulent or laminar). However, practitioners often refer to slushflows as a rapid and turbulent movement of water saturated snow and use other terms for slushflows with a more fluvial type movement that occur on gentle terrain. Another potential problem with the definition of slushflows is the lack of definition of water saturated snow. If we adopt the definition from soil physics, water saturated snow would be snow with all of the pore space filled with liquid water.

1.2 Slushflow formation

Slushflows release during periods where the ground has a seasonal snow cover. There are two methods that can produce high liquid water contents in the snowpack, the first being a snowpack that has restricted drainage (to the ground or down slope). The second is when the input of liquid water is faster than the movement of water through the snowpack. In Norway early and mid-winter slushflows are typically formed from rain on snow events (Jaedicke et al., 2013). Early season snow cover is often shallow which makes it easier to saturate than a thick late-season snowpack. Melt driven events tend to happen during warmer spring and summer days. Wind during warm days causes a convection effect which enhances the melt rate.

1.3 Slushflow dynamics

There is a great diversity in the initiation and dynamics of slushflows. Slushflows are often thought to form on flatter terrain as seen by Elder and Kattelmann (1993), however slushflows have formed on Mt Fuji in Japan on slopes between 25° and 35° (Pérez-Guillén et al., 2019). The flow movement has been described to span from almost laminar to fully turbulent flow (Hestnes, 1996). Because of the diversity in initiation and flow dynamics vague definitions of slushflows have been used in past work to cover all such movements. “Flowing mixtures of water and snow” has been used to describe river break ups and slushflow (Hestnes, 1996 from Washburn, 1979) and “rapid mass movement of water-saturated snow” was used to interrogate the body of slushflow knowledge worldwide (Hestnes, 1985).

Gude and Scherer (1998) describe the dynamics of a slushflow to exist between fluvial flood motion and snow avalanches, in which the starting conditions must be water saturated snow. The distinction between a river break up and a slushflow is not clear (Nyberg, 1989), and Washburn (1979) (as cited in (Nyberg, 1989)) states that a slushflow may release as a form of spring river breakups.

2. METHODS

To justify the need to further classify slushflows into subcategories we will examine three separate events that occurred in northern Norway in 2023 (Figure2). These events show the diversity in the flow dynamics, initiation, and formation of slushflows, considering terrain and weather.

The classification system should group events that show similar behaviors and therefore more similar causal drivers.

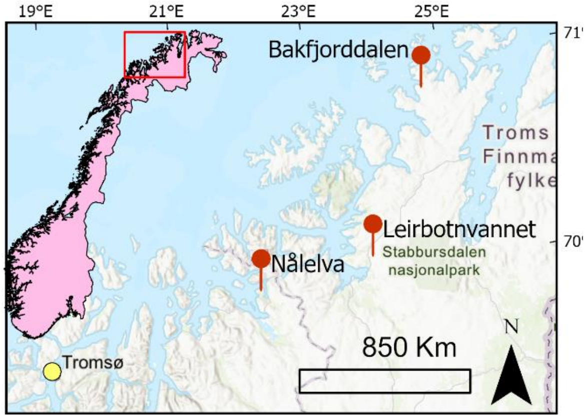

Figure 2: Location of the three slushflows described in this paper. They that occurred in Norther Norway in the 2022-2023 winter.

2.1 *Bakfjorddalen*

The slushflow event that occurred at Bakfjordalen, Finnmark on 17 February 2023 (Figure 3) swept an excavator and car off the road and down slope. The run out (about 0.35 km from 180 masl to 107 masl with an average slope angle of 12°) can be characterized as short due to the limited amount of snow and availability of liquid water. The slushflow entrained wet snow and some liquid water from the stream, however the amount of material was not that much as this is a small event. A patch of water saturated snow can be seen in Figure 3 above the release area (photo taken after the event). The release area can be characterized as a crown fracture (Hestnes, 1985) above a small drainage stream. The release area is considered steep for a slushflow, with parts of it over 30°. This could also be considered a human triggered slushflow as the excavator was clearing snow around the road. Most likely the drainage got clogged which quickly changed the release area snowpack hydrology. A rapid increase in free liquid water in the snowpack will change the strength of the bonds between snow grains (Schlumpf et al., 2024) and increase the pore pressure, both these factors likely played a role in this type of event.

The weather before this even was warm, between 3-5° C, which included some rain (less than 10 mm the day of the event) and moderate snow melt. There was about 40 mm spread out over the 4 days before the event.

Figure 3: Human triggered slushflow over a road in Finnmark. The release can be classified as a crown feature. Photo Trond Nilsen

2.2 *Nålelva, Burfjord*

On 24 April 2023 a slushflow event damaged a road in Burfjord, Troms, which left the road closed for several days. The slushflow blocked road access to several houses as the road was being rebuilt. This event started from a patch of water saturated snow located on bog land. The runout distance was between 1 and 2 km (about 450 masl to 0 masl), which mostly followed a stream bed ending in the fjord. The average slope of the flow was about 8°.

The release mechanism is surface runoff from a water saturated patch of snow. There was more drainage of melt/rainwater into the small catchment than outflow from the drainage system inside or below the snowpack. This resulted in liquid water runoff on the snow surface. The surface runoff eroded an increasingly larger drainage channel which led to increasing the amount of snow entrainment (seen in Figure 4). The amount of entrained material increased greatly as the flow moved into steeper terrain, where eventually it was able to carry soil and rock debris ripped from the stream bed.

The weather before the event was warm (up to 5° C) and rain (about 20 mm/day) until two days before the event where temperatures cooled down just blow 0° C and a small amount (2 cm) of new snow fell.

2.3 Leirbotnvannet

The event at Leirbotnvannet, Finnmark, on 13 May 2023 caused a main road into the city of Alta, Norway to be closed for several hours due to snow and ice deposition (Figure 5). The flow also damaged several parked cars, two of which were entrained and were deposited several hundred meters downstream on a frozen lake. This event had a runout of more than 6 kilometers (from above 300 masl to 158 masl), displaying a very long runout. The flow lost momentum as it reached a frozen lake.

Figure 4: Slushflow in Troms. Water draining on the top of the snowpack started this event. Photo Vilde Hansen

It appears that this event started from a water saturated bog where drainage from the top of the snowpack entrained snow into a slightly steeper slope. The slushflow first entrained more wet snow into the flow before entering an open river channel. Once the flow entered the river, river water plus ice blocks and snow from the sides of the channel became entrained in the flow, with unlimited water availability. At this point, it is likely that the flow transitioned from a turbulent flow into fluvial flood-like event. Most of the track consisted of a river channel which can be considered a very gentle slope (less than 2 ° on average). The high amounts of liquid water that joined this flow was the driving force of the extremely long runout on relatively gentle terrain. The movement type can be described as almost laminar flow with large ice blocks and lose snow mixed into the river.

Figure 5: The slushflow travelled down an open and flowing river. The runout was several km down a gentle sloped river. Debris of ice and snow can be seen on the road and in a parking lot. Photo Trond Nilson

On the day of the event and several days prior, air temperatures were approximately 5° C. There was also some rain and snow melt the day of the event and a few days before. The day of the event there was less than 20 mm of rain and the day before the event there was approximately 30 mm of rain. This is less than 40 mm / 24 hours of rain/melt water threshold used in the slushflow forecast.

3. DISCUSSION

3.1 Slushflow formation and forecasting

These three events highlight the difficulty of predicting when the weather, snowpack and hydraulic system are favorable for slushflow formation. The events presented occurred on days that had rain/meltwater well below the 30 mm – 50 mm threshold that has been associated with slushflow hazard (Jaedicke et al., 2013). Furthermore, it is not sufficient to quantify the capability of the slush snow to mobilize, as the path of the slushflow can also amplify the hazard via entrainment, which is rarely considered for snow avalanche forecasts. Lastly there are multiple processes that can lead to a failure in the snowpack: These events highlighted surface runoff, a crown fracture and human triggering. The regional slushflow forecast, currently in its infancy, assessed a low danger for slushflows or danger level 1 for all three events. The slushflow forecast states that it does not forecast human triggered slushflow events like the event at Bakfjordalen (section 2.1). Just before and during the events at Bakfjordalen and Leirvotnvannet (section 2.3) there was moderate rain and snowmelt, however the predicted amount of liquid water in the snowpack did not meet the necessary threshold for increasing the danger level in the slushflow forecast. After the Leirbotnvannet event the danger level was increased to level 2 for a very large part of Northern Norway (Most of Troms and Finnmark counties). The event at Nålelva Burfjord (section 2.2) had temperatures below freezing and a small amount of new snow the day of the event. The water inside the snowpack was from the previous few days where the region experienced light rain and positive temperatures. This shows that there can be a lag between the input of water in the snowpack and the triggering of an event. The mild weather preceding these events that were unpredicted shows that to refine the forecast to include these conditions would mean very large parts of the countryside would be in an increased danger level for large chunks of time, which is undesirable for an impactful forecast. More refinement of the process understanding is needed.

In the examples given there are two different release mechanisms displayed, the erosion and crown failure types. These release types have different formation/triggering mechanisms. For example, a crown failure type slushflow could be triggered by altering an established drainage system in the snowpack (like Bakfjorddalen), while another method for initiating a crown failure is strong rain on snow events leading to rapid weaking of large snow grains in the lower snow layers. To increase our forecasting capabilities, each release mechanism should be forecast separately. This is a similar method that snow avalanche forecasts around the world have adopted (Lazar et al., 2012; Statham et al., 2018).

Depth hoar and coarse-grained snow has been associated with the formation of slushflows (Hestnes, 1996; Sund et al., 2024). However, the rate of snow grain growth with the volumetric percentage of liquid water is non-linear (Brun, 1989). Snow grains at saturation (or in the funicular regime) will be quickly metamorphosed into rounded melt forms (Brun, 1989). Therefore, the strength of a saturated snowpack can be a function of snow grain size but not the snow grain form. Depth hoar and other coarse-grained snow are among the larger snow grain types. When these larger crystals get wet, they rapidly transform into large melt form crystals. The larger grains leave less bonds between crystals and a higher liquid water content with larger pores reducing the amount of water tension holding the snowpack together. This process would lead to a weakening of the lower layers of the snowpack which could promote a slushflow of the crown failure type, as seen at Bakfjorddalen. Mellor (1978) states that slushflows release due to weakening of bonds between snow grains via snow pore water pressure and metamorphism. The saturation at the top of the snowpack has little relevance to the process at the bottom of the snowpack where the failure initiates. Therefore, a fully saturated snow column is probably not necessary for the formation of the crown failure slushflows.

The size of the snow grains probably has little effect on the formation of erosion type slushflows like the Nålelva event. There has been evidence of erosion type slushflows starting from a sudden burst of water being released from a frozen lake after the lake was hit by a large snow avalanche, where the snow grains were probably not large melt forms (pers. comms. Krister Kristensen and Frode Sandersen 8, September 2023).

Contrast this to the Nålelva event where the slushflow started from drainage from the top of the snowpack. For this event the depth of the snow and the rates of water into and out of the catchment of saturated snow is important. The structure of the grains at the bottom of the snowpack are irrelevant to the formation of this type of flow as the process starts at the top. There is an opportunity to improve the predictive capabilities of slushflow risk by assessing formation conditions independently for different release mechanisms.

3.2 _Slushflow dynamics and runout modeling_

The examples of slushflows presented in this paper show both flow regimes, Bakfjordalen had a very short turbulent flow and Leirbotnvannet had a very long fluvial like flow. The difference in flow dynamics between the Bakfjordalen and the Leirbotnvannet events are probably due to the availability of additional water. When a slushflow enters an open stream with unlimited access to liquid water the flow becomes more laminar. Conversely release areas on open slopes may not run into a river channel and therefore have limited water uptake. The event at Nålelva also demonstrates an event in a stream channel that didn’t have unlimited water to entrain, and the flow remained a turbulent flow type.

A classification system needs to address the availability of water. Events with high water availability may consider using a simulation tool for river processes. Where an event with limited water availability should use a more turbulent flow simulation tool.

Slushflows start as the movement of water saturated snow but can quickly entrain material as it flows down slope. The debris at Nålelva was a mixture of water, snow, soil and rock when it crossed and destroyed a road. The Leirbotnvannet event have very little soil and rocks in the debris but contained large blocks of river ice. The amount, density and composition of the entrained material is important for numerical simulations of the runout or impact pressure of slushflows.

Hazard maps or hazard indication maps together with spatial planning are a good method for natural hazard risk reduction. Simulations on the spatial extent of the hazard is needed for widescale hazard mapping. Based on the diversity of slushflow dynamics there should be different simulation tools used for runout calculations between events demonstrating turbulent flow and laminar flow. Some slushflows may need to be simulated with multiple models as the dynamics transitions into a differ flow regime.

Three different friction parameters were suggested for modelling the runouts of slushflows within the simulation tool RAMMS Debrisflow (Christen et al., 2010; Kronholm, 2021). RAMMS Debrisflow shows some promising results for replicating turbulent slushflows with steeper release areas, however there are major shortcomings for events like Leirbotnvannet where the release area is flatter and the flow is more laminar (Hansen et al., 2024; Hansen, 2024). These friction parameters are suggested to be based on return periods 100, 1000 and 5000 years, based off of only five events. Defining return periods and developing a robust parametrization for slushflows is difficult due to the lack of quality historical data that is available (D'Amboise et al 2023).

The starting conditions of the slushflow also contribute to how events should be simulated. Erosion type events have a low initial mass of snow and start as an entrainment process. Crown fractures start with higher initial mass and may have a lower water content. There is another type of release mechanism that has not been described in this paper, which is when a large avalanche hits a lake (frozen or unfrozen). The pressure of the avalanche's debris may displace water in a surge out through the lake outlet into the snowpack starting the slushflow with some initial energy, high amounts of liquid water but low amounts of solid mass.

3.3 Norwegian infrastructure for slushflow data

In Norway, slushflow event data are included in the National Landslide database (NSDB, nasjonale skredhendelsesdatabasen) managed by the Norwegian Water and Energy Directorate (NVE). Slushflow is a sub-category of the types of slides in this database. Landslide, snow avalanches, debris flow, slushflows, and other gravitational natural hazard events are stored in the data base. Information on the location, date and time are necessary information for an event, and often it is the case that additional information is also stored with the event. The Bakfjordalen and Nålelva events are registered in this database, however the Leirbotnvannet event is not. That is probably because practitioners tend to use the term slushflow to describe turbulent flow of water and snow and river break out events for laminar flows.

The data quality for slushflows in this database is the limiting factor in terms of developing forecasting and spatial planning tools for risk reduction. There currently is not a standard method to include the release mechanisms, amount of liquid water, flow type, entrainment amount and material in the database. Getting basic information into the database on location of release, runout distance, and release type is critical for improving on the forecasting and simulations of slushflows. We propose a slushflow classification system, similar to the classification system of snow avalanches. This system should be developed, implemented and used to classify events in the NSDB, and elsewhere where slushflows are a concern. The classification should be based on the release mechanism, size, material composition and the availability of liquid water/flow regime. Further classification of the terrain of the release area, track and runout areas will help with runout model development.

4. CONCLUSION

Three slushflows that occurred in 2023 show the diversity of behavior that slushflows can display. In the Norwegian database two of the three of these events were registerd as a slushflow (Leirbotnvannet in section 2.3 is not in the database), but all three of them meet the defintion of slushflow put forward in the scientific literature. To increase the effectivenes of risk reduction measures a robust classification system is needed to group similar events. Runout simulations will be affected by the amount of liquid water and the terrain below the release area. The formation of slushflows can be snow surface processes such as the erosion types, or subsurface procesess that related to pore pressure and snow grain metamorphism in crown types. Forecasting these release mechanisms separately should enhance the predictive power of slushflow forecasts. The next steps to this work is to develop a classification system based on the composition, release type, water content, terrain and size of slushflows.

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