MUCH ADO ABOUT SLUSHING

Susanne Eide Haug[1], Louise Vick[1]*, Alfred Hanssen[1], Yoichi Ito[2], Satoru Yamaguchi[2], Chris D'Amboise[3], Dieter Issler[4]

[1] *Department of Geosciences, UiT The Arctic University of Norway, Norway*
[2] *NIED National Research Institute for Earth Science and Disaster Resilience, Japan*
[3] *Tromsø, Norway*
[4] *NGI Norwegian Geotechnical Institute, Norway*

ABSTRACT: Slush, or soaked now, is a poorly understood endmember of the wet–dry snow continuum that can produce fast, damaging flows. A commonly cited threshold for slush formation is a liquid water content (LWC) of ~15%, but that value remains largely untested. We performed rotating-drum experiments to observe how snow–water mixtures evolve under shear and how LWC, structure, and mechanical reworking control flow regime and morphology. LWC was varied between 0 and 100% by controlled additions and removals while we recorded material dynamics and flow modes. As LWC and mechanical reworking increased, behaviour progressed from dry granular flow to structured flow, then wet snow, slush, and finally slurry. By progressively adding and removing snow and water we found that different experimental runs showed different flow behaviour at the same LWC. Transitions between regimes were not governed by LWC alone but by the coupled effects of LWC, snow microstructure, mechanical history, rotation rate, and boundary conditions over time. Applying these laboratory findings to field settings suggests that slushflow initiation and evolution are sensitive to snowpack history and terrain morphology, and that when encounters with drainage pathways abruptly increase water content the knock-on effects are a change in flow regime, runout, and damage potential. We recommend new considerations for uptake in dynamic runout modelling, together with improved documentation of slushflow events, to improve data harmonisation in future hazard studies.

KEYWORDS: slushflow, soaked snow, snow laboratory experiments, rotating drum experiments, runout and hazard analysis.

1. THE PROBLEM

Slushflows consist of soaked snow with higher liquid water content than typical snow avalanches (Figure 1). They can initiate in many terrain types, across a wide range of slope angles and from early winter through late-season conditions (e.g. Hestnes, 1985). This diversity, combined with a lack of coordination in data collection, event recording, simulation tools, and hazard-management approaches, has produced substantial inconsistency in the available literature.

Events such as the Bakfjorddalen, Nåelva, and Leirbotnvannet slushflows in 2023–2024 in Norway highlight the consequences of this lack of coordination in slushflow management, with practitioners unsure of how to respond to and classify slushflow events – each of these (unpredicted) events led to economic losses due to infrastructure damage (D'Amboise et al. 2024). The path length of these events varied from 0.35 to 6 km from the source, with average slope angles of 5–12°. They all joined drainage paths and transitioned through the spectrum of avalanche–slushflow–flood, depending on where and when they met streams and the bulking of the flow/avalanche due to entrainment of snow. These transitioning events are quite typical, not unique in their complexity (Hestnes, 1985). The release and mobility depend on water supply, snowpack properties, terrain, drainage, and ground conditions (Hestnes, 1985, 1996; Sund et al., 2024). The internal behaviour of moving snow - water mixtures is difficult to observe directly. To understand what is driving material transitions and the resultant dynamic regime, we must inspect slush behaviour in a controlled laboratory setting.

This study used a rotating drum to investigate snow–water mixtures under controlled repeated forcing. The aim was not to simulate a full natural slushflow, but to identify material-scale behaviours relevant to slushflow dynamics. The specific objectives were to: (i) classify observed snow-water flow behaviour; (ii) assess the role of liquid water content and experimental pathway; (iii) investigate centrifuging and surface morphology; and (iv) evaluate the influence of drum-boundary interaction. On the basis of these results, we make recommendations for slushflow hazard management and runout modelling.

* Corresponding author address:
Louise Vick, Department of Geosciences
UiT The Arctic University of Norway
Tromsø, Norway
email: louise.m.vick@uit.no

https://doi.org/10.15788/1790098884

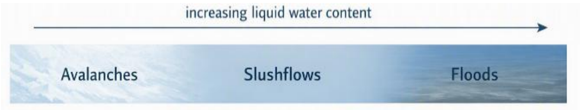


Figure 1. The snow-water mass movement spectrum showing increasing LWC of the snowpack leading to material transformation from snow avalanche to slushflow to flood. Although this framework is useful, we question the commonly cited 15% LWC threshold separating avalanche-like and slushflow behaviour.

2. METHODS

2.1 Setup

Experiments were conducted as part of a master thesis (Haug, 2026) in July 2025 at the Snow and Ice Research Center of the National Research Institute for Earth Science and Disaster Resilience (NIED) in Nagaoka, Japan. The snow was from multiple previous seasons, stored and mechanically crushed for preparation. It was stored at −5 °C and experiments conducted in a cold laboratory at approximately −1 °C.

The rotating drum had a diameter of 1.0 m and an internal width of 0.30 m. The main tests used drum speeds of approximately 21 and 38-40 rpm.

Several wall linings were tested to vary boundary conditions: smooth rubber, non-slip rubber, wooden treads (7 treads, 100 m high), rubber strips, combinations of wooden treads and rubber strips, and carpet.

Two cameras recorded the experiments: a Sony ZV-1 frontal camera at 120 frames per second and a GoProHero 13 side camera at 60 frames per second. The frontal view was used for most quantitative video analysis, while the side view was used as supporting documentation.

2.2 Procedures

Two complementary procedures were used (Figure 2).

1. **Snow-first experiments:** approximately 13 kg of snow was placed in the drum and water was added stepwise. In the main high-speed snow-first experiment, water additions ranged from 1 to 60% of the initial snow mass. A lower-speed snow-first experiment was conducted until centrifuging weakened and stopped.
2. **Water-first experiments:** the drum initially contained approximately 10 L of water. Snow was added incrementally, followed in some cases by stepwise water removal or further snow addition.

Mass-based LWC (LWC_M) was estimated using a melting-calorimetry method to determine the free or liquid water content of wet snow (Kawashima et al., 1998) given by:

$$W = \left[1 - \frac{1}{H}\left(\frac{(M_1 - M_0)(T_1 - T_2)}{M_2 - M_1} - T_2\right)\right] \cdot 100 \qquad (1)$$

Here, $H = 3.34 \cdot 10^5$, J/kg is the latent heat of fusion of ice (Kawashima et al., 1998), M_0 is the mass of the empty container, M_1 is the mass of the container with added hot water at temperature T_1, M_1 is the mass of the container after the snow has been added, and T_2 is the equilibrium temperature after the snow has melted.

Standard snow wetness classes are commonly expressed as volumetric liquid water content (Fierz et al., 2009) and concerns with sampling conditions and uncertainty in calorimetric LWC measurements have been discussed by Fasani et al. (2023) and Barella et al. (2024). The LWC estimates were therefore treated as approximate indicators of the experimental material state rather than exact thresholds for flow-behaviour transitions.

2.3 Flow observations and measurements

Flow behaviour was classified from repeated video review using material structure, surface morphology, visible water and air distribution, centrifuging, and wall interaction.

Dynamic surface angles- the angle of the flows surface during active rotation- were measured from selected video frames using the sports tracking software Kinovea. Friction tests compared carpet and rubber contact surfaces under dry, wet, very wet, and soaked snow conditions.

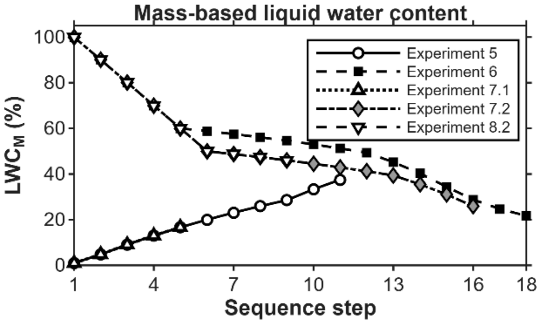
3. RESULTS

3.1 Effect of liquid water content and experimental pathway

The snow-first experiments showed a progression from granular behaviour toward wet structured and slush-like flow as water was added. The clearest sequence occurred in the high-speed snow-first experiment. At low water additions, snow became wetter and more compact but remained relatively granular. At intermediate additions, clusters, visible air pockets, and coherent rotational structures developed (Figure 5). At the highest water additions, the mixture became smoother and more deformable, with a flatter slush-like surface.

Water-first experiments showed the opposite evolution. Initially, the water-dominated stages were flat and slurry-like. As snow was added or water was removed, the mixtures became more textured, had steeper surfaces, and increasingly structured. In several runs, water removal or subsequent snow addition produced connected snow-rich masses and wet structured flow.

Comparable bulk water contents did not produce identical behaviour. For example, a snow-first stage (with LWC_M approx 28.6%) appeared more deformable and slush-like than a water-first stage (with LWC_M approx 28.8%), which was more structured. The difference reflects contrasting histories: gradual water addition to snow versus water-rich mixing, drainage, and later snow addition.



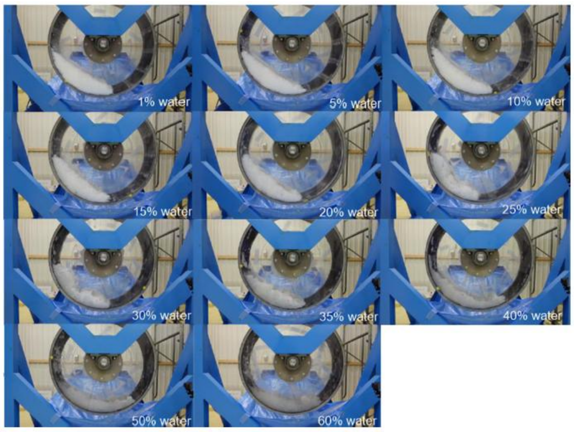


Figure 2A. LWC_M trends for Experiments 5–8. Experiments 5 and 7.1 followed snow-first procedures where LWC_M increased as water was added to snow. Experiments 6, 7.2, and 8.2 followed water-first procedures where LWC_M decreased as snow was added or water was removed. Figure 2B. Experiment 5 snow-first sequence. Water was added from 1% to 60% of the initial snow mass.

3.2 Mixture range and flow-behaviour classes

The snow-first and water-first procedures covered overlapping portions of the snow-water mixture spectrum. In the main snow-first experiment, LWC_M increased from 0.99% after the first water addition to 37.5% at the highest addition. In water-first experiments, LWC_M decreased from 100% in the water-only condition to 21.7–46.0% after snow addition and/or water removal.

Five descriptive classes of moving-flow behaviour were identified (Figure 3):

- **Granular-dominated flow**. 0–1.3% LWC_M: loose snow was carried upward by the drum and moved downslope along the free surface. This class occurred in dry and very low-water stages.
- **Structured granular flow**. 1–13% LWC_M: the snow retained a mainly granular character but developed weak clusters, connected patches, and local coherent structures.
- **Wet structured flow.** 13–50% LWC_M: wetter mixtures formed clusters, roll-like masses, irregular surfaces, air pockets, and locally water-rich zones. Material often moved as partly connected bodies.
- **Slush-like flow**. 26–60% LWC_M: water-rich but still structured and deformable material. Surfaces could remain inclined and locally clustered, but motion was smoother than in wet structured flow.
- **Flat slush/slurry-like flow**. 56–90% LWC_M: very water-rich, smooth, and relatively flat movement with limited distinct clustering.

The classes overlapped in calculated LWC_M. Consequently, they cannot be interpreted as fixed liquid-water-content categories.

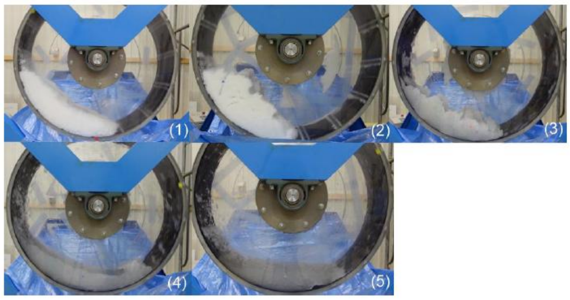


Figure 3. Examples of the five flow-behaviour classes: (1) granular-dominated flow, (2) structured granular flow, (3) wet structured flow, (4) slush-like flow, and (5) flat slush/slurry-like flow.

3.3 Surface morphology and apparent cohesion

Dynamic surface angle changed substantially during the experiments. In the main snow-first sequence, the angle increased from approximately 33° in the initial snow condition to 43° at intermediate water addition, then decreased to approximately 10° at the highest water addition. The steepest surfaces coincided with clustering and coherent rotational structures.

Water-first experiments started with low surface angles, commonly 2–10° during water-rich stages. Angles increased as snow was added or water removed, reaching approximately 27–36° in some later snow-rich stages.

Apparent cohesion was not measured directly, but was inferred from morphology and the persistence of coherent rotational structures. Apparent cohesion was strongest in intermediate wet structured stages rather than increasing continuously with water content. At high water content, the mixtures became smoother and flatter, suggesting reduced ability to maintain steep connected structures.

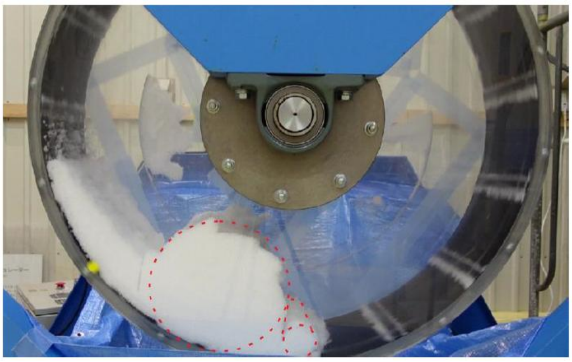


Figure 5. Coherent rotational structures observed during.

3.4 Boundary interaction

Boundary conditions strongly controlled mobility. Smooth rubber produced excessive slip, whereas wooden treads trapped snow. The rubber-strip configuration provided the most consistent movement.

Carpet lining promoted adhesion and pronounced surface irregularities. Dry snow developed spike-like protrusions with heights between 5 and 24 cm. In one snow-first carpet experiment, the material adhered after only limited water addition and failed to restart after the drum was stopped. In a water-first carpet experiment, flow ceased when LWC_M dropped to 46%. These results demonstrate that high bulk water content did not guarantee mobility when boundary interaction dominated.

4. DISCUSSION

This study shows that snow-water mixtures in a rotating drum cannot be described adequately by liquid water content alone. Although mass-based liquid water content provided a useful quantitative measure of bulk composition, the observed behaviour also depended on the sequence of water and snow addition, mechanical reworking, rotational forcing, snow structure, and interaction with the drum boundary. The experiments therefore support an interpretation of snow-water mixtures as evolving wet granular materials rather than homogeneous mixtures with fixed transitions between dry snow, slush, and water-rich flow.

4.1 Liquid water content as a descriptor, not a threshold

The snow-first and water-first experiments approached overlapping mixture compositions from opposite directions. This design demonstrated that similar LWC_M values could correspond to different visible flow behaviour. For example, mixtures with approximately 28–29% LWC_M showed different responses depending on their experimental history. Snow that had been gradually wetted behaved as a relatively deformable slush-like material, whereas mixtures produced through water removal and subsequent snow addition were more structured and snow-rich. This difference indicates that bulk liquid water content does not describe the internal distribution of water, the degree of snow aggregation, or the previous mechanical history of the material.

This result is consistent with observations from wet-snow research, where liquid water content may vary over short distances and where the mechanical effect of water depends on grain type, snow structure, and water distribution (Techel & Pielmeier, 2011). The calculated LWC_M should therefore be regarded as a bulk experimental descriptor rather than a universal predictor of snow–water flow behaviour.

4.2 Development of structure and apparent cohesion

The observed flow classes suggest that apparent cohesion was strongest at intermediate LWC. Dry and low-water stages were mainly granular or structured granular, with loose snow, weak clusters, and local coherent motion. As water was added, the material developed more persistent clusters, roll-like structures, air pockets, and steeper dynamic surfaces. At higher water contents, the mixtures became smoother, flatter, and more deformable. The highest dynamic surface angles occurred when clusters and coherent structures were most evident. This pattern resembles behaviour reported for wet granular materials. Small to moderate amounts of liquid may create capillary bridges between grains, increasing cohesion and promoting cluster formation, whereas highly water-rich mixtures may become less structured and more slurry-like (Fournier et al., 2005; Mitarai & Nori, 2006; Tegzes et al., 2002). However, snow differs from mineral grains because grain shape, bonding, and size can evolve during motion. The formation of coherent structures during dry and low-water stages shows that snow structure and mechanical reworking also contributed to apparent cohesion. The observed structures should therefore not be attributed solely to liquid water. Repeated rotation may have promoted compaction, aggregation, fragmentation, grain rounding, and temporary snow bonding. The material response was consequently dependent on both moisture state and deformation history.

The strongest visible structures occurred at intermediate wetness. This pattern is consistent with wet granular theory, in which small to moderate liquid contents can promote capillary cohesion and correlated clump motion (Fournier et al., 2005; Tegzes et al., 2002). However, snow adds important complexity because its grains can change during rotation. Dry or low-water snow occasionally formed coherent rotational structures after prolonged mechanical reworking, demonstrating that evolving snow structure can also create temporary apparent cohesion.

4.3 Boundary interaction and stopped flow

Boundary interaction strongly influenced the experimental response. Smooth rubber lining produced excessive slip, while wooden treads caused snow accumulation and cataracting. The rubber-strip configuration provided the clearest continuous movement, whereas carpet promoted adhesion, irregular surface morphology, and stopped flow. The carpet experiments are particularly important because they demonstrate that high LWC did not necessarily produce mobility. In one experiment, snow adhered to the carpet after limited water addition and did not restart after the drum was stopped. In another, flow ceased at a relatively high LWC_M.

These results show that the boundary must be treated as part of the system rather than as a passive container. In the rotating drum, the wall controlled whether the material was lifted, slipped, adhered, or stopped. The experiments demonstrate the general importance of snow-surface interaction for snow–water mobility.

4.4 Experimental limitations

The main limitations are the lack of direct measurements of local liquid water content, pore pressure, internal saturation, and full internal velocity fields. In addition, further rheological observations including starting angle and dynamic equilibrium angle as a function of rotation. The snow was stored, mechanically processed, and sometimes reused; it was therefore not equivalent to an undisturbed natural snowpack. Future experiments should include internal moisture or pore-pressure sensors, torque measurements, laser-based surface profiling, multi-angle particle tracking, and controlled variation of grain size, temperature, drainage, rotational speed, and wall roughness.

5. APPLICATION TO SLUSHFLOW HAZARD ASSESSMENT

A large part of assessing slushflow hazard is predicting the spatial extent of the runout. Numerical solutions to calculate runout based on terrain conditions and material parameters are a typical tool. Practitioners and researchers attempt to use tools such as RAMMS::Avalanche (Christen et al., 2010), Titan2D (Pérez-Guillén et al., 2019) or other runout models (e.g. Blatny et al., 2026); however, existing parameterisations may not adequately represent the evolving behaviour of snow–water mixtures. We provide observations of elements that should be considered based on our experiments, while noting these experiments were laboratory-based and provide only material-scale observations relevant to slushflow dynamics. Further investigation into the scaling behaviour of the laboratory-observed processes is required to draw meaningful conclusions.

5.1 Consider terrain morphology and roughness

Experiments showed that the boundary had a strong influence on flow properties. Interaction of the flow with the snow surface matters—users should be able to adjust terrain conditions according to how these may affect runout—. Of particular importance are changes in basal material such as frozen ground, bedrock, vegetation, or saturated soil. In addition, slushflows can initiate and travel in terrain that is substantially flatter than typical dry-avalanche terrain, especially where water accumulates in snow-filled channels, depressions, and poorly drained slopes (Hestnes, 1985; Jaedicke et al., 2022). slushflow hazard should therefore be assessed *in addition to* avalanche hazard; one needs to consider not only steep release areas but also hydrologically connected terrain, stream channels, terrain hollows, and transitions into flatter runout zones.

5.2 Use spatially variable rather than fixed material parameters

The results indicate that a snow-water mass may change behaviour during its evolution or movement. Gradual wetting can transform granular snow into structured and eventually slush-like material. Conversely, water-rich mixtures may become more structured when water is removed or when snow is incorporated. This is relevant to natural settings where water accumulates in snowpacks, stream channels, or depressions, and where moving slush may entrain additional snow, water, debris, or organic material increasing the hazard. Transition points or zones in the pathway—places where material entrains water or snow, effectively changing the flow behaviour—should be marked as thresholds by the user (based on field observations) where parameter sets representing slushflow behaviour shift.

The cohesion of the snow granules in a wet snow flow will affect its snow-entrainment ability and its ability to flow (Bartelt et al. 2017), and this effect this has on degree of hazard in a slushflow should be explored. Additionally, as we demonstrated prolonged mechanical working could promote cohesion, a more sensitive approach to cohesion during slushflow runout (i.e. making cohesion pathway-length dependent to a degree) should be explored. Similarly, the starting and finishing LWC of a slushflow should not be fixed, but adjustable based on records from observations, or transition zones from mapped pathway thresholds.

Overall, the results suggest that slushflow mobility should not be represented solely by a single density, friction coefficient, or bulk water-content value. Material state may change as water is redistributed, snow structure evolves, and boundary conditions vary. This complexity is relevant for numerical modelling, particularly where simplified models are applied to water-rich snow movements in low-gradient terrain.

5.3 *Improved event documentation*

As the community works towards a united classification system for slushflows, future inventories should record more than event location and runout length (D'Amboise et al., 2024). Useful observations include:

- estimated snow and water content at release and deposition (a guideline to proxy estimation in the field is required);
- precipitation, melt, and rain-on-snow conditions;
- drainage pathways and water sources;
- snowpack structure and ground condition;
- source locations and pathway of the movement; slope angle and channel geometry;
- transitions between snow-rich, slush-like, and water-rich flow;
- evidence of entrainment, erosion, deposition, or lateral spreading;
- flow interaction with streams, culverts, roads, and vegetation; and
- uncertainty in event classification.

More consistent reporting would improve comparison between events, support model calibration, and reduce ambiguity between slushflow, wet-snow avalanche, debris flow, and flood classifications.

6. CONCLUSIONS

Rotating-drum experiments demonstrate that snow–water mixtures do not transition from avalanche-like to slush-like behaviour at one universal liquid-water-content threshold. Instead, their behaviour depends on the interaction of liquid water content, water distribution, snow structure, mechanical reworking, rotational forcing, and boundary conditions.

Five descriptive flow-behaviour classes were identified: granular-dominated flow, structured granular flow, wet structured flow, slush-like flow, and flat slush/slurry-like flow. Intermediate water influence produced the greatest visible apparent cohesion, clustering, and coherent rotational structures. Water-rich mixtures became smoother, flatter, and more deformable, although high bulk water content did not guarantee mobility where boundary adhesion was strong.

The results suggest that slushflow runout can evolve along a path as a flow entrains snow, enters drainage pathways, receives additional water, drains, or encounters changing boundary conditions. Consequently, slushflow hazard assessments and numerical models should avoid reliance on a single LWC threshold or fixed material parameter set. Instead, field-based identification of hydrological and geomorphological transition zones should inform spatially variable representations of snow–water flow behaviour.

REFERENCES

Barella, R., Bavay, M., Carletti, F., Ciapponi, N., Premier, V., and Marin, C.: (2024). Unlocking the potential of melting calorimetry: a field protocol for liquid water content measurement in snow, The Cryosphere, 18, 5323–5345, https://doi.org/10.5194/tc-18-5323-2024.

Bartelt, P., Valero, C. V., Feistl, T., Christen, M., Bühler, Y., & Buser, O. (2015). Modelling cohesion in snow avalanche flow. *Journal of Glaciology, 61*(229), 837–850. https://doi.org/10.3189/2015JoG14J126

Blatny, L., Hamre, D., Gaume, J., Gauer, P., & Mears, A. (2026). Observations and modeling of slushflows from Atigun Pass, Alaska. *Cold Regions Science and Technolgy*. https://doi.org/10.1016/j.coldregions.2025.104812'

Christen, M., Kowalski, J., & Bartelt, P. (2010). RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. *Cold Regions Science and Technology, 63*(1–2), 1–14. https://doi.org/10.1016/j.coldregions.2010.04.005

D'Amboise, C. J., Edvardsen Hansen, V., & Vick, L. M. (2024). Motivation for slushflow classification. In *International Snow Science Workshop Proceedings* (pp. 759–765). https://hdl.handle.net/10037/35473

Fasani, D., Cernuschi, F., & Colombo, L. (2023). Calorimetric determination of wet snow liquid water content: The effect of test conditions on the calorimeter constant and its impact on the measurement uncertainty. *Cold Regions Science and Technology, 214*. https://doi.org/10.1016/j.coldregions.2023.103959

Fournier, Z., Geromichalos, D., Herminghaus, S., Kohonen, M., Mugele, F., Scheel, M., Schulz, M., Schulz, B., Schier, C., & Seemann, R. (2005). Mechanical properties of wet granular materials. *Journal of Physics: Condensed Matter, 17*(9), S477–S502. https://doi.org/10.1088/0953-8984/17/9/013

Haug, S. (2026). *From dry to soaked snow: Investigating water-driven flow in a rotating drum experiment* [Master's thesis, UiT The Arctic University of Norway]. https://nva.sikt.no/registration/019fdbf715b1-457cd15b-13e0-4b5e-812e-0fb5005a34c4

Hestnes, E. (1985). A contribution to the prediction of slush avalanches. *Annals of Glaciology, 6*, 1–4. https://doi.org/10.3189/1985AoG6-1-1-4

Hestnes, E. (1998). Slushflow hazard—Where, why and when? 25 years of experience with slushflow consulting and research. *Annals of Glaciology, 26*, 370–376. https://doi.org/10.3189/1998AoG26-1-370-376

Jaedicke, C., Kalsnes, B., & Solheim, A. (2022). *Sørpeskred: Egenskaper, historikk og sikringsløsninger* (Klima 2050 Report No. 38). SINTEF Akademisk forlag. https://hdl.handle.net/11250/3043827

Kawashima, K., Endo, T., & Takeuchi, Y. (1998). A portable calorimeter for measuring liquid-water content of wet snow. *Annals of Glaciology, 26*, 103–106. https://doi.org/10.3189/1998AoG26-1-103-106

Mergili, M., Fischer, J.-T., Krenn, J., & Pudasaini, S. P. (2017). r.avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows. *Geoscientific Model Development, 10*, 553–569. https://doi.org/10.5194/gmd-10-553-2017

Mitarai, N., & Nori, F. (2006). Wet granular materials. *Advances in Physics, 55*(1–2), 1–45. https://doi.org/10.1080/00018730600626065

Pérez-Guillén, C., Tsunematsu, K., Nishimura, K., & Issler, D. (2019). Seismic location and tracking of snow avalanches and slush flows on Mt. Fuji, Japan. *Earth Surface Dynamics, 7*, 989–1007. https://doi.org/10.5194/esurf-7-989-2019

Sund, M., Grønsten, H. A., & Seljesæter, S. Å. (2024). A regional early warning for slushflow hazard. *Natural Hazards and Earth System Sciences, 24*, 1185–1201. https://doi.org/10.5194/nhess-24-1185-2024

Techel, F., & Pielmeier, C. (2011). Point observations of liquid water content in wet snow: Investigating methodical, spatial and temporal aspects. *The Cryosphere, 5*(2), 405–418. https://doi.org/10.5194/tc-5-405-2011

Tegzes, P., Vicsek, T., & Schiffer, P. (2002). Avalanche dynamics in wet granular materials. *Physical Review Letters, 89*(9), Article 094301. https://doi.org/10.1103/PhysRevLett.89.094301