CASE STUDY OF A SLUSHFLOW IN SKARMODAL, NORWAY, IN 2010

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ABSTRACT: Slushflows are a well-known hazard in Arctic regions and, to a lesser extent, in alpine environments. With ongoing climate change, conditions that promote their release—such as specific weather patterns and snowpack structures—are expected to occur more frequently, increasing their relevance for hazard assessment. Despite this, observational data suitable for the development and validation of numerical models remain limited. Reliable back-calculations with dynamic models require well-constrained initial and boundary conditions, including release area and average release depth, as well as detailed observations of flow dynamics. In particular, run-out distance alone is insufficient for model calibration; velocity and flow depth data along the flow path are essential. This study focuses on the documented slushflow event in Skarmodalen on 16 May 2010, for which front velocities were determined over a distance of approx. 600 m in the central section of the path. Based on these observations, a profile of frontal velocity and a set of initial conditions are derived. These data are then used for back-calculations with a dynamic numerical model. The results contribute to improving the calibration and validation of slushflow models and highlight the importance of detailed field observations for hazard assessment under changing climatic conditions.

KEYWORDS: slush-flow; observations; dynamics

1. INTRODUCTION

Slushflows are rapid flows composed primarily of water and snow, with varying amounts of debris and entrained air, and can pose a considerable natural hazard (Hestnes et al. 2012; Hestnes et al. 2011; Hestnes and Jaedicke 2018). They are generally considered to occur primarily in Arctic and sub-Arctic regions, but have increasingly attracted attention in Alpine regions in recent years (e.g. Barbolini et al. 2024; Chiambretti et al. 2026). In Northern Norway, slushflows frequently threaten road infrastructure (Gauer et al. 2024), but they have also caused severe damage to buildings and resulted in fatalities.

One of the most destructive historical events occurred at Steira in Nesna Municipality on Handnesøya, Nordland County. In the early morning of 16 January 1967, several large slushflows and wet snow avalanches were released above the Litl-Steiro (Steira) farm in Steirogrenda. Additional events occurred at varying intervals until approx. 13:00, resulting in a total of 10–15 slushflows and avalanches. The largest events destroyed houses, barns, and other farm buildings and also damaged buildings on a neighbouring farm (Fig. 1). In total, seven buildings were destroyed, including four relatively new houses, and two people lost their lives.

Slushflows are a class of gravity-driven mass flows that may become more frequent as a result of climate change but have received relatively little attention in terms of numerical modeling until recently (e.g. Blatny et al. 2026; Palsson et al. 2019; Gauer 2004).

Figure 1: Slushflow event at Steira in Nesna Municipality on Handnesøya on 1967-01-16

2. SKARMODALEN EVENT 2026-05-16

In Skarmodalen, Nordland County, three slushflows occurred in the stream Rapbekken, close to the Swedish border, on 15–16 May 2010. Fig. 2 provides an overview of the stream channel together with estimated outlines of the three events. This was not the first occurrence of slushflows in Rapbekken. For example, the Swedish documentary *De kom över fjällen* (1945)[1] briefly shows a glimpse what is most likely a slushflow deposit from Rapbekken at around 4:21 min.

The area surrounding Rapbekken consists mainly of bare bedrock above an elevation of approx. 800 m asl. Below this elevation, a thin soil cover

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[1](http://www.oppetarkiv.se/video/1739244/journalfilm)

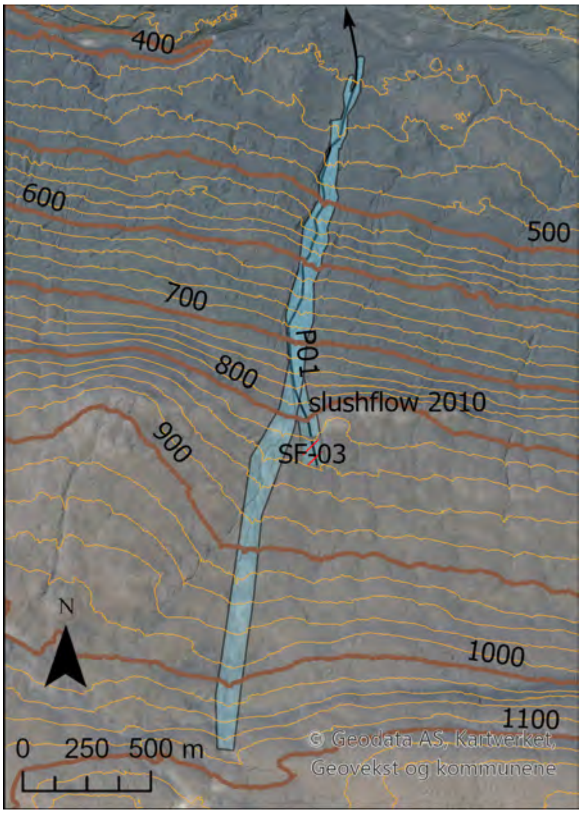

Figure 2: Overview of Rapbekken with estimates on the outline of the three slushflow events on 2010-05-15 and 2010-05-16.

supports sparse forest vegetation. The stream channel itself is composed predominantly of exposed bedrock.

2.1. Weather conditions

The weather conditions preceding the event are briefly discussed in Hestnes et al. (2012). According to the authors, a persistent high-pressure system transported warm air from Russia into Scandinavia, resulting in a sudden temperature increase of up to 20°C in parts of the region. This rapid warming caused exceptionally intense snowmelt, leading to peak runoff after 3–4 days and triggering a series of slushflows. At several meteorological stations in the larger region, the temperatures recorded in May were the highest observed in more than 150 years.

Unfortunately, no operational weather station was located in the vicinity of Skarmodalen. Therefore, we have to relay on the interpolated data from SeNorge (Lussana et al. 2018). Fig. 3 presents interpolated snow height and temperature data for Rapbekken.

The interpolated snow depth was below the climatological average throughout the winter and reached a maximum of approx. 1 m in March.

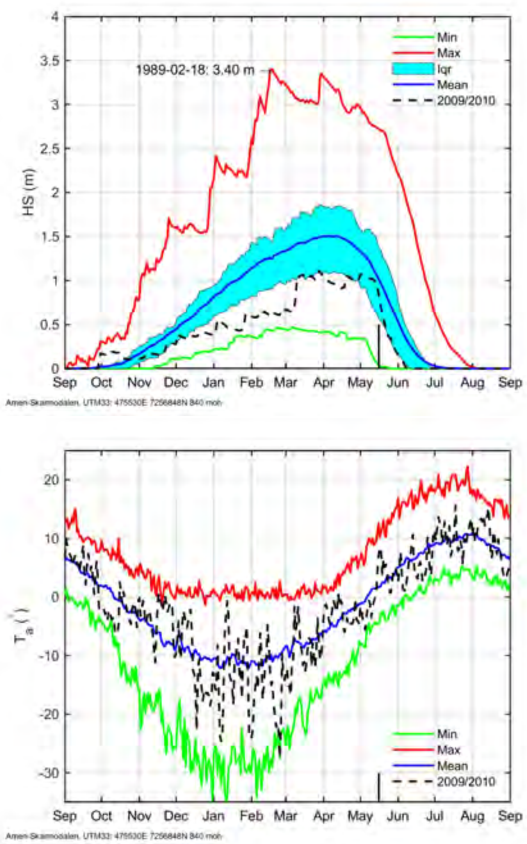

Figure 3: Interpolated snow depth and air temperature at Rapbekken derived from SeNorge. The dashed black line shows the data for the 2009/2010 season and the vertical line indicates the timing of the slushflow event.

The estimated snow depth of about 1 m immediately prior to the event is consistent with estimates derived from photographs. Although an increase in air temperature is evident, it appears to have been considerably smaller than that reported for other parts of the region. Nevertheless, the onset of rapid snowmelt during this period is clearly visible. The period from December to April was characterized by persistently low, and at times exceptionally cold, temperatures. Combined with the relatively shallow snowpack, these conditions likely favoured the development of faceted snow crystals. These observations should, however, be interpreted with caution, as the SeNorge interpolated data are subject to considerable uncertainty, particularly in mountainous terrain where the density of weather stations is low.

2.2. The Event

As noted above, three slushflows occurred within the same stream channel over a period of approx. 12 hours. Fig. 4 shows the channel together with the approximate outlines of the three events. The

Figure 4: First slushflow event on 2010-05-15 around 22:30 probably initiated slightly above the plateau at an elevation of around 1000 m asl. (Photo G. Prytz)

third event, which is the primary focus of this study, was released from the area labelled SF-03. The exact release areas of the first two events are more uncertain, but they appear to have followed the same flow path. Fig. 4 presumably shows the first slushflow on the evening of 15 May 2010, which most likely originated in the Rapbekken stream channel, slightly above the plateau.

Fig. 5 shows four examples from a photo series of 22 images captured by a local resident. The photographer's vantage point could be determined with an accuracy of a few metres, and several terrain and vegetation features were identified in both the photographs and ortho-rectified aerial imagery. This made it possible to track the position of the flow front throughout the image sequence and reconstruct the evolution of the front-velocity along the flow path. The accuracy of the velocity estimates is moderate because the flow front is irregular and does not advance at a constant rate. For a discussion of the limitations associated with this type of estimate, the reader is referred, e.g., to Zenke (1984). However, the time integral of the estimated front-velocity agrees well with the distance travelled by the flow between the first and last images in the sequence, indicating that the estimated mean front-velocity is reliable. The velocity align also with observations from other events (cf. Blatny et al. 2026; Issler et al. 2020).

For most of the event, the front-velocity ranged between 15 and 25 m s^{-1} along a flow path with rapidly varying slope angles of approx. 15° to 35°. Fig. 6 presents the results of the estimated front-velocity profile. The average slope angle of the track is approx. 15°. Below 460 m asl, in the runout area, the terrain becomes flatter, with an

Figure 5: Foto series of the slushflow event on 2010-05-16 09:27 staring slightly east of the previous two events. From top to bottom at time t; $\approx t + 9$ s; $\approx t + 19$ s ; $\approx t + 33$ s. (Photo L. Fontain, Skarmodalen)

average slope angle of approx. 6°.

The estimated release area was approx. 1 ha and was located in a slight depression, which may have favored snow deposition. Therefore, the average release height was estiamted to be 1–2 m, resulting in an estimated release mass of approx. 7– 14×10^6 kg. The average slope angle of the release zone was around 13°. Due to previous events, little snow remained in the track, and entrainment consisted primarily of the remobilization of previously deposited snow.

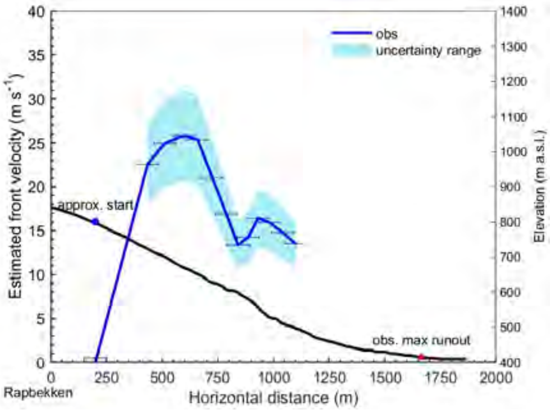

Figure 6: Estimated front-velocity. Error bars indicate the estimated uncertainty in the flow-front position at each time step, while the blue shaded envelope represents an estimate of the resulting uncertainty in the front-velocity.

The runout area of this specific event is uncertain because all three events followed the same path and the full extent of the runout area was not visible from the observer's position. However, the combined impact of the three events caused forest damage (Fig. 7 and Fig. 8), from which the maximum combined runout extent could be delineated. This provides an upper limit for the runout of the individual event.

Figure 7: Forest damage in the runout zone after the events from 15 and 16 May 2010. (Photo by L. Fontain on 2010-10-30)

Figure 8: Forest damage in the runout zone following the slushflow events of 15–16 May 2010. Aerial photographs from Flyfoto Helgeland (2005; left) and Nordland (2015; right) are shown for comparison. (Photos: Norge i Bilder)

3. MODELING EXAMPLE

This section presents a brief comparison between a model result and the observations. To this end, the depth-averaged model implemented in SAMOS-AT Sampl and Granig (2009) is employed. For a detailed description of the implemented rheological model, the reader is referred to (Blatny et al. 2026). The model parameters are similar to those used for the Atigun cases and are summarized in Tab. 1. The original forest in the lower part of the stream channel (see Fig. 8) was also accounted for in the simulation.

The simulation in presented Fig. 9. The simulated flow follows the stream channel and stops slightly short of the estimated outer limit of the runout distance. Since it is uncertain which of the three events produced the longest runout, the agreement between the simulation and the observations appears reasonable. This is also supported by a comparison of the estimated front-velocity with the simulated front-velocity. Fig. 10 compares the observed front-velocity with the simulated front-velocity derived from the simulated arrival times. This provides a more appropriate comparison than the simulated maximum velocity, which is not directly observable. Overall, the agreement between the observed and simulated front velocities is reasonable.

4. CONCLUDING REMARKS

The aim of this paper is to present rare observations of the velocity of a slushflow event, which can contribute to improving our understanding of these flows and to the development and validation of numerical models.

Table 1: Initial mass and parameters used in the depth-averaged model.

Path	*mass* (10^6 *kg*)	μ *(-)*	η_b *(Pa s)*	τ_c *(Pa)*	r_e^{max} *(kg* m^{-2}*)*	e_b *(J* kg^{-1}*)*
Rapbekken SF-03	14.5	0.09	15	100	50	1500

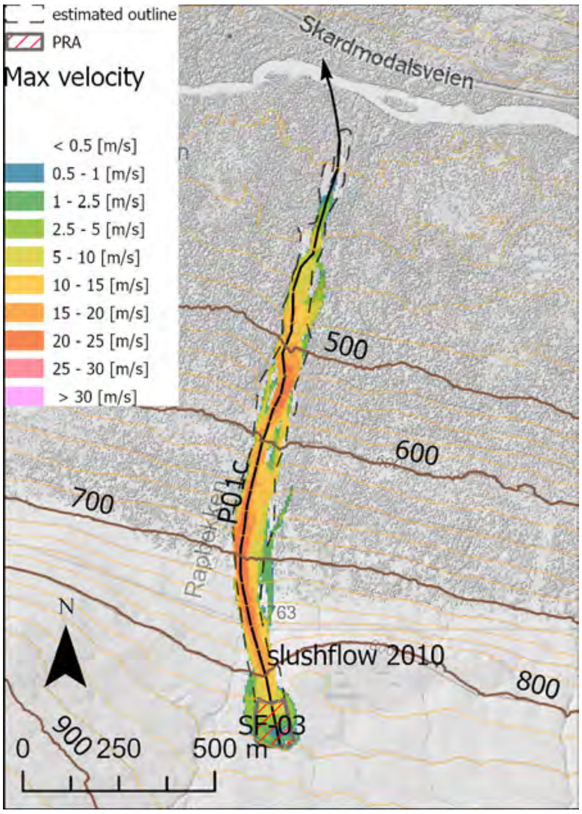

Figure 9: Back-calculation of the slushflow event in Skarmodalen on 2010-05-16 09:27 using SAMOS-AT

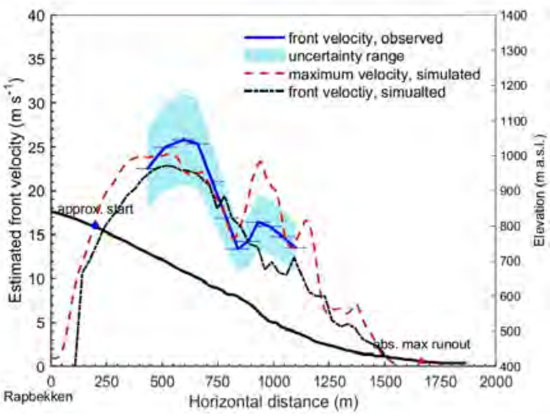

Figure 10: Comparison of the observed front-velocity with the simulated front-velocity and the simulated maximum velocity.

For meaningful back-calculations using a dynamical numerical model, both the initial and boundary conditions must be known with sufficient certainty. The necessary initial conditions include the release area and, at a minimum, the mean release depth. Ideally, the observations used for comparison should include the runout distance, as well as the velocity and flow depth as functions of time at several locations along the flow path. In particular, the runout distance alone is insufficient, although it has traditionally been used as the primary quantity for calibrating avalanche models.

At present, there are few documented slushflow events for which all of these quantities have been measured or can be extracted from the available raw data. The Skarmodalen event is not a perfect example either; nevertheless, it is one of the better-documented cases, with the front-velocity able to be determined over a distance of approximately 600 m along the middle section of the flow path.

The modeling example demonstrates how these data can be used to constrain the model results.

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