FROM SNOW TO SEDIMENT: MAPPING AND QUANTIFYING DIRTY SNOW AVALANCHE DEPOSITS

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ABSTRACT: Avalanches have the potential to harm people and livestock as well as damage or destroy infrastructure. Furthermore, avalanches can erode and transport topsoil material and therefore alter soils and landscape on a larger timescale. These so-called dirty snow avalanches evolve from wet-snow full-depth avalanches and mostly appear in spring after rapid warming or rain-on-snow events.
While conventional field methods such as snow sampling and mapping of deposits on aerial images have been applied to estimate the amount of material transported by dirty snow avalanches, the specific patterns and amounts of deposition they produce remain poorly quantified.
This study aims to bridge this gap by applying uncrewed aerial vehicle (UAV) Structure-from-Motion (SfM) photogrammetry in order to create digital elevation models (DEMs) of difference and map areas and volumes of deposition more accurately. Furthermore, surface debris sampling was employed to directly quantify the sediment mass transported by the avalanches as well as the sediment's characteristics.
We present the results of three avalanches observed and sampled in 2025 and 2026. This includes comparison of DEMs acquired shortly after the event and after the snow deposited by the avalanche has melted, as well as analyses of the sediment properties. We show that the visual appearance of the avalanche deposits and the sediment mass highly depend on the type and characteristics of the transported material.

KEYWORDS: dirty snow avalanches, UAV photogrammetry, remote sensing, spring avalanches, SfM, wet-snow avalanches

1. INTRODUCTION

Dirty snow avalanches are avalanches which shear directly over the ground and erode and entrain soil, rocks and vegetation (Heckmann et al. 2002; Schweizer et al. 2021). The material is accumulated in the snow balls that these avalanches usually form (Jomelli and Bertran 2001; Moore et al. 2013). It appears on the surface of the avalanche deposit during the snow melting process (Jomelli and Bertran 2001), which makes them appear as "dirty" in the landscape (Moore et al. 2013; Rapp 1960). Dirty snow avalanches usually evolve from wet snow or glide avalanches, which often happen in spring when there is rapid melting because of warmer temperatures or after rain-on-snow events (Clarke and McClung 1999; Höller 2024; Laute and Beylich 2014; Swift et al. 2021). By eroding soil, detaching vegetation and taking up rocks in the release area and along the flow path and depositing the material in the deposition area, dirty snow avalanches play an important role in the redistribution of surface material (Blikra and Nemec 1998; Heckmann et al. 2002; Luckman 1978). By doing this over the course of years, they have an impact on the soil (Ceaglio et al. 2012; King and Brewster 1978; Stanchi et al. 2014) and the landscape, and can change them as well as create new landforms (Korup and Rixen 2014; Swift et al. 2021).

The amount of sediment transport by dirty snow avalanches has previously been quantified by taking surface debris (SDS) or snow samples (SS) by, e.g., Bell et al. (1990, SS), Ceaglio et al. (2012, SS), Freppaz et al. (2010, SS), Heckmann et al. (2002, SDS), Korup and Rixen (2014, SDS), Moore et al. (2013, SDS) and Woodhurst and de Scally (2018, SDS). Furthermore, fallout-radionuclide-based methods (Cs-137) in combination with direct measurements (Ceaglio et al. 2012) and soil loss equations (RUSLE, Meusburger et al. 2014) have been used to investigate the longer-term influence of snow gliding on soil redistribution.

The literature study revealed a multitude of different parameters having been used to describe the amount of transported sediment. One of them is the deposition rate that ranges between 1.96 and 5.45 kg/m² (Bell et al. 1990), 2.75 ± 0.31 kg/m² (Ceaglio et al. 2012) and 0.98–24.08 kg/m² (Freppaz et al. 2010) depending on the year and study

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site. The annual accretion of sediment was estimated as 0.21 and 0.74 mm (Bell et al. 1990), 2.29 ± 0.26 mm (Ceaglio et al. 2012), 0.8–20.1 mm (Freppaz et al. 2010), 3.18–4.31 mm (Moore et al. 2013) and 0.9–3.8 mm (Woodhurst and de Scally 2018).

In the aforementioned case studies, the avalanche deposit was mapped by hand to estimate the deposit area. This could be improved by using high-resolution orthoimages and digital elevation models (DEMs) of the avalanche deposit. This offers a higher accuracy in the determination of the avalanche area and volume and therefore a better estimate for the amount of sediment transported by dirty snow avalanches. While uncrewed aerial vehicle (UAV) Structure-from-Motion (SfM) photogrammetry has been applied, e.g., by Eckerstorfer et al. (2015) to map avalanche deposits in general, we combine it with in-situ measurements of the sediment content of dirty snow avalanches. Furthermore, there is a gap in the analysis of the sediment's characteristics, especially the carbon content (so far only quantified by Freppaz et al. 2010 and Korup & Rixen 2014). Therefore, the aim of this study is to quantify and characterize the amount of sediment transported by dirty snow avalanches. The research questions addressed are (1) how much sediment is transported by dirty snow avalanches and (2) what the characteristics of this sediment are.

2. STUDY AREA

The study area includes three different avalanche slopes in the Tyrolean Alps, Austria (Fig. 1) that reliably experience dirty snow avalanches on an annual basis. The Haggen Avalanche (HK) in the Kraspes Valley and the Gleirsch Avalanche (GL) in the Gleirsch Valley are both situated in the Sellrain Valley in the Stubai Alps, in the crystalline Oetztal-Stubai-Complex (Hoinkes et al. 2021). The main rock types are paragneiss, amphibolite, amphibolitegneiss, eclogite and peridotite (Brandner 1980). The nearest weather station is in Gries im Sellrain (1227 m a.s.l.) in 5 km distance of GL and 7 km distance of HK with an annual mean temperature of 6.9 °C and an annual precipitation of 910 mm (2017–2022) (BMLUK 2025). Both release areas are dominated by grassland and lead into an avalanche chute. The deposition area is alpine pasture that is grazed by livestock (cattle, goats and sheep). Outside of the deposition zone, bushes, mainly alpine rose (*Rhododendron ferrugineum*), blueberry (*Vaccinium myrtillus*), lingonberry (*Vaccinium vitis-ideae*) and juniper (*Juniperus spec.*), can be found. At the GL site, there are also pine trees (*Pinus spec.*) outside of the deposition zone. The foot of the avalanche deposit lies at approximately 1800 m a.s.l. for HK and 1650 m a.s.l. for GL.

The third slope, Breitlahn (BL), lies on the west side of the Gepatsch Lake within the Kauner Valley in the Oetztal Alps, also in the crystalline Oetztal-Stubai-Complex (Hoinkes et al. 2021). The main rock types here are granite gneiss and migmatite (Brander 1980). The nearest weather station is in Vergötschen (1269 m a.s.l.) in 14 km distance with an annual mean temperature of 6.1 °C and an annual precipitation of 834 mm (1998–2023) (BMLUK 2025). The release area is dominated by grassland and also leads into an avalanche chute. The deposition area is grassland, too, with a significant channel and a population of marmots (*Marmota marmota*). The foot of the avalanche deposit lies at 1773 m a.s.l., but can also extend over the road and continue into the Gepatsch lake a few dozen meters lower.

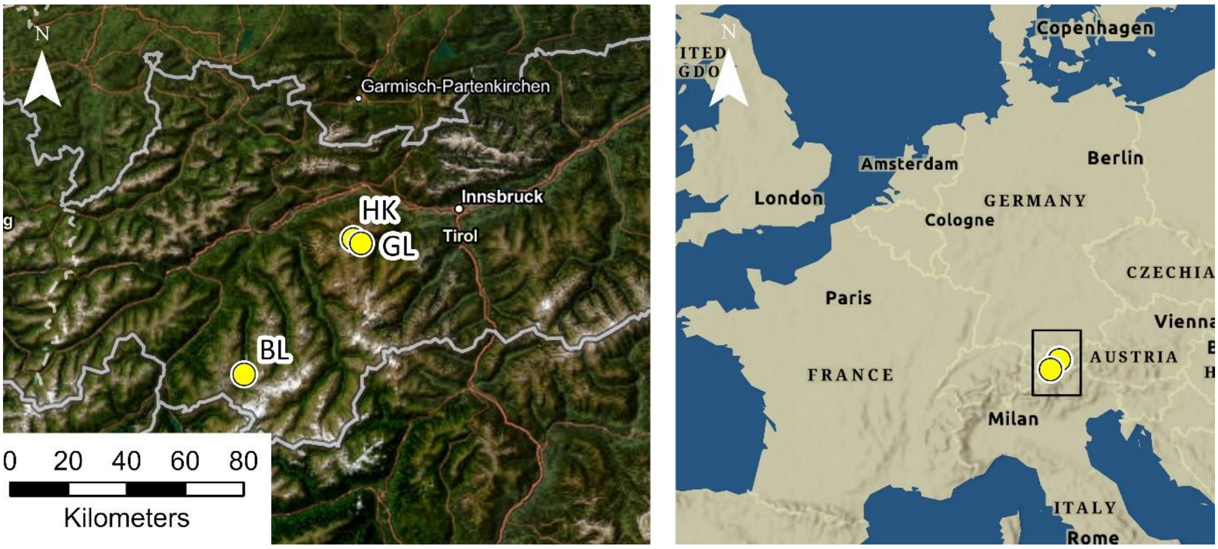

Figure 1: Map of the study areas in Tyrol, Austria, (left) and location in Europe (right).

3. METHODS

The three avalanche areas (HK, GL, BA) were investigated over two seasons each (2025 and 2026). Per investigation, two UAV surveys were conducted for each study site. The first one was carried out soon after the avalanche had happened and field work conditions were considered safe. The second one was carried out after the melting of the avalanche snow.

In order to georeference the produced DEMs, ground control points (GCPs) were placed on and around the avalanche deposit and measured using a Trimble Catalyst DA2 GNSS receiver (Trimble 2025, accuracy 0.02–0.04 m). Then, a drone flight (DJI Mini 4 Pro; camera model FC8482) was conducted, taking pictures of the avalanche deposit to create a DEM and orthoimage using SfM photogrammetry. Additionally, the avalanche deposit was categorized into three to seven areas of homogeneous debris cover. In these areas, at least two surface debris samples were taken per category on plots of 0.25 m². Larger stones (approx. > 5 cm) were weighed in the field and not taken to the lab. An exception from this procedure was the HK avalanche in 2025, where the melting process had not proceeded enough yet for the debris to collect at the surface. Instead, snow samples were taken along a line from the top to the bottom of the deposit and additionally from two transects (resulting in 10 samples in total).

All samples were taken to the lab, melted, dried at 40 °C and sieved to 2 mm. In the last step, coarse organic material was picked out. Furthermore, the organic matter content was determined by loss on ignition (3 h at 550 °C) and the grain size of the fine sediment was measured using a laser diffractometer (Malvern Mastersizer 3000; Malvern Panalytical Ltd. 2026). After processing the UAV photos (Agisoft Metashape Pro Version 2.1.3; Agisoft 2025; Table 1) the areas of the homogeneous debris cover and the entire avalanche were digitized from the orthoimage. The difference between the winter and summer DEM was used to quantify the volume of the avalanche deposit. The amount of sediment was averaged over the samples per category and extrapolated over the homogenous areas. By adding up these areas, the total amount of sediment per avalanche was computed.

Table 1: Processing parameters

Avalanche	Alignment accuracy	Ground resolution (mm)	Number of images	GCP error (cm)	DEM pixel size (mm)
HK 2025 Winter	High	14.3	374	6.73	28.6
HK 2025 Summer	High	8.03	1048	7.13	16.0
HK 2026 Winter	High	4.09	1583	4.25	8.2
HK 2026 Summer	High	6.11	1996	7.69	12.2
GL 2025 Winter	High	9.18	371	24.29	18.3
GL 2025 Summer	High	4.78	1149	10.61	9.6
GL 2026 Winter	High	2.60	1579	9.67	5.2
GL 2026 Summer	High	4.63	1203	4.58	9.3
BL 2025 Winter	High	6.55	1122	16.31	13.1
BL 2025 Summer	High	3.49	2354	6.12	7.0
BL 2026 Winter	High	3.55	3380	6.94	7.0
BL 2026 Summer	High	4.60	3775	12.68	9.2

4. RESULTS

Figure 2 shows an example of the winter orthophoto of the Gleirsch avalanche in 2025, where the homogeneous areas and sample locations are mapped (A) and the DEM of difference (DoD; winter-summer) showing the snow depth in the avalanche deposit (B). It can be seen that there are areas of homogeneous debris cover with only little sediment at the top of the avalanche deposit (sample points 1 and 2) and the very bottom (below points 10 and 14), some more in the middle and close to the end (points 5, 6, 9, 10 and 14), a higher amount in the core of the lower half of the deposit (points 7, 8, and 11-13) and the most on the left edge (points 3 and 4). The DoD shows the largest snow depth in the middle of the deposit, especially in the little gully, with a maxium depth (vertical distance) of 3.7 m, as well as a characteristic rampart at its lowest end.

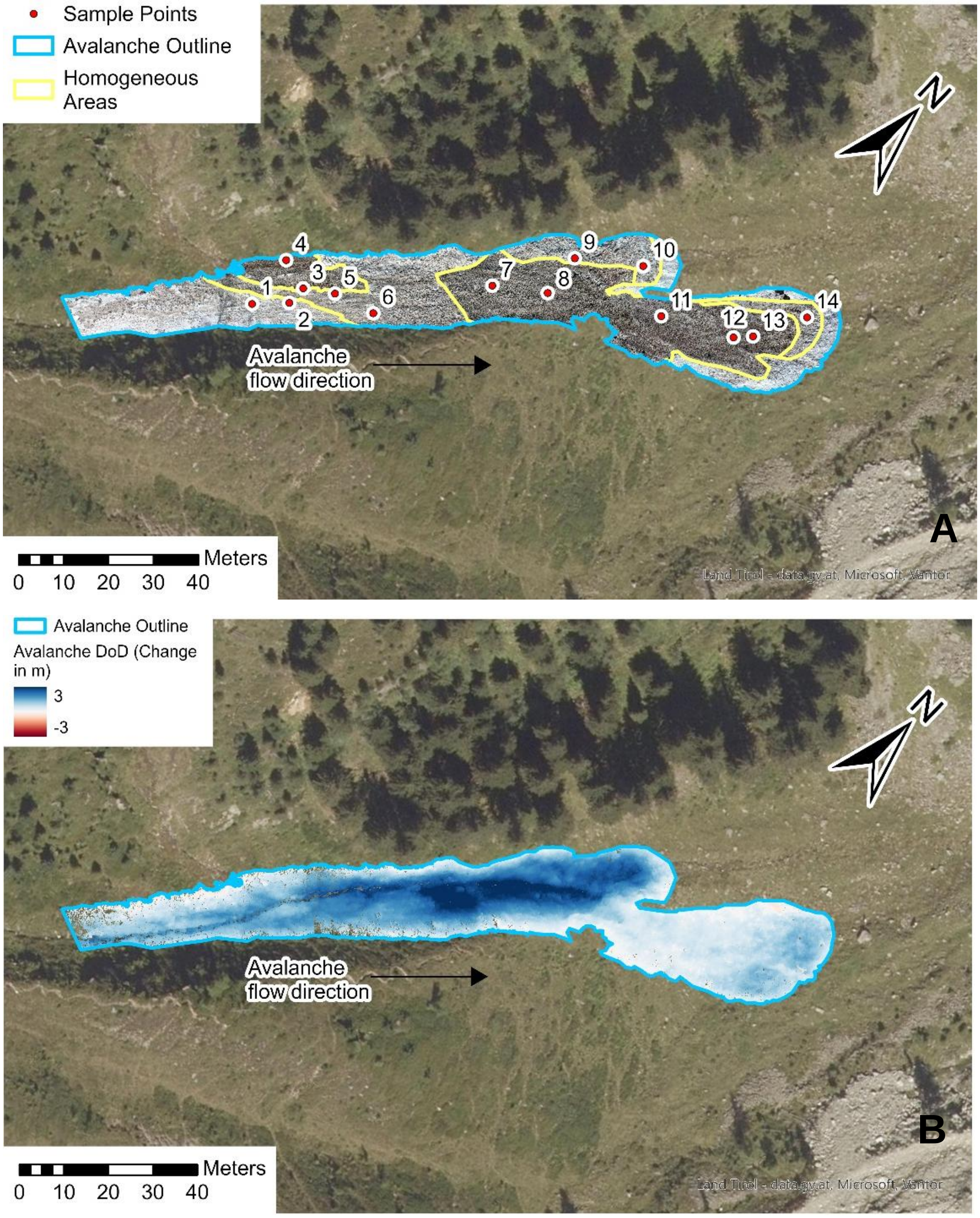

Figure 2: A) Orthoimage with homogeneous areas and sampling locations and B) snow depth in avalanche deposit of the Gleirsch avalanche in 2025.

The parameters of the investigated avalanches and the sediment characteristics are shown in Table 2. While the avalanche areas and volumes are in the same order of magnitude of a few thousand square and cubic meters, respectively, the (specific) sediment mass differs for the investigated avalanches and lies between 1.0 and 34.5 Mg or 0.37 and 8.35 kg/m². There is also a difference in the amount of coarse organic matter, which varies between 2.8 and 44.5 %. The grain size fractions differ as well with coarse mineral material being the most prominent fraction for HK and BL, whereas for GL fine material (sand, silt and clay) has a higher amount, apart from the high amount of coarse organic material.

Table 2: Parameters of the avalanches and sediment characteristics. The shaded columns add up to 100 %. The last column shows the organic matter content of the fine earth (sand + silt + clay)

Avalanche	Avalanche area (m²)	Avalanche volume (m³)	Sediment mass (kg)	Spec. sediment mass (kg/m²)	Coarse organic matter (%)	Coarse mineral material (%)	Sand (%)	Silt & clay (%)	Organic matter content fine material (%)
HK 2025	4962	5618	6668	1.34	5.4	50.9	29.5	14.2	20.7
HK 2026	4655	5229							
GL 2025	2819	3426	1048	0.37	44.5	11.8	23.7	20.1	57.2
GL 2026	1836	1916							
BL 2025	4133	6841	34515	8.35	2.8	78.1	11.0	8.1	14.0
BL 2026	6608	18104							

5. DISCUSSION

5.1 Results

Figure 2 shows that the highest amount of debris is not necessarily found in the areas with the largest snow depth. Most of the sediment is found close to the avalanche foot, but above an area with relatively clean snow. The latter results from snow that has never been in contact with the ground as underlying snow shears over the ground and the top layer glides up on it, which forms a clean rampart at the end of the deposit.

The numbers for the specific sediment mass (mass per area) lie within the span of the studies mentioned in the introduction. The amount of coarse organic matter is below (HK & BL) and above (GL) the numbers in the study by Freppaz et al. (2010), who indicated it with 10–20 %. However, they sampled only one avalanche with alpine tundra in the release area and differences between avalanches in other areas are possible. Furthermore, the sediment mass in the avalanche is related to the amount of coarse organic matter. When comparing different dirty snow avalanches of similar size, it becomes evident that the ones with a low coarse organic matter content, e.g. HK and BL, have a significantly higher sediment mass than the ones with a high coarse organic matter content (GL). This is due to the lower density of organic material compared to mineral material. Consequently, a higher amount of coarse mineral material, i.e. rocks and rock fragments larger than 2 mm, leads to a higher sediment mass. The case of the avalanche pictured in Figure 2 shows that an avalanche with a relatively low sediment mass looks still very dirty. On the other hand, avalanches with a higher sediment mass, i.e. with a higher amount of rocks, appeared less dirty. This was also found by Moore et al. (2013) who stated that the organic matter is responsible for the dark or dirty appearance of the avalanches. Moreover, the comparison between 2025 and 2026 shows that the avalanche area and volume for HK were similar, whereas the values differed for GL and BL. For GL, on the one hand, the area and volume were smaller in 2026 than 2025. This is mainly due to the advanced melt-out of the avalanche deposit at the time of sampling in 2026. For BL, on the other hand, the area and volume were larger in 2026 than in 2025 since the avalanche deposit reached significantly further up in the gully of the deposition area.

5.2 Limitations

The limitations and challenges of this study can be classified into two categories: timing and GIS work.

The issue of the timing is to identify the right day to conduct field work. It is necessary to wait for safe conditions after avalanche occurrence. Additionally, it and makes sense to wait some time as the sediment is usually within the snowballs that form the avalanche and only appears at the surface during the melting process (Jomelli & Bertran 2001; Moore et al. 2013). Only then, it is possible to identify areas of homogeneous debris cover. Furthermore, the avalanche surface smooths out over time and facilitates estimating the deposit volume using SfM. However, during the melting process of the avalanche that enhances the mentioned measurements, the volume and area of the deposit decrease, which leads to an underestimation of these variables. Apart from the avalanche danger, it is important to consider the weather conditions (mainly wind and rain) due to the use of a UAV. Additionally, snowfall after the event would also complicate the research as homogeneous areas cannot be identified under a fresh snow cover. An alternative – if the fieldwork is conducted early after the event – is to take snow samples in transects, as was done for HK in 2025. Another tradeoff exists with the summer drone surveys. For these surveys, all avalanche snow should have melted. However, with spring proceeding, vegetation growth intensifies and starts to overgrow the gullies, creating elevation overestimations and snow volume underestimations.

Concerning the GIS analysis, there is limited uncertainty in the digitization of the avalanche outline and the individual homogeneous areas. As a manual operation, the decisions taken are subjective and different researchers will produce different results when drawing the borders of the homogeneous areas and the deposit on the orthoimage. In this study, only areas that are covered or completely surrounded by avalanche snow at the time of the survey were considered as avalanche deposit, even if it is obvious that the avalanche extended more towards the edges but has melted away since then. This leads to an underestimation of the snow volume, avalanche area, and, consequently, erosion mass. Furthermore, the DEM includes some no-data values where no volume is quantified, leading to an underestimation of the snow volume. In this case, the specific sediment mass is a better value for comparisons.

6. CONCLUSIONS & OUTLOOK

The results obtained from combining UAV SfM photogrammetry with in-situ measurements of the sediment content of dirty snow avalanches show a specific sediment mass of 0.37–8.35 kg/m² (2025) with avalanche deposit areas of 1836–6608 m² (2025–2026), volumes of 1916–18104 m³ (2025–2026) and a mass of 1048–34515 kg (2025) per avalanche. The sediment mass highly depends on the amount of organic matter in the avalanche debris. A higher amount of organic material results in a deposit of a dirtier appearance, but a lower sediment mass.

The data shown in this study is already consistent with earlier studies. However, in order to compare better between different years, avalanches in different geological settings and areas with different characteristics of the release area, more data is needed over consecutive years and will be published in future studies.

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