TRACKING WATER IN SNOW: BRIDGING SENSOR DATA AND MODEL SIMULATIONS

Andrea Bruckmeier[*1], Christoph Mitterer[3], Robyn Gotz[1], Eric Sproles[1,4], Erich Peitzsch[2,1]

[1]*Department of Earth Sciences, Montana State University, Bozeman, Montana, USA*
[2]*U.S. Geological Survey, Northern Rocky Mountain Science Center, West Glacier, Montana, USA*
[3]*Avalanche Warning Service Tirol, Innsbruck, Austria*
[4]*Geospatial Core Facility, Montana State University, Bozeman, Montana, USA*

ABSTRACT: Forecasting wet slab avalanches remains one of the most demanding challenges in operational avalanche forecasting. A key obstacle is the difficulty of observing and quantifying liquid water content (LWC) and tracking its infiltration into the snowpack. Field measurements are labor-intensive, highly variable in space, and often influenced by user application or sensor design — making them impractical for forecasting operations. In this study, we evaluated LWC measurements obtained from two capacitive sensors, the SLF SnowPro-17 and -25, and compared them with simulations from the snow cover model SNOWPACK. We analyzed five selected days with pronounced melt events during spring 2025 at Bridger Bowl Ski Area, Montana. The SnowPro-17 measured LWC on the sidewall and the SnowPro-25 was inserted into the pit wall. We then analyzed measurements from the two sensors to assess consistency and potential bias. For each of the five days, we also analyzed liquid water infiltration by layer, comparing field measurements with model-simulated LWC. This allowed us to assess how well the model captured both the timing and magnitude of infiltration processes relative to in-situ observations. Our results show that, the absolute LWC values differ by approximately 1% by vol. on average between measurements from the capacitive sensors, but the timing of liquid water infiltration is largely consistent across both measurements and model simulations. Within our sample, the SnowPro-17 consistently reports higher mean LWC values than the SnowPro-25, and exhibits greater variability, indicated by a larger standard deviation. We found good agreement when we compared in-situ sensor measurements to LWC infiltration in snow cover model simulations. This suggests that, despite measurement challenges and sensor variability, SNOWPACK can provide valuable information on the timing of LWC infiltration. For practitioners, this work highlights that reliable forecasting of wet slab avalanches depends on understanding when and how liquid water reaches critical layers. Because direct LWC measurements are rarely feasible in operational settings, using physically based models may offer a practical pathway forward.

KEYWORDS: liquid water content, SNOWPACK, in-situ measurements, avalanche forecasting

1. INTRODUCTION

Snow is a highly dynamic, porous medium that undergoes continuous microstructural evolution because it exists at temperatures close to its melting point. These changes occur even faster when snowpack temperatures approach 0°C and/or liquid water begins to infiltrate the snowpack (Colbeck 1972; Colbeck 1975). When liquid water is present in the snowpack, it moves in two principal ways: 1) with high water input, it forms preferential flow paths that commonly have high spatial variability, or 2) as a more uniform flow front, known as matrix flow (Colbeck 1975; Birkeland 2025). As a result, the combination of rapidly changing snow conditions and high spatial variability makes measuring wet snow conditions exceedingly difficult and has challenged researchers and avalanche forecasters for decades (Waldner et al. 2001).

Several methods have been developed to quantify the liquid water content (LWC) in snow. To measure through the entire depth of the snow, upward-looking ground-penetrating radar (upGPR) uses changes in snow permittivity to monitor snowpack wetness and liquid water distribution (Mitterer et al. 2011a; Wever et al. 2015). At the point scale, instruments such as the Denoth-Meter and Snow Fork estimate LWC from the dielectric properties of snow (Techel and Pielmeier 2011). The Denoth-Meter, developed by Denoth (1989), provides volumetric LWC values based on dry snow density measurements and the contrast between the dielectric properties of water, ice, and air (Fierz and Föhn 1994).

Building on the principles of the Denoth-Meter, researchers have recently developed a series of capacitance-based sensors, including the SnowPro-17, SnowPro-25 (now released as the SnowPro-30), and SnowPro-40 (Wolfsperger et al. 2023; FPGA Company GmbH 2026a; FPGA Company GmbH 2026b). Although the SLF SnowPro

* *Corresponding author address:*
Andrea Bruckmeier, Montana State University, Department of Earth Sciences
Traphagen Hall 126, Bozeman MT-59717
email: andrea.bruckmeier@montana.edu

https://doi.org/10.15788/1790099154

sensors have been used in only a limited number of published studies to date, there is a potential for them to provide robust and reliable measurements of snow density and LWC: In field tests comparing the SnowPro sensor to the Denoth-Meter across 13 snow profiles, permittivity measurements agreed closely, with an average relative error of 0.5% overall and about 1.5% within individual profiles. Agreement was strongest in dry snow and weakened somewhat in wet snow, where deviations between the two instruments were larger (Donahue et al. 2022; Wolfsperger et al. 2023). Techel and Pielmeier (2011) found that collecting at least three LWC measurements in each layer over a 50 cm distance helps constrain the impact of spatial variability on the measured volumetric LWC results.

However, the use of capacitance-based sensors can be labor-intensive for avalanche forecasters. Their limited spatial resolution restricts data collection to discrete points at the centimeter scale, and safety considerations prevent their use in avalanche starting zones, where the data would be most informative (Techel and Pielmeier 2011). To improve wet snow avalanche forecasting Mitterer et al. (2011b) used the Denoth-Meter to collect LWC measurements and compared the values with snow cover simulations of LWC to establish the foundation and thresholds for an LWC_{index} (Mitterer et al. 2013) using the one-dimension (1-D) physically based snow cover model SNOWPACK (Lehning et al. 2002; Bartelt and Lehning 2002). To verify the water infiltration schemes in SNOWPACK simulations Wever et al. (2015) compared the upGPR data with the simulations. They found that the differences among the three water transport schemes implemented in SNOWPACK were small relative to the discrepancies between the simulated and observed meltwater fronts. These results indicate that the capability of 1-D snow cover models to accurately reproduce both snowpack runoff and the internal snowpack structure under wet snow conditions remains limited.

Now, a decade later, the same lingering question remains: What is the simplest and most practical way to accurately measure wet snow conditions? And do snow cover model simulations line up with observations? In this study, we collect and analyze data from two recently developed capacity sensors - SnowPro-17 and SnowPro-25 - and compare observed results with model simulations from the physically based 1-D snow cover model SNOWPACK at our field site in southwest Montana, USA.

2. STUDY SITE

We conducted this study at our field site that is protected from skier traffic (2,000 m a.s.l.; 45.74803, −110.91300) near the southern boundary of the Bridger Bowl Ski Area, Montana, USA which we call ”Below Schlasman's”. The site was located on a predominantly east-facing slope, and snow depth was relatively uniform across the study area throughout the entire winter season 2024/25. We installed an automated weather station at this site equipped to measure air temperature, wind direction and speed, relative humidity, net radiation, and snow height.

3. METHODS

3.1. LWC In-Situ Measurements

During spring in 2025, we collected LWC measurements on five occasions: 13 March, 20 March, 27 March, 3 April, and 10 April. We measured LWC in distinct snow layers that we identified based on hand hardness, grain type, and grain size. We only considered layers with a minimum thickness of 5 cm and excluded thinner layers from the analysis to match the size of both sensors.

We used two slightly different LWC sensors, the SnowPro-17 and the SnowPro-25 (FPGA Company GmbH, Tann, Switzerland). Both sensors are capacitive probes and therefore operate according to the same fundamental measurement principle, but they differ in probe size (Table 1), and how we manually applied them in the snowpit (Wolfsperger et al. 2023). Due to different measurement directions of the two sensors, we placed the SnowPro-17 against the side wall of the snowpit, where it measures approximately 17 mm into the snowpack (Figure 1). In contrast, we inserted the SnowPro-25 directly into the snow, where it reads LWC approximately 25 mm above and 25 mm below the sensor which is 50 mm in total (Figure 2).

For each sensor, we collected three measurements per layer, spacing the measurements approximately 20 cm apart to account for the spatial variability of liquid water within the snowpack (Techel and Pielmeier 2011). We used the SnowPro-17 first to account for an undisturbed snowpack. Dry snow density is a required input for both sensors, but cannot be accurately measured once the snow is wet. We estimated the dry snow density as 300 kg m^{-3} based upon our density measurements before water infiltration into the snowpack and according to the common densities of settled snow (Muskett 2012). To account for this source of inaccuracy, we held the estimated

Table 1: Overview on the parameters of the two capacity sensors (FPGA Company GmbH 2026a; FPGA Company GmbH 2026b).

Parameter	***SnowPro-17***	***SnowPro-25***
measurement direction	downward	upward and downward
penetration depth	17 mm	50 mm (25 mm up; 25 mm down)
measurement footprint	45 * 95 mm	117 * 130 mm
measured volume	72 cm^3	608 cm^3
measurement frequency	20 MHz	20 MHz

Figure 1: Example of how we placed the SnowPro 17 on the side wall of a snowpit while performing measurements. (Photo: Robyn Gotz, Montana State University, 17 April, 2026)

Figure 2: Using the SnowPro 25 inserting it into the side wall of the pit. (Photo: Robyn Gotz, Montana State University, 17 April, 2026)

dry snow density constant across both sensors, so that the resulting inaccuracies would affect the SnowPro-17 and SnowPro-25 measurements in the same way. Over the measurement period, we sampled 50 unique snow layers with both sensors, yielding a total of 300 LWC measurements (Bruckmeier et al. 2026).

3.2. Snow Cover Simulations

We simulated snow cover using SNOWPACK, a physically based 1-D snow cover model (Bartelt and Lehning 2002; Lehning et al. 2002), forced with hourly meteorological observations from our weather station at the study site, including snow height, air temperature, net radiation, wind speed, and relative humidity, over the winter season (December 01, 2024 - April 30, 2025). Within the model, water transport was simulated using the bucket mode, one of three implemented water transportation schemes in SNOWPACK. This approach is consistent with the configuration commonly applied in operational SNOWPACK simulations (AWSOME Core Team 2024). In this approach, each snow layer stores liquid water up to a defined threshold. Once this threshold is exceeded, excess water is transferred to the layer below (Mitterer et al. 2011a; Wever et al. 2015). We visually evaluated model performance against the observed snow profiles throughout the winter season.

4. RESULTS

4.1. LWC Sensor Comparison

Both sensors produced identical readings under dry-snow conditions when snowpack temperatures were below 0°C (−4.5 to −1°C), with LWC measurements of 0 vol.% (Figure 3). Measurements differed when liquid water was present in the snowpack.

Across all 50 paired observations, LWC values measured by the SnowPro-17 and SnowPro-25 differed significantly (paired t-test, $t(49) = 4.13$, $p < 0.001$; Figure 4). The mean paired difference between the two datasets was 1.00 vol.% (95% CI: 0.51–1.48 vol.%), with a median paired difference of 0.73 vol.%.

The standard deviations calculated from the three replicate measurements per layer reached 2.8 vol.% for the SnowPro-17, whereas the maximum standard deviation observed for the SnowPro-25 was 1.8 vol.% (Figure 3). This pattern indicates a lower measurement precision of the SnowPro-17, particularly in layers with a LWC of 3 vol.% and higher.

The measurements obtained with the two sensors were moderately positively correlated (r = 0.59, Figure 5). However, substantial scatter around the 1:1 line was observed, particularly at higher LWC values.

In our sampled datasets, the results indicate that SnowPro-17 tends to report higher LWC values and exhibits greater measurement variability than SnowPro-25. Although both sensors produced identical measurements under dry-snow conditions, differences became increasingly apparent as LWC increased.

4.2. Modeled and Measured LWC

SNOWPACK captured the seasonal transition from predominantly dry to increasingly wet snow conditions during five days in the spring melt period, 13 March, 20 March, 27 March, 3 April, and 10 April 2025 (Figure 6). Simulated LWC remained close to zero on 13 and 20 March, whereas the sensor observations indicated the presence of wet layers within the snowpack. From 27 March onward, the model simulated substantial wetting, with LWC increasing to approximately 4–5% in the upper and middle parts of the snowpack.

The two sensor profiles showed considerable variability in both the magnitude and vertical distribution of LWC compared to the model. However, the SNOWPACK simulations generally fell within the range of observed values during the later stages of the melt season. Despite reproducing the general timing of snowpack wetting, SNOWPACK failed to capture several wet layers identified in the measurements, particularly in the lower part of the snowpack, where the observed LWC remained elevated but the model simulated little to no liquid water.

5. DISCUSSION

The two LWC sensors produced identical measurements under dry-snow conditions, but diverged once liquid water was present in the snowpack. In our dataset, SnowPro-17 consistently measured higher LWC values and exhibited greater variability within the layer than SnowPro-25. These differences likely reflect the different measurement approaches of the two sensors (FPGA Company GmbH 2026a; FPGA Company GmbH 2026b). SnowPro-17 measures LWC directly on the snow surface or, in our study, the snow-side wall and samples a relatively small snow volume making it more sensitive to local heterogeneity such as preferential flow paths and potentially more susceptible to influences from air temperature and side-wall exposure. Despite best attempts at keeping the side wall ”realistic” and shaded, there was undoubtedly change to LWC as soon as we exposed the pit wall. This measurement technique could be a source for higher values of measured LWC and greater standard deviations for the three layer measurements (Colbeck 1975; Wolfsperger et al. 2023). In contrast, SnowPro-25 is inserted into the snowpack and samples a larger volume, which may reduce sensitivity to small-scale variability and external disturbances. The moderate correlation between sensors indicates that both captured similar temporal patterns in snow wetness, although differences in measured LWC became increasingly apparent under wetter conditions (Figure 5).

SNOWPACK reproduced the overall transition from dry to wet snow conditions during the melt season but did not capture the observed accumulation of liquid water in the lower snowpack. Instead, the model concentrated liquid water primarily in the upper and middle layers. This behavior is likely related to the bucket mode water transport scheme used in the simulations. The bucket approach represents water movement as a threshold-controlled downward redistribution and does not explicitly account for preferential flow paths or localized water ponding (Wever et al. 2015). As a result, the model did not reproduce the wet layers observed in the lower snowpack. These findings highlight the limitations of the bucket scheme for simulating vertical liquid water redistribution during advanced melt conditions and reconfirm findings of previous studies (Wever et al. 2015; Mitterer et al. 2011a; Mitterer et al. 2011b).

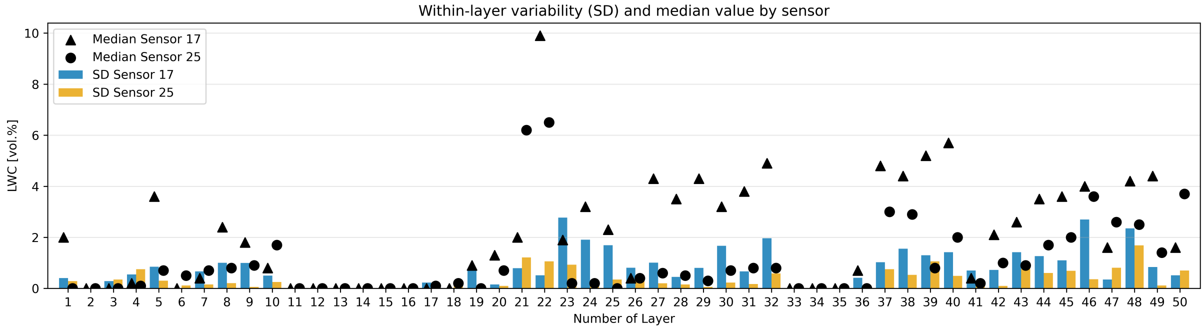

Figure 3: Median LWC and within-layer variability for the SnowPro-17 and SnowPro-25 sensors across all sampled snow layers for our entire sampling period (5 days). The layers are listed in the order sampled. Triangles and circles indicate the median LWC derived from three measurements per layer for the SnowPro-17 and SnowPro-25, respectively. Bars represent the corresponding standard deviation (SD) of the three measurements and therefore quantify the variability of LWC values within a layer as captured by each sensor.

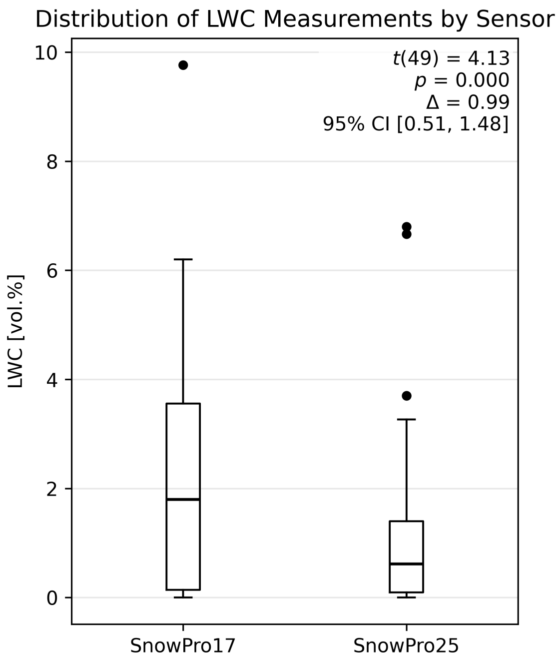

Figure 4: Distribution of liquid water content (LWC) measurements obtained with SnowPro-17 and SnowPro-25. Boxes represent the interquartile range (IQR), the horizontal line within each box indicates the median, whiskers extend to 1.5 × IQR, and points denote outliers. SnowPro-17 measured consistently higher LWC values than SnowPro-25, with a mean paired difference of 1.00 vol.% (95% CI: 0.51–1.48 vol.%). A paired t-test indicated a statistically significant difference between sensors (t(49) = 4.13, p < 0.001, n = 50).

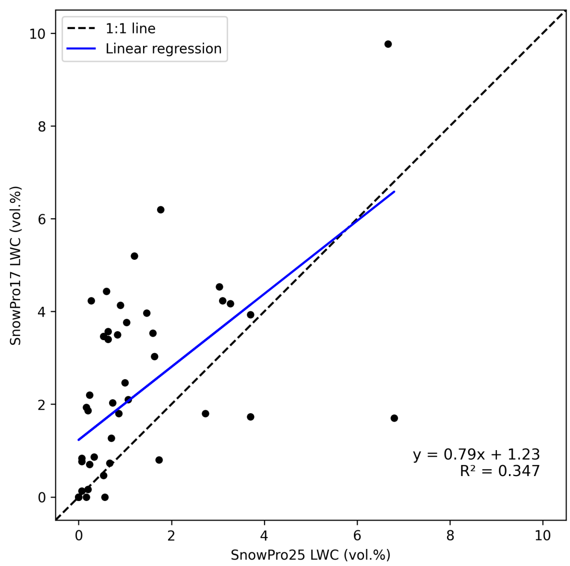

Figure 5: Comparison of mean LWC measurements obtained with the SnowPro-17 and SnowPro-25 sensors for 50 snow layers. Each point represents the mean of three measurements collected within a layer. The dashed line denotes the 1:1 relationship, and the solid line shows the linear regression fit ($y = 0.79x + 1.23$, $R^2 = 0.35, r = 0.59$). Measurements from both sensors showed only moderate agreement, with the SnowPro-17 generally reporting higher LWC values than the SnowPro-25.

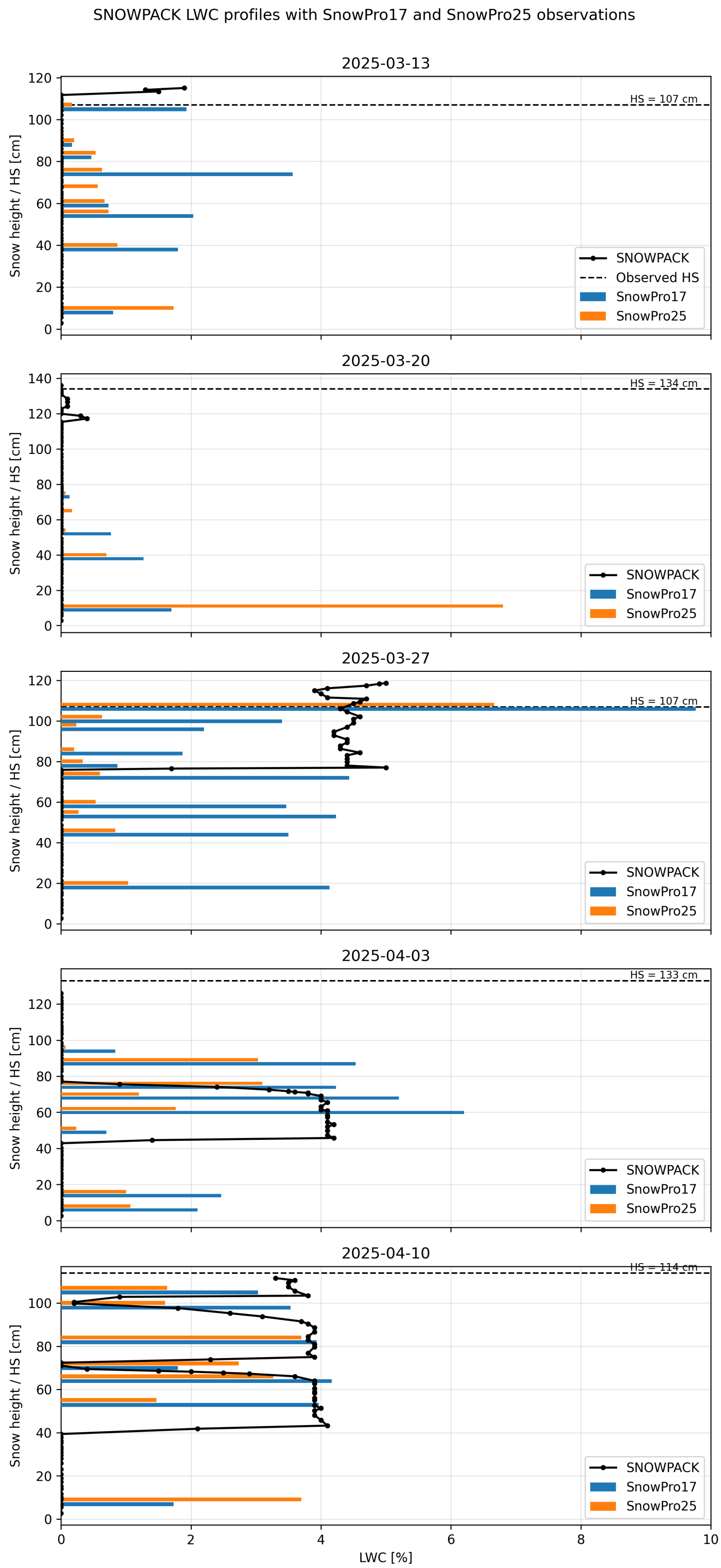

Figure 6: Vertical profiles of liquid water content (LWC) measured in snow pits and simulated with SNOWPACK for five observation dates during the 2025 melt season (13 March, 20 March, 27 March, 3 April, and 10 April). The black line with circular markers shows the SNOWPACK-simulated LWC profile. Horizontal blue and orange bars indicate observed LWC measured with the SnowPro-17 and SnowPro-25 sensors. The dashed horizontal line marks the observed snow height (HS) from the snow pit on each date. LWC is expressed in percent (vol.%) and snow height in centimeters (cm).

6. CONCLUSION

This study demonstrated that measuring and modeling liquid water content (LWC) remains challenging, however, different measurement approaches can influence the consistency and magnitude of LWC observations. Both sensors agreed under dry-snow conditions. However, there was variability between the sensors, particularly at higher LWC, in wet snow conditions. Measurements collected using a sensor that is inserted into the pit wall, may be less affected by immediate changes in LWC when the pit wall is exposed. Due to the variability within individual layer measurements, no systematic bias between the sensors could be identified, SnowPro-17 recorded, on average, approximately 1 vol.% higher LWC values than SnowPro-25. This difference became more pronounced as the snowpack became wetter.

The SNOWPACK simulations confirmed the known limitations of the bucket water transport scheme, particularly in the lower part of the snowpack.

This study focused solely on melt-induced infiltration of liquid water into the snowpack and did not consider rain-on-snow events. Future research could compare melt-induced and rain-on-snow conditions to provide additional insights into wetting-front evolution and model performance in wet snowpacks.

ACKNOWLEDGEMENTS

The authors thank Bridger Bowl Ski Area - Jason Prasek, Pete Maleski, Richard Griffen and the entire Ski Patrol - for the support to access and install our weather station and to conduct field work. Further, we thank Eddie Webb, Erich Schreier, Nioclas Hinz and Maddie Beck for their support in the field. This work was supported by the U.S. Geological Survey North Central Climate Adapatation Science Center and the Ecosystems Land Change Science Program. This research employed a variety of AI tools: generative AI for manuscript editing, and AI-assisted coding for data processing. All AI-generated outputs, including text, code, and analytical results, were reviewed, validated, and, where necessary, modified by the authors to ensure scientific rigor, integrity, accuracy, and compliance with USGS standards.

DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

AWSOME Core Team (2024). AWSOME: Avalanche Warning Service Operational Meteo Environment. Software. AWSOME Core Team.

Bartelt, P. and Lehning, M. (2002). A physical SNOWPACK model for the Swiss avalanche warning: Part I: numerical model. In: Cold Regions Science and Technology 35.3, pp. 123–145.

Birkeland, K. W. (2025). The Starting Zone. PressBooks.

Bruckmeier, A., Mitterer, C., Gotz, R., Sproles, E., and Peitzsch, E. H. (2026). Liquid Water Content Measurements from Bridger Bowl Ski Area, MT, March and April 2025. U.S. Geological Survey data release. https://doi.org/10.5066/P1RWKHAE.

Colbeck, S. (1972). A theory of water percolation in snow. In: Journal of glaciology 11.63, pp. 369–385.

Colbeck, S. (1975). A theory for water flow through a layered snowpack. In: Water Resources Research 11.2, pp. 261–266.

Denoth, A. (1989). Snow dielectric measurements. In: Advances in Space Research 9.1, pp. 233–243.

Donahue, C., Skiles, S. M., and Hammonds, K. (2022). Mapping liquid water content in snow at the millimeter scale: an intercomparison of mixed-phase optical property models using hyperspectral imaging and in situ measurements. In: The Cryosphere 16.1, pp. 43–59.

Fierz, C. and Föhn, P. (1994). "Long-term observation of the water content of an alpine snowpack". In: Proceedings of the International Snow Science Workshop. Vol. 30, pp. 117–131.

FPGA Company GmbH (2026a). SLF SnowPro-17. URL: `https://snow-sen.com/slf-snowpro-17/` (visited on 07/07/2026).

FPGA Company GmbH (2026b). SLF SnowPro-40. URL: `https://snow-sen.com/slf-snowpro-40/` (visited on 07/07/2026).

Lehning, M., Bartelt, P., Brown, B., Fierz, C., and Satyawali, P. (2002). A physical SNOWPACK model for the Swiss avalanche warning: Part II. Snow microstructure. In: Cold regions science and technology 35.3, pp. 147–167.

Mitterer, C., Heilig, A., Schweizer, J., and Eisen, O. (2011a). Upward-looking ground-penetrating radar for measuring wet-snow properties. In: Cold Regions Science and Technology 69.2-3, pp. 129–138.

Mitterer, C., Hirashima, H., and Schweizer, J. (2011b). Wet-snow instabilities: comparison of measured and modelled liquid water content and snow stratigraphy. In: Annals of Glaciology 52.58, pp. 201–208.

Mitterer, C., Techel, F., Fierz, C., and Schweizer, J. (2013). "An operational supporting tool for assessing wet-snow avalanche danger". In: Proceedings ISSW. Vol. 33, pp. 334–338.

Muskett, R. (Jan. 2012). Remote Sensing, Model-Derived and Ground Measurements of Snow Water Equivalent and Snow Density in Alaska. In: International Journal of Geosciences 03, pp. 1127–1136. https://doi.org/10.4236/ijg.2012.35114.

Techel, F. and Pielmeier, C. (2011). Point observations of liquid water content in wet snow–investigating methodical, spatial and temporal aspects. In: The Cryosphere 5.2, pp. 405–418.

Waldner, P., Huebner, C., Schneebeli, M., Brandelik, A., and Rau, F. (2001). "Continuous measurements of liquid water content and density in snow using TDR". In: Proceedings of the 2nd International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications, pp. 5–7.

Wever, N., Schmid, L., Heilig, A., Eisen, O., Fierz, C., and Lehning, M. (2015). Verification of the multi-layer SNOWPACK model with different water transport schemes. In: The Cryosphere 9.6, pp. 2271–2293.

Wolfsperger, F., Geisser, M., Ziegler, S., and Löwe, H. (2023). "A new handheld capacitive sensor to measure snow density and liquid water content". In: Proceedings of the International Snow Science Workshop, pp. 1532–1536.