AN INVESTIGATION OF THE DEVELOPMENT OF LIQUID WATER CONTENT IN DIFFERENT SNOW TYPES AS INPUT TO SLUSHFLOW EARLY WARNING

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ABSTRACT: Slushflows are rapid mass-movements of water-saturated snow that can occur when liquid water content (LWC) becomes high enough (> 15 vol. %), melting bonds and lowering cohesion until the snow releases as a flow. Slushflows stand out due to their low release angles and their potential for extremely long runouts. They occur primarily during rain-on-snow events or by strong melting, and usually require an impermeable basal layer to cause meltwater to accumulate.

The development and propagation of liquid water through the snowpack are highly influenced by snow type. This is an important consideration for further development of the regional early warning of slushflows in Norway. To address this, we measured LWC in snow profiles before and during weather events conducive to slushflow occurrence using an SLF Snow Sensor. In addition, we aimed to evaluate the SLF Snow Sensor as a tool to measure LWC and compare it to the traditional hand wetness test.

Results indicate that certain snow types, such as precipitation particles impede homogeneous water percolation and favor preferential flow, leading water to the bottom of the snowpack while large parts of the interior remain dry. In contrast, melt forms tend to promote a more uniform matrix flow. Mode of flow can be important for slushflow early warning, as preferential flow may lead water to vulnerable snow types, such as depth hoar, at the bottom of the snowpack faster than expected. Lateral flow likely plays a large role in slushflow initiation.

Comparison of LWC estimates from the hand wetness test and SLF Snow Sensor showed agreement with literature, confirming the hand wetness test as a useful qualitative LWC assessment, especially for internal comparison. The hand wetness test provides adequate LWC estimates for the slushflow early warning, especially with multiple measurements to track water movement over time. However, for precise values, the SLF Snow Sensor is necessary. The need for external density measurements to calculate LWC, combined with snow's lateral variability, makes the SLF Snow Sensor labor-intensive due to the numerous measurements required.

KEYWORDS: LWC, liquid water content, slushflow, snow wetness, snow hydrology.

1. INTRODUCTION

If the volumetric liquid water content (LWC) of a snowpack reaches around 15%, slushflows, rapid mass-movements of water-saturated snow, can occur (Hestnes, 1998). Slushflows differ from other avalanches by their low release angles (< 30°) and long runout distances (Gude and Scherer, 1998; Hestnes et al., 2012). With climate change, slushflows may become more common (Relf et al., 2015). They pose significant economic and human risks, with historical incidents like the 1945 event in Japan that killed 88 people (Kobayashi et al., 1994).

The Norwegian Water Resources and Energy Directorate (NVE) provides a regional slushflow early warning (SEW) in Norway (Sund et al., 2024). Snowpack knowledge is crucial for estimating slushflow hazards (Hestnes and Bakkehøi, 2004). Previous studies highlight that an impermeable layer, such as frozen or saturated ground, is needed for water accumulation (Onesti and Hestnes, 1989). Fine-grained snow and ice crusts increase stability (Hestnes, 1998), whereas porous snow types like precipitation particles and depth hoar are more susceptible to slushflows (Hestnes et al., 1994; Sund et al., 2020, 2024). Higher water supply can trigger slushflows regardless of snow type (Hestnes, 1998). The SEW categorizes snow stratigraphy into four types, focusing on the lower 0–1 m of the snowpack: facets/depth hoar (FC/DH) near the ground, new snow (PP) on an impermeable layer, melt forms (MF), and other types (OTH), listed from high to low susceptibility (Sund et al., 2024).

Vertical movement of water through snow primarily occurs in two ways: matrix flow or preferential flow. Matrix flow is described as a semi-uniform wetting front that gradually and evenly wets the

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entire snowpack, typically starting from the snow surface (Donahue and Hammonds, 2022). Homogeneous snow promotes matrix flow, which becomes dominant in ripe springtime snowpacks composed of melt forms (Brandt et al., 2022; Williams et al., 2010). In contrast, preferential flow channels liquid water into flow fingers that efficiently transport it downward ahead of the background wetting front (Marsh and Woo, 1984). During preferential flow, the water supply is higher and the pores are more saturated, making it much quicker than matrix flow (Clerx et al., 2022; Marsh and Woo, 1984). Stratified, heterogeneous snowpacks tend to promote preferential flow, though the exact mechanisms are not yet fully understood (Brandt et al., 2022).

Sund et al. (2024) emphasize the need for more data on how specific snow types affect water transport to improve the SEW. The primary objective of this study was to measure LWC during conditions favorable for slushflow initiation in a variety of snow types. Measurements were planned to capture snowpack conditions before wetting and during/after significant rain or melt events. The secondary objective was to evaluate the SLF Snow Sensor's effectiveness in the field, comparing its LWC values with those from the less labor-intensive hand wetness test.

2. METHODS

Testing of the SLF instrument began in January 2021, including the development of data collection routines. The brunt of the measurements were taken during the winters of 2022-2023 and 2023-2024 (Parmentier, 2024).

2.1 Site selection

We selected field sites based on several criteria. Weather was the most limiting factor; sites were chosen based on forecasts predicting over 30 mm of rain or sudden temperature increases. Proximity to weather stations was also important for accurate meteorological data. Ideal snow depth ranged from 50 to 100 cm, suitable for observing water flow through the whole snowpack and good depths for potential slushflow release (Gude and Scherer, 1995; Hestnes et al., 1994). Varsom Xgeo was used to identify areas with the desired snow depth (Varsom, 2024b), while Varsom Regobs provided snowpack observations (Varsom, 2024a). When specific data was unavailable, assumptions on snow type were made based on surrounding snowpack observations and applied knowledge of their formation processes. We selected terrain conducive to water accumulation, such as flat, impermeable, or fully saturated ground. In addition, safety needed to be considered, meaning sites had to be out of potential runout zones from slushflows or snow avalanches. Balancing these criteria required compromises. Specific snow depths and liquid precipitation confined the search to certain altitudes. Therefore, proximity to weather stations was often deprioritized. While cabin access was beneficial for drying equipment, tents offered greater flexibility. Effective field measurements were achieved by selecting multiple locations and finalizing the site based on the latest weather and snowpack data.

2.2 Measurement procedure

In the field, we recorded meteorological data and performed a standard snow pit investigation including estimating wetness using the hand wetness test (Fierz et al., 2009; NVE, 2022). After completing the snow pit investigation, LWC measurements were conducted using an SLF Snow Sensor, which uses a capacitive sensor to measure the dielectric permittivity of 45 × 95 × 17 mm snow samples (FPGA Company, 2018). It measures density directly in dry snow, but requires separate dry snow density measurements to calculate LWC in wet snow using empirical calibration equations. The SLF sensor measures LWC in the range of 0 – 20 vol. % with an accuracy of ± 0.5 vol. % (FPGA Company, 2018).

Due to the lateral variability in snowpack structures and flow patterns, Techel and Pielmeier (2011) recommend multiple LWC profiles spaced more than half a meter apart. Figure 1 shows the standardized setup used in this study, consisting of three parallel profiles spaced 60 – 80 cm apart. Early density measurements involved a 17 cm long cylinder with a volume of 600 cm^3, raising questions about the variability of snow density and its representativity compared to the smaller volume of the LWC measurement. To address this, we switched to using a 250 cm^3 snow density wedge sampler to extract snow samples, which were then weighed to calculate density. Two samples were taken from each depth, and the mean density was used as input for the SLF sensor. The SLF sensor was placed horizontally on a flat snow surface, and two measurements were taken per depth in each profile, resulting in six LWC measurements per depth.

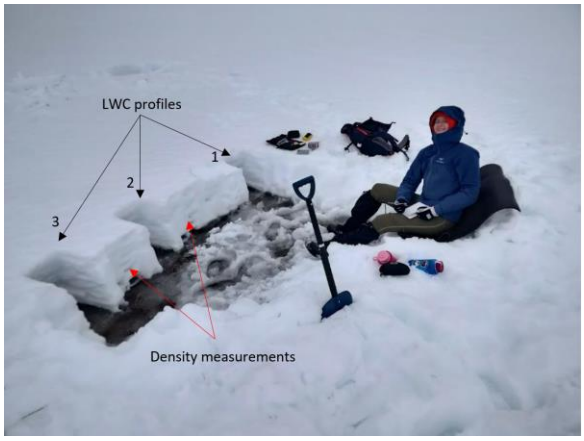


Figure 1: Liquid water content (LWC) measurements being taken in the field. LWC was measured twice per depth in each LWC profile, and required separate measurements of density, which were taken between LWC profiles.

To minimize exposure time and prevent melting, measurements followed this sequence:

1. Extract and weigh the first density sample.

2. Extract and weigh the second density sample, then calculate mean density.

3. Input mean density into the SLF sensor.

4. Excavate LWC profile 1 and perform two LWC measurements.

5. Excavate LWC profile 2 and perform two LWC measurements.

6. Excavate LWC profile 3 and perform two LWC measurements.

7. Repeat for each depth.

For follow-up LWC measurements, around 70 – 100 cm of snow was removed horizontally into the pit wall to access undisturbed snow. A challenge during rainy measurements was wetting of the LWC sensor. Water droplets were removed when possible, and the sensor was kept sensor-side down. An umbrella was used, when conditions allowed, to keep the equipment drier.

2.3 Data analysis

FPGA Company (2018) recommends measuring density before the snow becomes wet, but this wasn't always feasible, so wet snow density was used instead. This causes a small error in the LWC values. To remedy this, an iterative correction method can be applied, using the empirical calibration equations supplied in the instruction manual, to approach true density and LWC values (FPGA Company, 2018). The change in LWC was small, ranging from 0.001% to 0.99% for snow with less than 15% LWC. The absolute change was largest between 8% and 9% LWC, but as a percentage, it was greatest for smaller values and decreased with increasing LWC (Parmentier, 2024).

Hypothesis testing using permutation was used to determine if the median LWC at each depth differed significantly between measurement series. It was also used to test whether median LWC differed between snow samples of varying hand wetness classes.

3. RESULTS AND DISCUSSION

3.1 Modes of flow

The results were dominated by the difference between matrix flow and preferential flow. Therefore, we present one experiment showing each mode of flow.

Figure 2 shows the results from experiment 1, performed on a sunny day in May 2023. The snowpack was isothermal and entirely composed of MF grains. The field site was located between a lake and a marsh, saturated ground acting as the impermeable layer. For timestep (T) 1, there was a water table between 40 and 45 cm, indicated by a leap in LWC at the bottom of the profile. Seven hours later, the water table had risen by 5 cm, preventing LWC measurements at 45 cm for T2. Estimated snowmelt from Varsom Xgeo was 29 mm for the day, which was the only source of added water. Median LWC increased at all depths except 10 cm, though only four depths show statistically significant increases. Variability is similar across depths, with the IQR typically spanning 3% – 4% LWC.

Figure 3 shows the results from experiment 2, performed during a rainstorm in December 2023. The snowpack consisted of fresh PP on top of RGxf, with DH at the base. The site was a gravel parking lot with frozen ground acting as an impermeable layer. T1 was measured at 18:00 on 15.12.23, showing a completely dry snowpack. T2 was measured at 15:00 on 16.12.23, 21 hours later. Estimated rain and snowmelt were 39 mm and 3 mm, respectively, according to Varsom Xgeo. A garden rain gauge recorded over 50 mm of rain by 12:00 and an additional 12 mm by 15:00. The snowpack thinned by about 9 cm, mainly in the PP layer, which reduced from 19 cm to 10 cm. T2 showed very wet snow (LWC_median = 12.8%) in the top 5 cm and much drier snow (LWC_median = 1.0%) at 10 cm. The interior of the snowpack was virtually dry, with no significant difference between T1 and T2 at these depths. The DH layer at the base was completely saturated, with the frozen gravel preventing water infiltration.

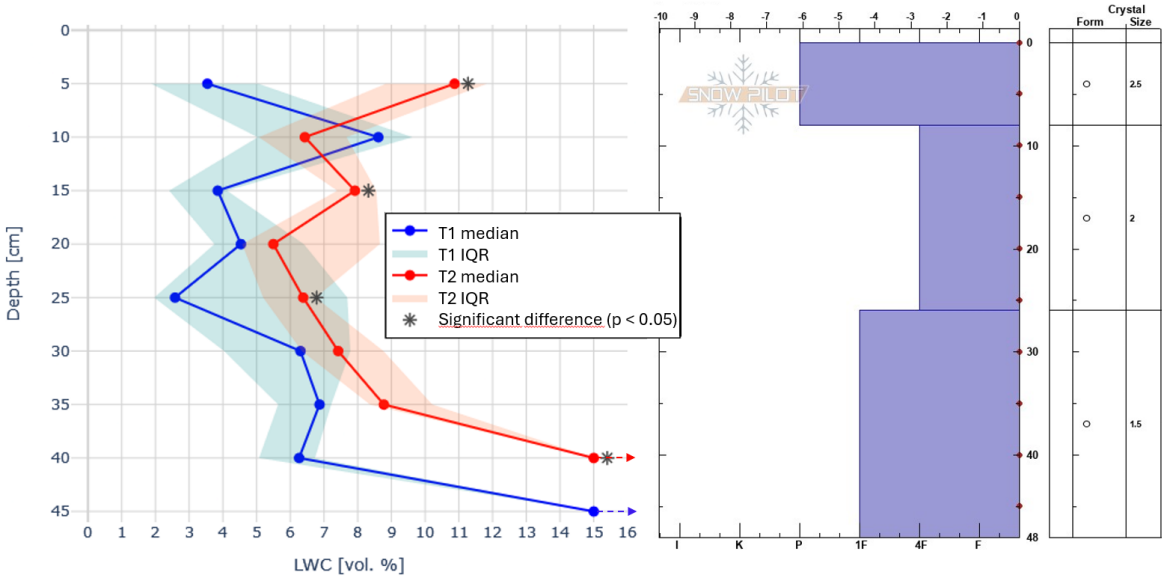


Figure 2: Comparison of LWC profiles (left) in experiment 1, where the snowpack (right) consisted of MF. The first measurement (T1, blue) was taken at 10:00, and the second measurement (T2, red) was taken at 17:00. Dots represent median LWC at their respective measurement depths, solid lines indicate linearly interpolated median LWC, and shaded areas denote the interquartile range. Asterisks (*) mark depths where the difference in median LWC between T1 and T2 is statistically significant ($p < 0.05$). LWC values above 15% are shown as 15%.

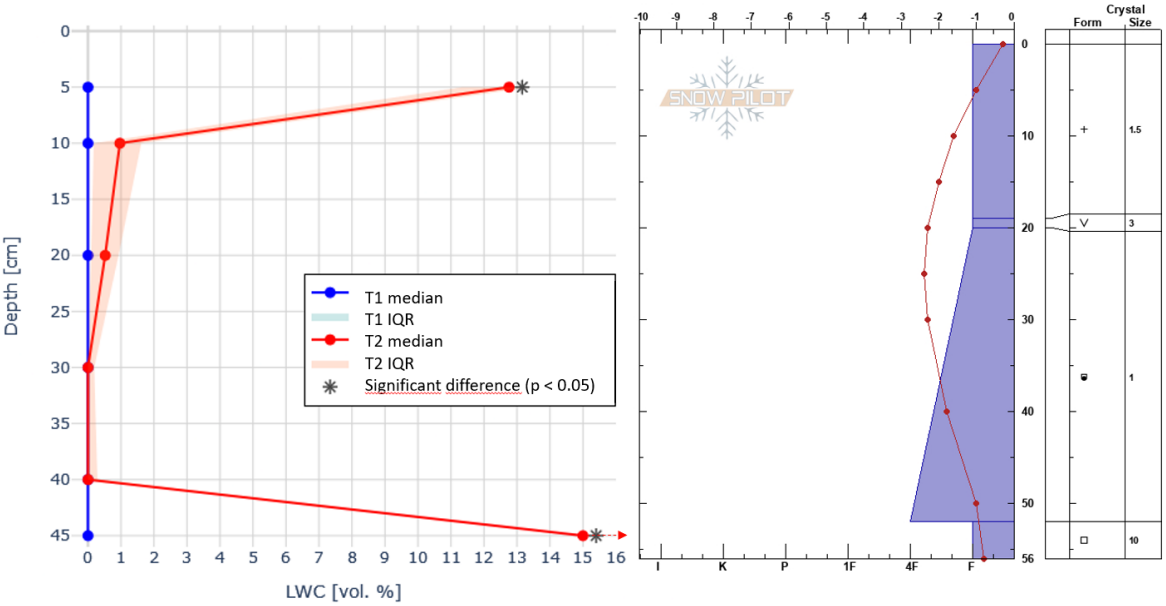


Figure 3: Comparison of LWC profiles (left) in experiment 2, where the snowpack (right) consisted of PP over RGxf. The first measurement (T1, blue) was taken at 18:00, and the second measurement (T2, red) was taken at 15:00 the following day. Dots represent median LWC at their respective measurement depths, solid lines indicate linearly interpolated median LWC, and shaded areas denote the interquartile range. Asterisks (*) mark depths where the difference in median LWC between T1 and T2 is statistically significant ($p < 0.05$). LWC values above 15% are shown as 15%.

Experiments 1 and 2 illustrate the differences between, respectively, matrix flow and preferential flow quite well. Experiment 1 (Figure 2) shows a homogenous snowpack consisting of MF experience an even and uniform increase in LWC throughout the snowpack, fitting the description of matrix flow (Donahue and Hammonds, 2022; Marsh and Woo, 1984). The largest increase in LWC occurred at the surface, where most of the melting likely occurred due to incoming shortwave radiation from the sun.

Experiment 2 (Figure 3) showed a snowpack getting wet at the surface and the base, but with few signs of water in the interior. This means that the water must have reached the base in a way that was not picked up by the standard measurement procedure. Preferential flow, leading water in flow fingers through the snowpack has that capacity. This could lead to slushflows releasing earlier than expected, especially if the snowpack base consists of vulnerable snow types like depth hoar (Hestnes et al., 1994; Sund et al., 2024). The results from experiment 2 may indicate that the presence of PP at the surface promotes the formation of preferential flow. However, it is not only snow type that differs between experiments 1 and 2. The formation of preferential flow paths may also depend more on water supply volume and rate than on snow type, as suggested by Sund et al. (2020, 2024).

The results from this study indicate that preferential flow is more common in PP, while matrix flow dominates in MF. This could help explain why PP is more vulnerable to slushflows at lower water input, while larger water supply is needed for melt forms and more resistant snow types where grain bonds are stronger (Sund et al., 2024). This means that the current approach for assessing slushflow hazard on a regional scale by assessing various amounts of water supply to different snow types is still useful.

Experiments 1 and 2 showed water pooling at the snowpack base, forming or raising a water table, which is only possible with impermeable ground conditions. Literature supports this as a key factor for slushflow release (Gude & Scherer, 1998; Hestnes, 1998; Hestnes et al., 1994; Sund et al., 2020, 2024). However, none of the experiments resulted in a water table rise beyond approximately 5 cm, and no slushflows were triggered. Although witnessing slushflow release was not a direct objective and was avoided for safety reasons, these findings suggest that impermeable ground alone is insufficient for slushflow initiation. This underscores the importance of lateral flow, especially at larger scales than the individual snow pits studied (Eiriksson et al., 2013). Water funneling from a larger catchment is more likely to trigger slushflows than localized rain or melting snow. Terrain features and topography that cause water accumulation, such as valleys, play a crucial role (Gude and Scherer, 1998).

3.2 Persistence of depth hoar

A result of note from an experiment not shown here was that depth hoar was observed persisting for multiple hours despite being exposed to liquid water. Snow crystals still clearly recognizable as depth hoar were observed after a minimum of six hours after exposure to liquid water.

The importance of snow type might be questioned since all snow eventually transitions to MF when in contact with liquid water. However, the persistent moist DH observed suggests snow type remains relevant. Original grain form might be less important when water accumulates over several days, allowing crystals time to transition to MF. For the rapid and intense water supply rates typical in this study, there may not be enough time for complete transformation to MF before slushflow release.

3.3 Evaluation of SLF sensor

Figure 4 shows the results from the comparison between LWC estimated using the hand wetness test and LWC measured with the SLF sensor. Median LWC appears to increase exponentially with hand wetness class and the medians for all groups are statistically significantly different from each other.

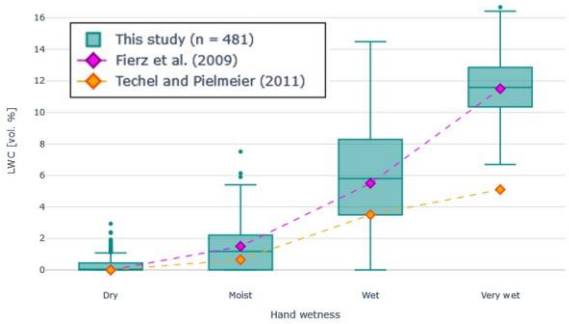


Figure 4: Comparison of liquid water content estimated using the hand wetness test and measurements from the SLF sensor. For comparison, mean values from Fierz et al. (2009) and median values from Techel and Pielmeier (2011) are shown.

Comparing the hand wetness test and SLF sensor data (Figure 4), median values from Techel and Pielmeier (2011) are lower than those in this study for each wetness class except “dry.” Their LWC values increase more linearly and deviate noticeably in the wettest categories. This discrepancy may be due to the subjective nature of the hand wetness test, despite standardized guidelines (Fierz et al., 2009). Additionally, they used a Snow Fork, not an SLF sensor, which may yield different results. When looking at the values from Fierz et al. (2009), however, the alignment to this study is quite good. Despite differences from Techel and Pielmeier (2011), the findings of this

study indicate that the hand wetness test remains effective, at least for approximate LWC values. That implies that this could be an effective observation tool for acquisition of real-time data for the slushflow hazard forecasters, being a less work-intensive method compared to the SLF sensor.

When more precise values are required, however, the SLF sensor is a very portable, compact, easy to use, and practical tool for measuring LWC in the field. However, the need for a separate density measurement to calculate LWC is both time-consuming and error-prone. The manual suggests doing density measurements before the snow gets wet, typically in the morning (FPGA Company, 2018). This doesn't account for structural changes and settling in the snowpack due to liquid water exposure, though. While this method may work for old layers of RG or MF, porous PP layers change significantly when wet. The density of unwetted PP differs from that of wetted PP (Waldner et al., 2004).

3.4 Limitations

A clear limitation of this study is the destructive nature of the measurement process. It was not possible to measure the same snow sample during the second series of measurements, introducing the effect of lateral variability. Assuming consistent snowpack properties over short lateral distances may be adequate for grain form, grain size, and layer thickness, but certainly not for the patterns of flow fingers. This also slightly skewed the alignment of measurements between series. Using the snow surface as the reference point meant that melting and settling misaligned follow-up measurements. Using the ground as the reference point might have improved this, as most melting and settling occurred near the surface. Ideally, aligning measurements according to layer boundaries would have provided more accuracy.

Although the field experiments in this study were conducted under realistic slushflow weather conditions, controlled conditions may offer advantages. Future studies could use sprinkling experiments near a weather station, eliminating the dependency on specific and rare weather events. This approach would also simplify fieldwork, allowing it to be conducted in dry conditions and preventing equipment from getting wet.

4. CONCLUSION

This study investigated the development of liquid water content (LWC) in different snow types by measuring LWC profiles using an SLF Snow Sensor. Measurements were taken before and during meteorological conditions favorable for slushflow release, including intense rain and strong melting. The central findings are summarized here.

Research objective 1: Investigate how liquid water develops in different snow types during weather situations where slushflows can occur.

- The differences between preferential flow and matrix flow are important for how water travels through snow. Water supply rate and volume may influence this.
- Ripe melt forms likely promote matrix flow.
- Precipitation particles may promote preferential flow in snow.
- Moist depth hoar can persist for multiple hours, if not days, without fully melting or turning into melt forms.
- Mode of flow can be important for slushflow early warning, as preferential flow may lead water to vulnerable snow types, such as depth hoar, at the bottom of the snowpack faster than expected.
- Lateral flow likely plays a large role in slushflow initiation.

Research objective 2: Evaluate the SLF Snow Sensor as a tool for measuring LWC in the field.

- The SLF sensor is practical, easy to use and gives good point-measurements of LWC in the field. However, the need for an additional density measurement increases the workload substantially.
- The hand wetness test is effective for approximate values of LWC, but when more precise values are needed, the SLF sensor is a more suitable tool.

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