MOTIVATION AND THE INITIAL STEPS FOR A DATA SCIENCE INVESTIGATION ON SLUSHFLOWS IN NORTHERN NORWAY

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ABSTRACT: Slushflows are rapid mass movements where the mass consists of snow that is water saturated (or close to saturation), often entraining ice, soil, and rock debris. Understanding slushflow formation requires the evaluation of a number of variables related to the terrain, snowpack, weather and hydraulic conditions. This is difficult, as events are limited, and observations are sparse and often misrepresented (as avalanches or debris flows) in databases due to limited understanding. In this study we investigate the data quality and spatial distribution of slushflow events in Norway using the Norwegian National Mass Movement Database (NSDB), which contains 1051 unique slushflow events assigned a data quality grade. The data quality grades are based on a mix of spatial and temporal accuracies, and it was found that grade A and B were of sufficient accuracy for most temporal studies. However, we conclude that even the spatial accuracy of the highest quality grade (A) does not meet the requirements needed for robust investigations on the spatial influence of slushflow formation. This is because most of the data collected is missing information on the location of release areas. The data suggest that hydraulic sinks calculated on a 10 m DEM resolution could be an indicator for the formation of a type of slushflow that are released from bogs, depressions, and lakes. Our findings highlight the need to continue to improve on data collection of slushflow events. A focus should be put on collecting an accurate location for the release areas and runout zones of slushflows.

KEYWORDS: Slushflows, Data Science, Spatial Data, Terrain Characteristics

1. INTRODUCTION

A slushflow is a type of rapid mass movement that consists of very wet to saturated snow. Often the ground acts as the sliding surface causing the entrainment of ice, soil and rock into the slushflow (Hestnes and Sandersen, 2000; Hestnes, 1985; Hestnes et al., 2017), making the deposit look similar to a debris flow. Extremely highwater content makes the flows sensitive to terrain features which result in seemingly erratic bends in the track and runout areas (Blikra and Nemec, 1998). High water contents result in dramatically long runouts.

Slushflows occur less frequently than snow avalanches. Even in the most active known slushflow areas such as the Gilsbakkagil and the Bú√argil catchments in Iceland, there may be several years between slushflow events. Alternatively, they may also have clustered repeat events in the same season, such as in 1997 and 1998 where there were 3 and 2 events respectively (Decaulne and Sæmundsson, 2006). The low frequency of events makes it difficult to justify a highly instrumented field site to study slushflow formation. Hence, most literature on slushflows is comprised of event case studies (Elder and Kattelmann, 1993) or statistical analysis of events (Jaedicke et al., 2013).

The formations of slushflows requires specific terrain features, snowpack, weather, and hydraulic conditions. These variables are split between static and dynamic variables. Static variables are those considered constant on a greater than a yearly time scale. Some examples are terrain characteristics such as elevation, slope, and curvature. Dynamic variables can change on a sub-daily time scale, such as the precipitation, radiation, snowpack and hydraulic conditions of the snow and soil.

Slushflow formation needs liquid water contents as high as 35-50 % volumetric water content (Nobles, 1966; Mellor, 1978), where typical seasonal snow cover has < 5 % (D'amboise et al., 2017; Vionnet et al., 2012). Melt water and rain on snow are the two drivers that can saturate the snowpack (Scherer et al., 1998), and in arctic regions the low angle of the sun accelerates melt on some steeper south facing slopes (Onesti, 1985). The highly saturated snowpack in the release area can be distinguished visually by their gray and/or blueish color compared to non-saturated seasonal snow cover (Hestnes, 1985). Gude and Scherer (1995), state that water pressure is an

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important release mechanism, but the destabilizing effect of grain metamorphism is not that important.

There have been some snow layer types that have been associated with slushflow formation such as weak cohesionless coarse grain snow, crust layers and cohesionless new snow (Hestnes, 1985). The description by Hestnes (1985) of cohesionless coarse grain snow is most likely to be facets or depth hoar, but the description is left a little ambiguous. Wet snow metamorphism acts on the scale of several hours to several days and is enhanced in saturated conditions (Colbeck, 1986).

Slushflows often start in flatter water saturated areas where meltwater inflow is higher than outflow (Scherer et al., 1998). Scherer (1998), states that melt alone cannot pool water in the snowpack there must be a downhill transport of water from a larger catchment area into a bottle neck area to reach the necessary saturation for slushflow when derived from meltwater. To achieve such high water contents there must be some mechanism that hinders drainage of the snowpack such as weakly developed soils, bedrock (no soil) and frozen ground (permafrost or seasonally frozen soils) (Scherer et al., 1998). Terrain steepness seems to be important to slushflow formation because steeper terrain drains water through the snow matrix, at the snow-soil interface and through to the soil layer. Slushflows can form on low angle terrain such as the one reported to have started on a 6 ° slope and traveled over a track with an average steepness of 3 ° (Elder and Kattelmann, 1993).

Hestnes (1985) outlines three main types of release types for slushflows:

1. Sudden release from crown surface
2. Rapid drainage of snow-embanked saturated snowfields through narrow outlets
3. Rapid headward increase in bogs or terrain depressions

We hypothesize that these release mechanisms have similar dynamic variables contributing to slushflow formation, however the static variables (terrain features) differ. As a first step to explore this hypothesize, we look at the available data with regards to quantity and quality and develop a strategy for acceptable methods to be used in further studies on slushflow formation which utilizes this dataset. Particular interests of this study are put on the static variables to characterize terrain that is favorable to slushflow formation.

2. DATA SOURCES

2.1 The National rapid mass movement database

Slushflows in Norway are reported in the National mass movement database (Nasjonale skreddatabasen, NSDB) (www.skredregistrering.no) (Jaedicke et al., 2009) managed by the Norwegian water and energy directorate (NVE).

The NSDB contains all rapid mass movement types such as landslides, rockfall, debris flows, snow avalanches and ice falls. Slushflows are categorized as a subtype of snow avalanches (Jaedicke et al., 2009). The major attributes collected in NSDB are the location of the rapid mass movement (as a GIS objects), the date/time of the event and the type of mass movement. The location of the datapoints are not standardized to a specific spot on the slushflow (release area, runout, or track), and in most cases there is no indication on what part of the slushflow has been used.

As of spring 2023 the NSDB database contains 1051 unique slushflow events with more being added each year. Data on events is and has been collected by different people and institutions in Norway. Some of the institutions include The Geological survey of Norway, The Norwegian Geotechnical Institute, The Directorate of Public Roads, The National Rail Administration and the NVE. Additionally, individuals can register observations of slushflows amongst other natural hazard events or hazard indications via the Regobs app or website (Regobs.no). The observations in Regobs that have been tagged as a slushflow event are automatically collected and added to the NSDB. Photos and other supplemental material such as snow pit observations can also be uploaded to the NSDB.

NVE has started assigning a data quality grade to the slushflow events in the database. There are 4 quality categories that look to verify the type of mass movement, the location of the event and the date/time of the event. The quality grades are:

- Grade A: Know date, time and position
- Grade B: Time accuracy 24 hours, location accuracy within 50 m.
- Grade C: Confirmed as a slushflow but time and location not verified.
- Grade D: Unassigned but reported as a slushflow.

New data added to the database are automatically assigned grade D but can be upgraded to higher grades if there is supplementary material (photos, newspaper articles, etc.) which can verify the mass movement type, location, and date/time.

2.2 *Digital elevation Models*

In this work we used the location information and digital elevation models (DEMs) to attach an elevation (Z) value to the locations of the slushflows and to calculate the steepness of the terrain. These DEMs were downloaded from the Norwegian Mapping Authority (kartverket). The 10 m and 50 m DEMs were used in this study.

2.3 *Hydrological layers*

Two Hydrological GIS layers were calculated from the DEM via Python. The Pysheds library was used to calculate the hydraulic sinks (a cell or cluster of cells in the DEM which has no downhill neighbor cell for drainage) in the terrain and the “flow accumulation” which will henceforth be called uphill potential. The reason for the terminology is not confused flow in ”flow accumulation” which is a catchment hydrology term with the flow of the rapid mass movement. The uphill potential of a raster cell is calculated from the DEM and is the number of how many raster cells are draining into it (using a steepest decent method). Locations at the top of a hill will have a lower uphill potential than a location at the bottom of the hill.

3. STATISTICAL METHODS AND RESULTS

Slushflows have a release area, track and runout or deposition area similar to snow avalanches. One of the largest open questions on data quality is where the location of the observation has been placed (release area, track or runout area). For the purpose of characterizing the terrain associated with slushflow release areas it is desirable to have the locations of the event in the NSDB database to be located at the release area. However, the location reported in the database is often located at the point where the mass movement crosses some infrastructure, or the furthest reaches of its runout (Jaedicke et al., 2009). This is from the result of compilation from a number of different data sources from different institutions. Data collected from the National Rail Administration and the Directorate of Public Roads understandably report the location of mass movement events at points where they were observed crossing or impacting rail tracks and roads.

The NSDB has 1051 slushflow events as of spring 2023. Table 1 shows the breakdown of the quality grades in the NSDB as of spring 2023.

Quality grade	A	B	C	D
Events	15	75	260	701

Table 1: The number of events in each quality grade in the NSDB as of spring 2023.

Studies based on dynamic variables and the temporal evolution of slushflow formation required more data (weather and snowpack) and will be examined in future studies to extend this work.

3.1 *Yearly distribution of events*

The recording of slushflow events span from 1951-2023. Figure 1 shows the yearly distribution of the events in the database. The majority of the data is in the quality grade D. In the early 2000s there were few (< 20) events recorded each year. There has been a major increase in recorded events in recent years (excluding 2022 and 2023).

The quality grades have been manually issued in the past few years by NVE. The strategy was to start with the more recent data and work back in time to assign quality grades. Before 2012 there were no events quality checked past grade C. This is because to grade an event as A or B it must be manually checked, whereas some data sources could automatically confirm the mass movement type as a slushflow, hence the assignation of a grade of C.

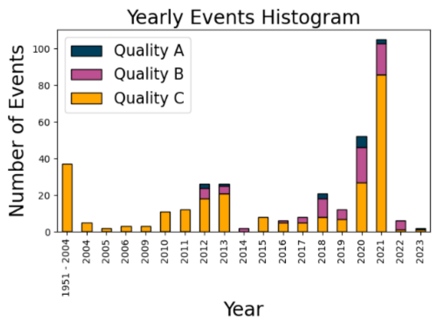

Figure 1 shows the number of slushflow events that happened each year. The colors distinguish the data quality score.

3.2 *Location distribution*

The spatial distribution of slushflow events that have been recorded in the database are shown in figure 2. The data shows that more events were recorded in southern Norway than in the north. This is likely in part due to the bias in the data where events in areas close to inhabited places and infrastructure are reported more often than in rural areas.

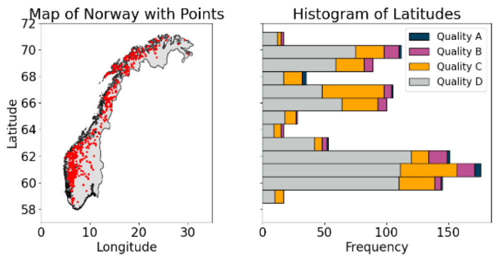

Figure 2 shows the latitude of the events in the database.

The map in figure 2 shows that there tends to be a higher frequency of events close to the coast. This is probably because the coasts tend to be the more mountainous regions in Norway, as well as experiencing a maritime snow climate. A maritime snow climate is characterized as warmer and wetter than the continental snow climate. There are often rain on snow events throughout the winter in maritime snow climates.

3.3 <u>Elevation of events</u>

Figure 3 shows a box plot of the elevation of the recorded point of the slushflow. Quality grade B and grade C have a similar distribution of elevations. However, there are many more outliers at higher elevations on grade C data, probably because many of the events at elevation are wet snow avalanches that have been mischaracterized in Regobs by backcountry users who are unaware of the technical definitions of very wet snow and slush. It is also noteworthy to see that grade A data has a similar median value however the upper quartile (~900 m) and max value (~1200 m) are much larger. Verified slushflow events therefore occur across most elevations, and predominantly below 1000 m

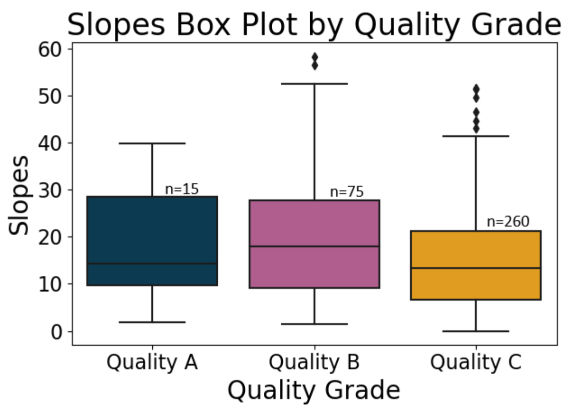

Figure 3: Box plot of elevation of slushflow events as recorded in the NSBD. The three highest data quality categories are show.

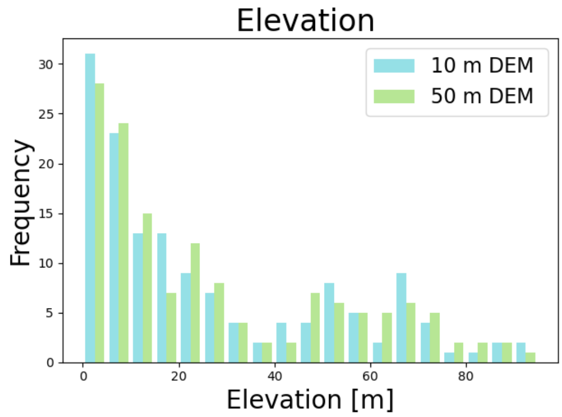

Figure 4: Histogram of the elevation of the points in the national databased classified as slushflows with a quality A, B and C. Blue shows elevations derived from the 10 m DEM where green shows elevations derived 50 m DEM.

Figure 4 shows that there is little difference between the distribution of events at different elevations when calculated with a 10 m and 50 m DEM, which is expected. Figures 3 and 4 show that there is a majority of events happening at lower elevations. The most frequent reported events show elevations were within 0 - 25 m above sea level for data graded A, B and C, see figure 4. This suggests that the locations reported in the NSDB is frequently not the location of the release area, even for the best quality data.

3.4 <u>Slope of events</u>

Slushflows have been reported to start on gentler terrain when compared to snow avalanches (Scherer et al., 1998). The slopes morphology can help to identify the actual release areas, as they will not be found in steep terrain. However, slushflows often release from areas where flatter terrain rolls over to steeper terrain, which might register as steep terrain when calculated from a DEM. Events that have been recorded at elevations < 25 m or on terrain steepness >20 ° are strong indications that the point is not located on a slushflow release area, see Figure 5. The majority of the data is located at low slope angles < 20 °, which is expected for slushflow starting areas but could also be on the tracks or runout areas. Figure 5 snows that there are some events reported on slopes steeper than 20 ° for all quality grades.

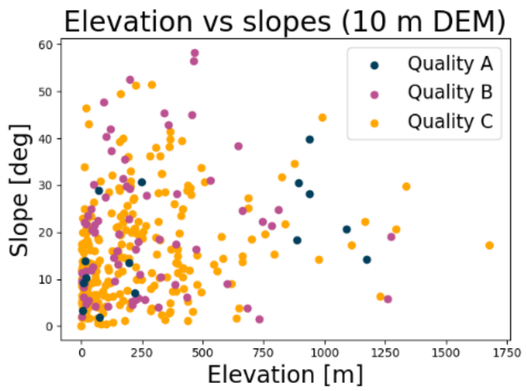

Figure 5 shows the elevation of observations vs the slope of the terrain. The colors show the data quality grades.

3.5 Hydraulic sinks

Some slushflows form in bogs, depressions, water saturated snowfields and lakes (Hestnes et al., 2017). On the DEM some of these features can be identified as a hydraulic sink. These are areas with an unreasonable flow direction calculated from a DEM, meaning all neighboring cells direct flow into a central sink with no outflow.

The occurrence and location of these sinks is related to the resolution of the DEM. They are typically cells on the DEM to which no flow direction can be assigned because all neighboring cells are at a higher elevation.

	Sinks	No sinks
10 m	4	86
50 m	1	89

Table 2: The number of points in the NSDB located in a hydraulic sink for data quality A, B and C.

Table 2 shows that there are some, but very few slushflow reported in sinks at 10 m and 50 m resolution. Event points that have been registered on the runout track or where the slushflow interacts with infrastructure are not expected to be located in hydraulic sinks, these criteria rule out a large part of the NSDB data. Therefore, it is expected that the number of points from the NSDB located in hydraulic sinks is very low. Furthermore, bogs, depressions and lakes are associated with one of the three release types as reported from Hestnes (1985), making hydraulic sinks only relevant for a subset of slushflow events. This further reduces our expectation of having events recorded in hydraulic sinks.

3.6 Uphill potential

Figure 6 shows that the majority of slushflows observations occur on terrain that doesn't have a very large uphill potential. That means there isn't too much terrain that drains into the slushflow observation point. This is unexpected as pooling of water would be associated with places that have a large catchment (large uphill potential) draining into the area. Furthermore, it is expected that points located in the runout areas would have a larger uphill potential than release areas. Figure 7 checks to see if there are areas around the observation area that have a larger uphill potential. By including the neighboring raster cells, it increases the spatial extent while maintaining the resolution of the DEM it was calculated from. Using the maximum uphill potential from the neighbor cells is an attempt to compensate for the unknown spatial accuracy of the NSDB. The results from Figures 6 and 7 show that the majority of slushflows were not reported in or next to stream beds or rivers.

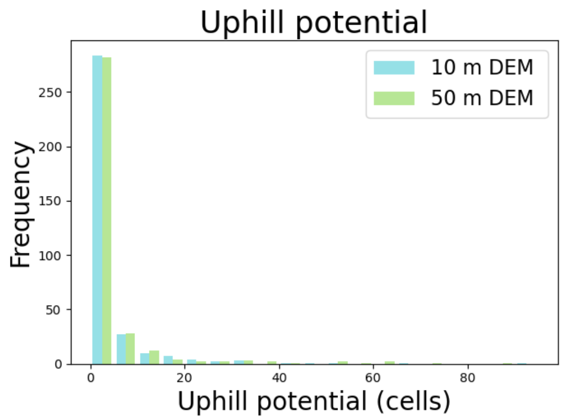

Figure 6: Histogram of the uphill potential. Where the Blue is taken from the 10 m DEM and the green is from the 50 m DEM.

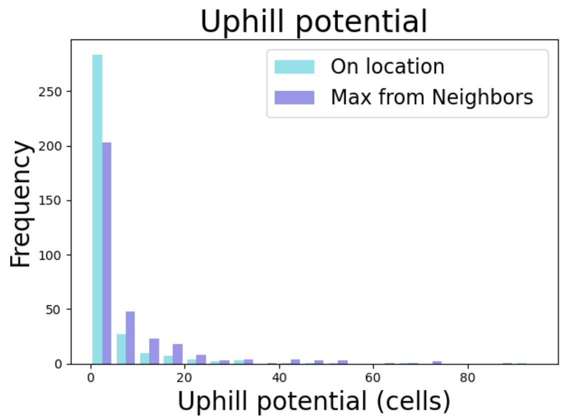

Figure 7: histogram of the uphill potential from the 10 m DEM. The blue histogram shows uphill potential for the raster cell that contains the location of a slushflow event. The purple shows the maximum uphill potential for the cell that contains the location of a slushflow event and the neighboring cells.

4. DISCUSSIONS

4.1 Data Quality

Data quantity and quality is one of the major issues that slushflow research faces. One reason why there is little data and the quality is not great is that slushflow deposits are not always easy to recognize. The debris caused by a slushflow is often misclassified as from a debris flow or wet snow avalanche because they can be initiated by wet snow avalanches which transition to a slushflow and/or could transition from a slushflow to a debris flow (Hestnes and Kristensen, 2010). Another reason for data quality issues is that there has not been a standardized method to record events in Norway. The Geological survey of Norway reports slushflow events at the location of fatalities, injuries, or structural damage. The Directorate of Public Roads and The National Rail Administration report on events at the location where slushflows crossed the roads or rail lines. To advance research on slushflow formation the static variables that have a spatial relevance to slushflow formation (slope, elevation, curvature, hydraulic sinks, and uphill potential) must be analyzed. Therefore, the most relevant data to record (accurately) is the release location and the location of the furthest runout. Preferably these would be recorded as GIS polygons outlining the release area, track and accumulation area of the slushflow.

Despite the issues with data quality data from the NSDB, these data can still be used to research some aspects of slushflow formation. This study investigated the NSDB for its limitations for different potential data science applications. The NSDB has a data quality grade that has been and is currently being applied to events. The time distribution of recorded events in Figure 1 shows that there are strong improvements to the number of quality events recorded each year. The quality of the data has also been improving in the last 6 years where almost half the events were quality levels A or B (excluding the year 2021, where there were over 100 events recorded). The grading considers a combination of temporal and spatial aspects as well as the degree of certainty of an event being classified correctly as a slushflow.

Data quality grades A and B are of a sufficient quality to use for investigations on the dynamic variables that affect slushflow formation. However, currently there are only 90 events that meet these data quality standards, which is too little for some sophisticated machine learning methods. Each year there are about 10-20 quality events that are added to the database at a high-quality grade, and each year some older events are being upgraded to A and B grades. For temporal studies more than 900 additional events with quality grades C and D could be potential used. Quality grade C and D have time associated with them however the majority of the events temporal accuracies have not been or cannot be quality checked.

There is a time lag between the water input to the snowpack and the snowpack/hydraulic response to the added water. For temporal studies on wet snow avalanches correlating event activity to snowpack or weather conditions of the prior 1 to 5 days has been a common method (Mitterer and Schweizer, 2013). We believe a similar method could be relevant for investigating slushflow formation. Time accuracy finer than a day is of lesser importance for improving slushflow forecasting because forecasts are made on regional spatial scales of several to many km^2. Dynamic variables will evolve differently across forecast region with respect to terrain features such as elevation, slope, and aspect. Threshold values used to relate dynamic variables to slushflow activity must consider the effect of terrain amplifications on melt water and the snowpacks hydrology which might not be well represented by dynamic variables defined on a regional spatial scale.

4.2 Distribution of slushflow

Slushflows have been recorded around the world in areas with a seasonal snow cover (Onesti and Hestnes, 1989). However, Hestnes (2017) states that slushflows are associated with arctic communities more often than communities outside of the arctic. If we take the events in the NSDB that have been quality checked (all occurred within the previous 12 years) 162 of 350 have occurred south of the arctic circle in Norway (65 ° N). A little more than half the slushflows have occurred in the arctic and about half the land mass of Norway is located above the arctic circle. The majority of Norway's population reside in large urban centers below the arctic circle, where slushflow observations are assumed to be more commonly reported and skews the data southward. However, there is a only small amount of Norway that is not considered climatically arctic or sub-arctic. Therefore, it would be interesting to compare the effects of latitude on slushflow formation in areas such as the west coast of the USA and Canada where there is undisturbed mountainous terrain. In the USA and Canada there are continuous transitions in the climate (arctic to non-arctic) and snow climate (maritime to continental) which would help more precisely describe how climate conditions effect slushflow formation.

4.3 *Hydraulic sinks and catchment size*

Hestnes (1985) identified rapid drainage of snow-embanked, saturated snowfields through a narrow outlet as one of the three main methods for slushflow initiation. The hydraulic sinks were used to try to identify areas in the terrain that could cause water saturated snow fields and would have a narrow drainage outlet. Although there are major questions about data quality regarding what part of the slushflow are used for the location of the event within the NSDB, it doesn't seem that hydraulic sinks as calculated from the 50 m resolution is a good indicator for slushflow release areas as only 1 out of 90 event points were located in a sink.

A small amount of terrain in Norway (1.4 %) is classified as a hydraulic sink when calculated from a 10 m resolution DEM. Looking at the quality grades A and B, 4.4 % (4 of 90) of the observations were located in hydraulic sinks. This percentage is high considering that sinks could indicate the location of a slushflow release area and a large portion of the 90 events were not recorded on the release area. Slushflows that release from depressions and bogs consisted of 8.8 % (3 of 34) of events in Hestnes' (1985) study, which was the least common release mechanism reported. Therefore, hydraulic sinks calculated from 10 m resolution DEM have the potential to be a good indicator of slushflow release areas for one of the three slushflow release types.

Since melt rates alone cannot make saturations high enough for slushflow formation it is thought that terrain features and the size of the catchment or uphill potential is also a factor in the formation of water saturated snowpacks (Scherer et al., 1998). Larger catchment areas would tend to have larger uphill potential values than smaller catchments. However, figures 6 and 7 showing that uphill potential is relatively low at the observation points does not support this claim. It seems from these data that most slushflows were observed in areas where there was low uphill potential. The uphill potential should be larger at the runout of the slushflow than the starting zone in most cases. The data suggest that many of the points were recorded in the track or runout zones of the slushflow, but the uphill potential remains low. We conclude that the uphill potential calculated in this manner is not a good indicator for slushflow terrain. There are other methods that could be used to calculate an uphill potential that might summarize the uphill terrain in a way that is more significant for the identification of slushflow catchments. Alternatively catchments characteristics may not relate to the formation of slushflows which has been stated in another study on the relevance of catchment size on slushflow release (Hestnes et al., 2017).

5. CONCLUSIONS

Slushflows are a rapid mass movement that affects mountainous areas in Norway. The quality of the slushflow event data in the NSDB has been examined. There are different data quality needs depending on the research question. The slushflow event data is not suitable for spatial investigations on the release areas of slushflows because many of the slushflow observations report on the runout areas and not the release areas. However, it seems that hydraulic sinks may be an indicator for the type of slushflow that release from bogs, lakes, or depressions in the terrain. That data in the NSDB is better suited for temporal investigations as there are at least 90 data points that have an accuracy of 24 hours or better and over 1000 events recorded with lower data quality.

The quality grade is based on a mix of the spatial and temporal accuracy. The quality grading of the database should address spatial and temporal resolution separately. The data quality has been improving over the last few years. In the next year it is important to collect high quality data on slushflow events and to continue to organize the existing data by the spatial and temporal quality. An emphasis on reporting the release areas of slushflows is needed.

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