# SLUSHFLOW DOCUMENTATION: POSSIBILITIES AND LIMITATIONS

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ABSTRACT: Slushflows are rapid mass movements of water-saturated snow that annually cause damage to roads and infrastructure in Norway. This mass movement type is less known among recreationists, which affects the frequency of observations. Underreporting poses a challenge for documentation, as the relatively low preservation potential of slushflow deposits often requires rapid data collection before the evidence is lost. Slushflow incidents are frequently reported via the crowdsourcing tool Varsom Regobs, with most observations concentrated along road and railway networks, creating a spatial bias in the documentation. This bias indicates a need for more data collection, particularly to better understand the meteorological conditions involved in slushflow initiation. While identifying the starting zones of slushflows is essential for this purpose, they are recorded far less frequently than runout zones. Therefore, to further advance the regional early warning for slushflow hazards, it is imperative to improve both the quantity and quality of slushflow documentation. Firstly, efforts must be undertaken to enhance public awareness about slushflows and the Varsom Regobs tool to encourage reporting from remote areas. Secondly, while unmanned aerial vehicles (UAVs) are effective in documenting slushflows and are often used for hazard assessments, small adjustments to the surveying process can greatly increase the utility of the captured data for scientific studies. Developing a protocol for drone pilots will help to ensure comprehensive documentation and improve the data quality.

KEYWORDS: Avalanches, Slushflows, Documentation, UAVs.

## 1. INTRODUCTION

Slushflows are rapid mass movements of water-saturated snow that can entrain sediments, soil, and vegetation. They occur during periods of rainfall and/or snowmelt in areas with seasonal snow cover (Hestnes, 1985; 1998). A prerequisite for slushflow initiation is the accumulation of water within the snowpack, a process that requires relatively gentle slopes (0-30°) in the release area (Luckman, 1977; Hestnes, 1985; Nyberg 1985; Onesti, 1985).

Slushflows constitutes a major natural hazard in Norway, causing frequent road closures and substantial financial losses annually (Sund et al., 2024a). Despite their destructive potential, slushflow events have historically been underreported and misclassified (Hestnes and Sandersen, 1987; Hestnes et al. 2012). Consequently, the majority of recorded events are biased towards roads and infrastructure, resulting in incomplete data that poses a major challenge for contemporary slushflow research and early warning (Sund et al., 2024b). Many slushflow events may go undocumented due to their occurrence in more remote areas, creating an unrealistic picture of slushflow distribution (Svendsen et al., in prep.). Further data on slushflow activity, particularly accurate locations of starting zones, will contribute to advancing the early warning of slushflow hazard. This information can be linked to the corresponding hydrological and meteorological data from the time of slushflow initiation. Knowing the precise elevation of a starting zone enables e.g. differentiation between rain and snow and determining the amounts received at the location. This, in turn, allows for assessment of snow conditions, such as snow depth and type at the time of release.

Here, we examine important aspects of UAV documentation of slushflows, with a focus on identifying starting zones. We discuss the limitations that hinder the collection of useful data and explore possibilities for improving documentation. We present case studies from three slushflow sites around Norway, each with varying levels of documentation.

## 2. FIELDWORK

Fieldwork was conducted at three slushflow sites in Norway. Imagery of starting zones and flow paths were collected using a DJI Mavic 2 Pro drone. At Kistrand, approximately 25 km east of Bodø, northern Norway, a large slushflow event occurred on 25th January 2023. Fieldwork at this site was carried out three days after the event, once the Riksvei 80 highway had reopened. Sogndalsdalen in western Norway also experienced a slushflow on 25th January 2023. Fieldwork at this site was conducted seven days later. The third site, Stavsro, southeast of Gaustatoppen in southern Norway, had a slushflow incident in April 2019. Fieldwork at this location was conducted in August 2023.

## 3. REPORTING OF SLUSHFLOWS

Observations of slushflows are often reported through the crowdsourcing tool Varsom Regobs (Ekker et al., 2013), which facilitates the sharing and accessing of real-time information. The Norwegian Public Roads Administration (NPRA), highway contractors, avalanche professionals, and recreationists utilize the platform to register observations and avalanche incidents. These records are transferred to a national slushflow database, available at www.skredregistrering.no, and subsequently undergo quality assessment (Sund et al., 2024b). The spatial bias in the slushflow database complicates efforts to improve early warning operations and implement effective mitigation measures, such as hazard maps, RAMMS modelling, and structural solutions. Enhancing both the quality and quantity of slushflow data is essential for achieving these improvements.

## 4. SLUSHFLOW SITES

Slushflows are characterized by their high density and can attain high velocities as they move downhill, enabling them to generate destructive impacts (Hestnes, 1985; 1998; Hestnes and Bakkehøi, 2004).

### *4.1 Stavsro slushflow event in April 2019*

A slushflow was released on 28th April 2019, at Stavsro in southern Norway. The alpine site features a flat, blockfield-covered mountain plateau at approximately 1480 m a.s.l. where water accumulates and drains downslope, forming a stream that pass beneath Gaustavegen road (FV6430). UAV imagery (see Figure 1a) shows that the slushflow was released on the slope just below the plateau. While the starting zone itself was very small, the flow path widened significantly downslope, resulting in a large-scale slushflow that caused damage to the road and car park situated at 1172 m a.s.l, as well as to a hiking trail. Just before reaching the road, the slushflow transitioned into a debris flow. Consequently, it only the run-out zone had been documented, the incident could easily have been misclassified as a debris flow. However, the UAV imagery enabled the starting zone to be identified (see Figure 1b) and showed that the event was a slushflow.

### *4.2 Sogndalsdalen slushflow event in January 2023*

A slushflow released on the north-facing slope of Sogndalsdalen, western Norway, came to a halt just before reaching a nearby road on 25th January 2023. Photographs captured with a mobile phone during the event (see Figure 2a) show that the slushflow was released in a river draining the western side of Vardafjellet mountain (1016 m a.s.l.). Because the upper slopes of the slushflow are undocumented, the starting zone cannot be accurately identified. However, the gradient increases downstream approximately 260 meters above the runout zone, as the river flows into densely forested slopes (see Figure 2b). Both the photographic evidence in Figure 2a and the topography indicate that the slushflow was released above this point.

### *4.3 Kistrand slushflow event in January 2023*

Multiple slushflows were released at Kistrand in northern Norway on 25th January 2023, blocking the highway and railway. UAV imagery (see Figure 3a) captured by the Norwegian Public Roads Administration shows that the slushflows were released in streams at various elevations on the mountainside of Kistrandfjellet (989 m a.s.l.) (Svendsen et al., in prep.). However, the UAV imagery was captured at low heights along the foot of the mountain and included mostly vertical views, which complicates the identification of starting zones that are located several hundred meters upslope (see Figure 3b).

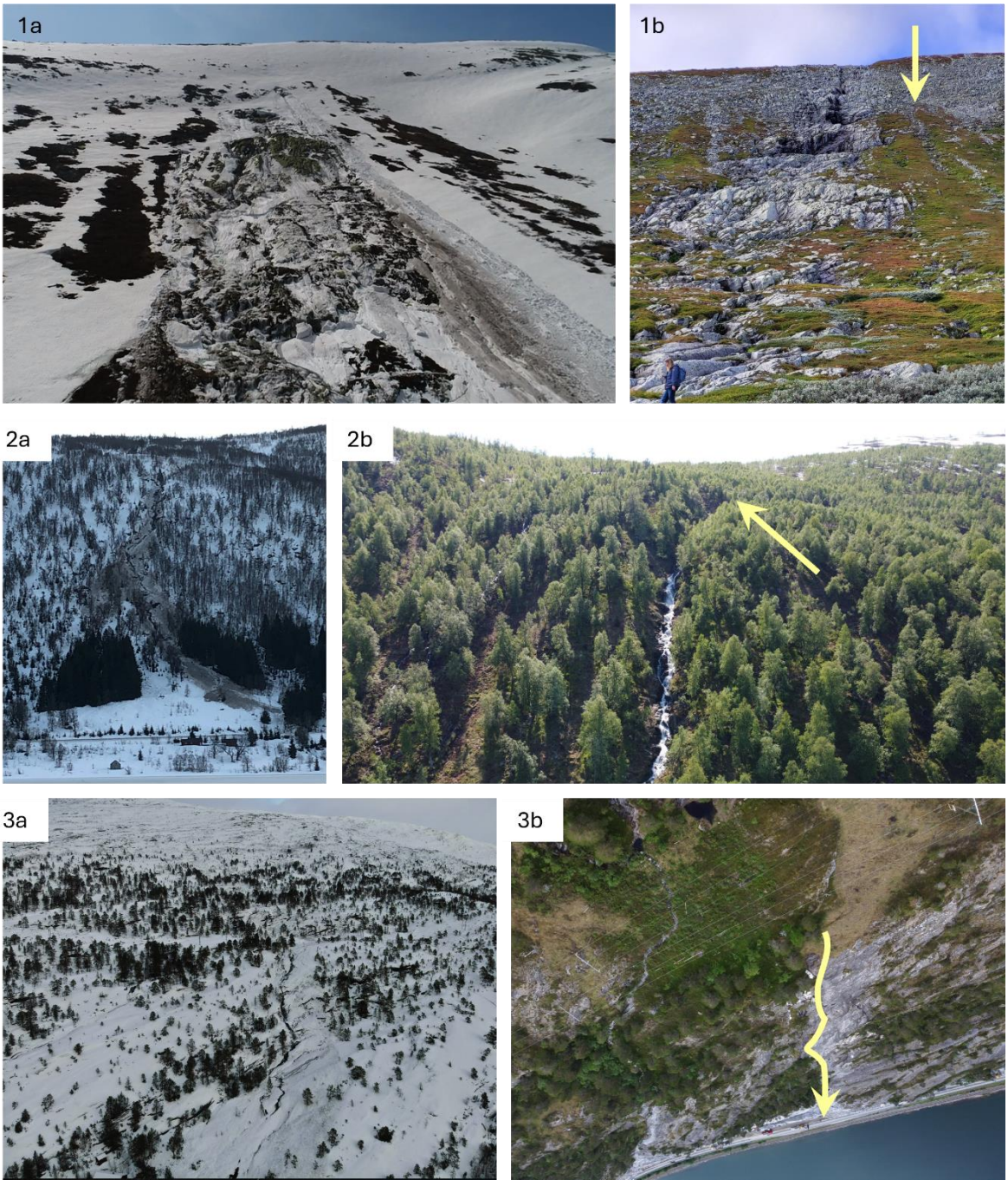


Figure 1: 1a: UAV imagery of the Stavsro slushflow starting zone captured on the day of the event (Espen Faane, NCC) 1b: Photograph taken of the Stavsro site during fieldwork in August 2023, with the starting zone shown by the yellow arrow. 2a: Photograph taken with a mobile phone from the opposite side of the valley during the Sogndalsdalen event (Helge Torstad). 2b: UAV imagery of the upper slopes of the Sogndalsdalen site taken during fieldwork in May 2024. The absence of aerial imagery prevents accurate identification of the starting zone, which is likely situated just above where the gradient increases downstream (marked by an arrow). 3a: UAV imagery captured one day after the Kistrand event (Norwegian Public Roads Administration). The imagery was captured for assessing of slushflow hazards and focuses on the lower mountain slopes. For research purposes, however, the most valuable data is found higher up where the starting zones are located. 3b: UAV imagery captured during fieldwork at the Kistrand site in June 2024 showing one the few identifiable starting zones and flow paths (arrow) based on the 3a image. Greater flying altitude, overview shots, and close-up images would have allowed for more starting zones to be identified.

## 5. DISCUSSION

### 5.1 Slushflow release and documentation

Slushflows can occur in a variety of topographic settings (Onesti and Hestnes, 1989). The flow path often steepens downstream, demonstrating that slushflows are not confined to low-relief terrain, but frequently initiate on shallow gradients within otherwise steep, high-relief mountain slopes. The information available for documented slushflow events varies depending on the accessibility and visibility of the starting zone, as well as the equipment used for documentation (e.g. mobile phone, handheld camera, UAV). Starting zones are particularly important to document but are often inaccessible and out of view from lower elevations, which complicates efforts to document them through ground-based photography. Additionally, slushflows can be difficult to identify via satellite imagery due to low temporal resolution and the relatively poor preservation of slushflow deposits (Sund et al., 2024b). Furthermore, slushflows are often released in streams and rivers, featuring relatively small starting zones and narrow flow paths that require high spatial resolution. One option is to use UAVs, which can quickly capture high-resolution images of hard-to-reach areas, such as starting zones. Unlike other remote sensing technologies, UAVs offer a rapid and inexpensive means of data collection and are particularly useful for studying small-scale features and surface changes.

### 5.2 Challenges in documentation

The three slushflow sites presented above highlight some of the challenges associated with slushflow documentation. Data collection can be hindered by adverse weather conditions, road closures, a lack of equipment or by not fully leveraging available equipment to its potential. The Sogndalsdalen slushflow demonstrate the limitations of ground-based photography in identifying starting zones which are often situated several hundred meters upslope. This challenge likely contributes to the scarcity of documented starting zones in the Norwegian slushflow database. Consequently, more advanced equipment may be required to comprehensively document slushflows at specific sites. For the Stavsro slushflow incident, UAV imagery was essential not only for identifying the starting zone but also for accurately classifying the type of mass movement.

Even with the necessary equipment, however, documentation of slushflows need not be straightforward. While UAV surveying of snow avalanche sites often involve steep mountain slopes with minimal vegetation, surveying of slushflow sites may involve overcoming more variable topography, including densely forested slopes, incised or sinuous channels, and narrow river valleys. Moreover, slushflows can attain high speeds and do not decelerate before entering nearly flat terrain. The resulting flow path may be several kilometers long, testing the limits of UAV flight distance.

The duration for which slushflow evidence is preserved is another factor that effects documentation. Preservation is largely dependent on weather conditions. For instance, fieldwork conducted three days after the Kistrand event in 2023 proved challenging due to the melting of slushflow deposits triggered by rainfall. Conversely, by the time fieldwork was carried out one week after the Sogndalsdalen event, the slushflow deposits had been buried under heavy snowfall. Therefore, it is crucial to seize opportunities to quickly collect the data needed to identify starting zones before evidence is lost.

### 5.3 Improving reporting and data collection

Given the limitations of the slushflow database and its importance for advancing early warning, both the quantity and quality of data need to be improved. Hence, the possibilities for improving slushflow documentation is twofold: first, to facilitate recreationists to collect data from more remote areas; and second, to increase the usefulness of data gathered by professionals and e.g. highway contractors with access to more advanced equipment. Although slushflows have been gaining more attention in the geohazard field in Norway in the last few years, introducing a public awareness campaign to inform the public about slushflows and the Varsom Regobs platform could be beneficial, particularly through social media channels popular among recreationists.

To enhance the quality of slushflow data, the focus should be on professionals using UAVs in their work. However, the effective use of UAVs for slushflow documentation requires undertaking specific flight maneuvers to enable the precise locating of starting zones. It is important to note that most of the slushflow imagery presented above was collected for purposes other than research, such as assessing slushflow hazards in real-time. Therefore, implementing these flight maneuvers should not be time consuming. Small improvements in the data collection can significantly enhance its value for further study. For example, after the Kistrand event, minor adjustments to the UAV surveying would have greatly improved documentation. By flying the drone at slightly higher altitudes and capturing close-up shots of the upper sections of flow paths, more starting zones could have been captured, thus significantly improving the value of the data.

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We suggest developing a protocol for documenting slushflow incidents specifically for drone pilots. This protocol could contain a checklist that outlines the necessary flight maneuvers and procedures for comprehensive documentation. Such procedures may include maintaining an appropriate flying height and capturing imagery of the upper part of the flow path where the starting zone is located. In areas with high relief, it may be necessary to fly as high as regulations allow to capture close-up shots of starting zones. Furthermore, overview shots of flow paths are also important for mapping purposes, as fragmented imagery complicates mapping. Additionally, capturing imagery of the surrounding area may be important for determining whether multiple slushflows have been released, as was the case in the Kistrand event. Developing such a protocol will contribute to more high-quality data that will enhance the early warning of slushflow hazards and aid in the development of effective mitigation measures.

## 6. CONCLUSION

Slushflows are snowmelt phenomena that often require rapid data collection before evidence is lost. Years of misclassification and underreporting of slushflow events have created a need for more data to advance early warning. Informing the public, particularly recreationists, about slushflows and the Varsom Regobs tool is important for expanding data collection. Further, efforts should be made to increase the value of data collected by avalanche professionals and highway contractors. Determining the exact location of starting zones is essential for advancing early warning procedures and with tools as efficient and inexpensive as UAVs available, their potential ought to be fully utilized. The three case studies presented show that while UAVs can provide valuable imagery of slushflows and are particularly effective in documenting starting zones, they need to be utilized in a way that enables the precise locating of starting zones. We suggest developing a protocol for drone pilots to improve the collection of high-quality data. The protocol should outline the necessary flight maneuvers and procedures to ensure comprehensive documentation of slushflow sites, such as maintaining sufficient flying height to capture starting zones and adequate distance for overview shots, as well as scanning the surrounding terrain to assess potential nearby releases.

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