WHERE TO PUT THE WEATHER STATION? – OPTIMIZING THE LOCATION FOR AUTOMATED SNOW DEPTH MEASUREMENTS BASED ON REMOTE SENSING, AVALANCHE MODELING AND TERRAIN CHARACTERISTICS

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ABSTRACT: Automated weather stations (AWS) measuring snow-related parameters are essential for avalanche warning in many regions. Key data include new snow accumulation, wind direction, and wind velocity, especially in remote, high-elevation terrain. This information is critical for decisions such as when to close and reopen roads. Given the high spatial variability of snow depth distribution in mountain areas, the positioning of AWS is crucial. High-resolution, spatially coherent snow depth measurements acquired by drones, airplanes, or satellites reveal significant variability within short distances of just a few meters. Therefore, it is important to place weather stations at relatively flat locations with representative snow depth values. Areas where the snowpack is strongly influenced by wind or avalanches, either removing or depositing large amounts of snow, are unsuitable.

We developed an automated approach combining remotely sensed snow depth maps with terrain characteristics (e.g., slope or homogeneity) and simulated avalanche scenarios to identify optimal positions for AWS. We demonstrate how this approach can enhance safety-relevant information in the Dischma Valley near Davos, Switzerland. This approach could be applied globally wherever high-quality digital elevation models are available and spatially coherent snow depth maps can be acquired. Currently, the positioning of AWS relies heavily on expert judgment. Our tool could help make these decisions more comprehensible and serve as a second opinion, ensuring the optimal placement of AWS.

KEYWORDS: Weather station, spatial variability, remote sensing, snow depth, hazard indication mapping, avalanche warning.

1. INTRODUCTION

Automated weather stations (AWS) enable near real time, weather independent information on new snow amounts, wind speed and direction as well as temperature in poorly accessible mountain terrain. Therefore, they are the backbone of avalanche warning services around the globe and are a major input source for the activation and deactivation of temporary measures such as road closure or evacuations.

Some existing networks are quite dense such as the Intercantonal Measurement and Information System (IMIS) in Switzerland (Egli, 2008) with 189 stations over the Swiss Alps (https://www.slf.ch/en/avalanche-bulletin-and-snow-situation/measured-values/description-of-automated-stations/) or the Avalanche Warning Service Information System (LAWIS, https://www.lawis.at) with 583 stations over the Austrian Alps. Other networks in more remote mountain ranges are less dense such as the Norwegian (https://www.senorge.no/ infoAboutSeNorge), the Canadian (https://avlanche.ca/weather/stations) or the Colorado US network (https://avalanche.state.**co.us** /weather/weather-stations).

All these stations were placed by local experts based on their judgment and experience. In a few cases, the stations were repositioned after a few years of measurement, as the information was judged as unreliable, mainly due to wind effects on snow depth distribution or because of avalanche danger.

As the snow depth distribution is very complex in mountain terrain and avalanches can destroy the stations or their deposits can distort the measured snow heights, the positioning of AWS is critical. To get meaningful measurements, the station should not be positioned in wind affected terrain like ridges (less snow due to erosion) or in terrain depressions (more snow due to wind shelter, leading to deposition). Certainly, the station should not be endangered by avalanche activity and the measured snow depth should be representative for a larger region and not only for an isolated point location.

In this paper we propose a new, systematic approach combining remotely sensed, spatially continuous snow depth measurements with avalanche hazard indication modelling and terrain parameter selection to identify optimal AWS loca-

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tions. We demonstrate the approach for the example of the "Luksch Alp" station (Figure 1) in the region Büelenberg close to Davos, Switzerland, where it was applied and tested in collaboration with the natural hazard experts of the community of Davos. Based on the discussions initiated by the model, the position for the new AWS was selected.

Figure 1: Installation of the IMIS station "Luksch Alp" (DAV6) close to Davos, Switzerland at an elevation of 2290 m a.s.l. in November 2022 (picture: Sensalpin GmbH).

2. SNOW DEPTH DISTRIBUTION MAPPING

Recent advancements in remote sensing have demonstrated its unique capability to measure the spatial variability of snow depth distribution in complex mountainous terrain with very high spatial resolution and accuracy. Drone-based photogrammetric mapping is a powerful and cost-effective tool to cover smaller areas of several square kilometers (Vander Jagt et al., 2015; Bühler et al., 2016; Harder et al., 2016; De Michele et al., 2016). Light detection and ranging (LiDAR) can also be utilized under difficult illumination conditions or in forested areas where photogrammetry is limited (Bühler et al., 2017; Harder et al., 2020; Koutantou et al., 2022).

For larger regions, airplane-based photogrammetry (Bühler et al., 2015; Nolan et al., 2015; Meyer et al., 2022; Bührle et al., 2023) or even satellite-based photogrammetry (Marti et al., 2016; Shaw et al., 2020) can be applied. However, these methods come with reduced spatial resolution and positioning precision, leading to lower snow depth accuracy.

Drone-based snow depth mapping achieves accuracies of approximately 0.1 m, while airplane-based mapping achieves approximately 0.15 m. In contrast, satellite-based mapping is limited, with accuracies of approximately 0.5 m, especially in areas with shallow snowpacks (Eberhard et al., 2021). Not yet applicable are snow depth mapping approaches based on synthetic aperture radar SAR (Lievens et al., 2022) because the achieved spatial resolution (> 100 m) and accuracy are still insufficient for our purpose, even though the measurements would be independent on cloud coverage.

Spatially continuous snow depth distribution maps enable the identification of areas where snow depth is representational (e.g., close to the mean snow depth) for a larger region and where the snowpack is not significantly affected by topographic features and wind. To capture snow depth distributions significant for typical weather and wind patterns, several data acquisitions might be necessary. Applying the more flexible and enconomic drone data acquisition might therefore be the best option.

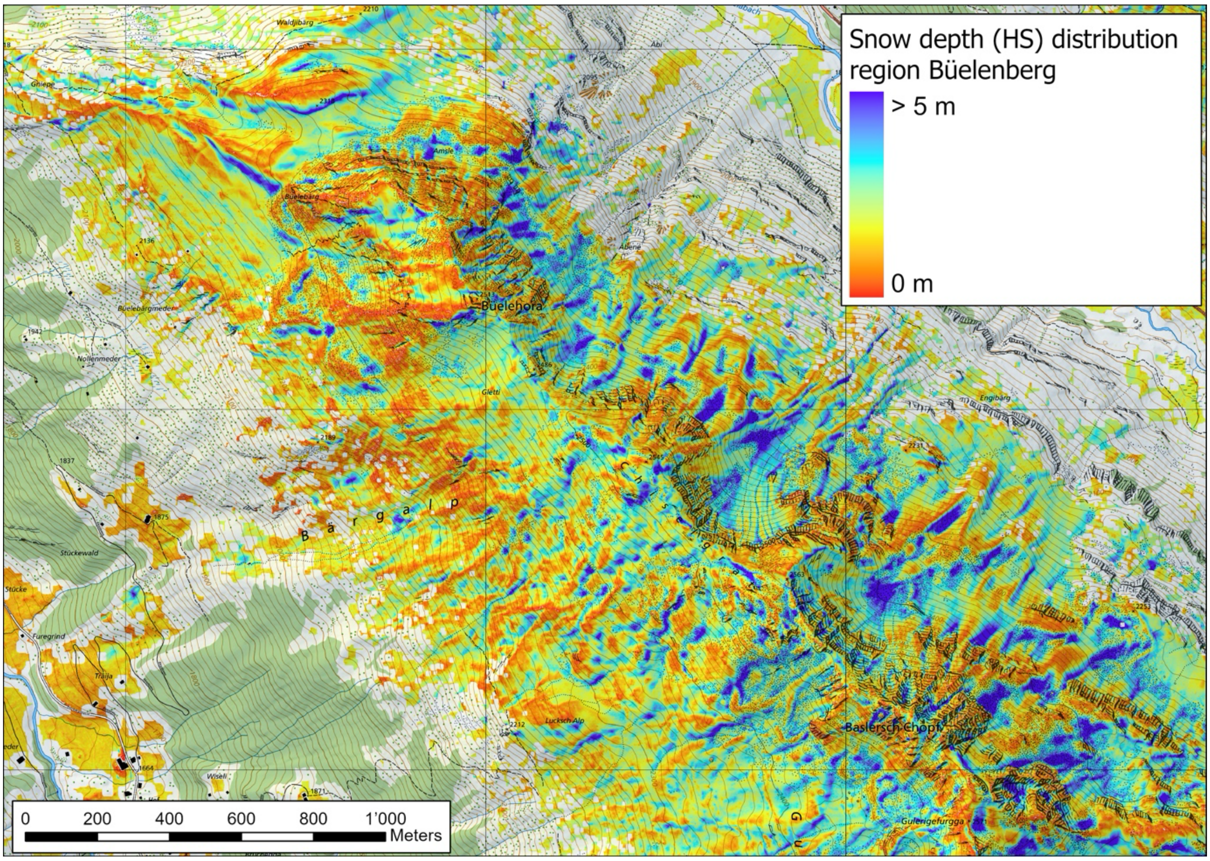

Figure 2: Snow depth map of the Büelenberg region captured by airplane photogrammetry (Bührle et al., 2023) on 16 April 2019, after a very snow rich winter, demonstrating the very high spatial variability of the snow depth distribution.

3. AVALANCHE HAZARD INDICATION MODELLING

A major danger for AWS in mountain regions is the risk of destruction by snow avalanche events. Even non-destructive avalanches are problematic because their deposits can distort the measured snow height. Therefore, identifying and excluding endangered areas is crucial. Depending on the terrain characteristics, a significant portion of the area might be threatened by avalanches, leaving only a few safe spots for AWS placement. We applied the Large Scale Hazard Indication Modeling (LSHIM) approach developed at SLF over the past decade (Bühler et al., 2013; Bühler et al., 2018; Bühler et al., 2022) to identify areas with high avalanche danger.

This tool was developed to generate avalanche hazard indication information in areas outside of the official hazard maps. These official hazard maps encompass only 10% of the entire area of the canton of Grisons, meaning most potentially suitable areas for AWS placement are not covered.

To expand the potential placement area, we applied the frequent avalanche simulation scenario with 10 years return period. This means more extreme avalanches are not considered, and there remains a risk that stations could be affected by larger avalanche events.

Alternative methods for identifying avalanche-prone areas include using the NAKSIN model, recently developed in Norway (Issler et al., 2023), ATES model (Toft et al., 2024) or utilizing mapped avalanches from well-maintained cadasters, if available.

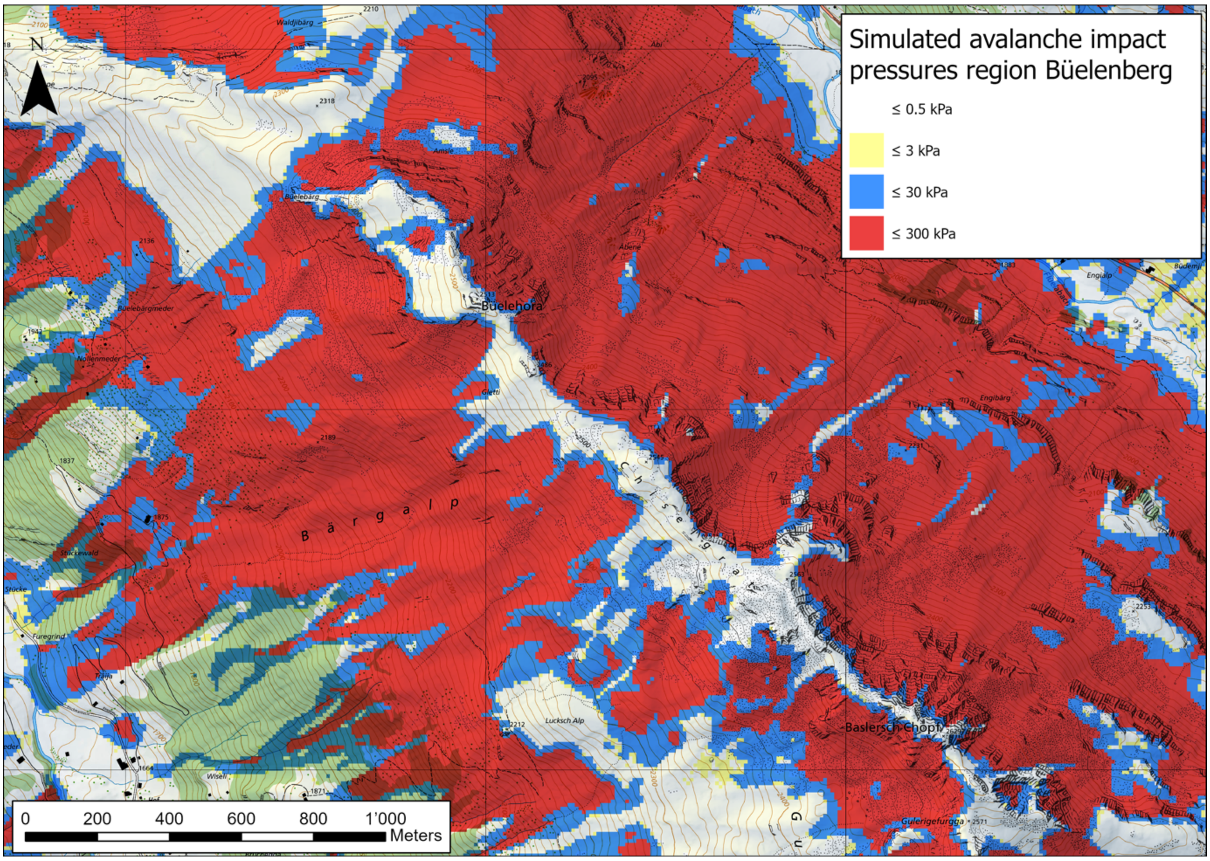

Figure 3: Simulated avalanche impact pressures in kPa for the scenario with 10 years return period over the Büelenberg region. Only a few spots are not exposed, even to quite frequent avalanche activity.

4. TERRAIN CHARACTERISTICS

The local terrain characteristics such as elevation, slope angle and roughness are also key factors for the positioning of AWS. For avalanche forecasting, specific elevation bands are of major interest. Stations should be placed near and at a similar altitude as the relevant avalanche-prone areas. Furthermore, the stations should not be placed in steep or rough terrain. Although stations in slopes may provide more meaningful data for evaluating a specific release area, since they can directly measure the potential fracture height of avalanches, flat-field stations are more suitable for assessing the avalanche situation in a particular area and for operating SNOWPACK (Bartelt and Lehning, 2002) and further downstream models which run on the data of AWS.

Further criteria include a homogeneous snow distribution around the snow depth measurement sensor and a representative snow height for the area being assessed. Ideally AWS should be placed at wind-protected locations and away from ridges. These requirements are also considered in the model.

5. SUITABILITY MODELLING

The factors described above are combined in the ArcGIS suitability model workflow (Esri, 2024). By transforming the values to the common suitability scale and weighting the criteria (Figure 4) a suitability map is generated (Figure 5).

A continuous function is selected to transform criteria represented by continuous values such as elevation, slope, ruggedness, and snow depth, whereas the categorical avalanche hazard data is transformed to unique categories. We assign the highest weight to the avalanche exposure because the affection of an AWS by avalanches is most critical. The second highest weight is given to the snow depth distribution as we want the measurements to be as representative as possible over a larger region. The third highest weighting is given to the terrain characteristics. How these weights are set specifically must be decided by the local experts taking region specific characteristic into account.

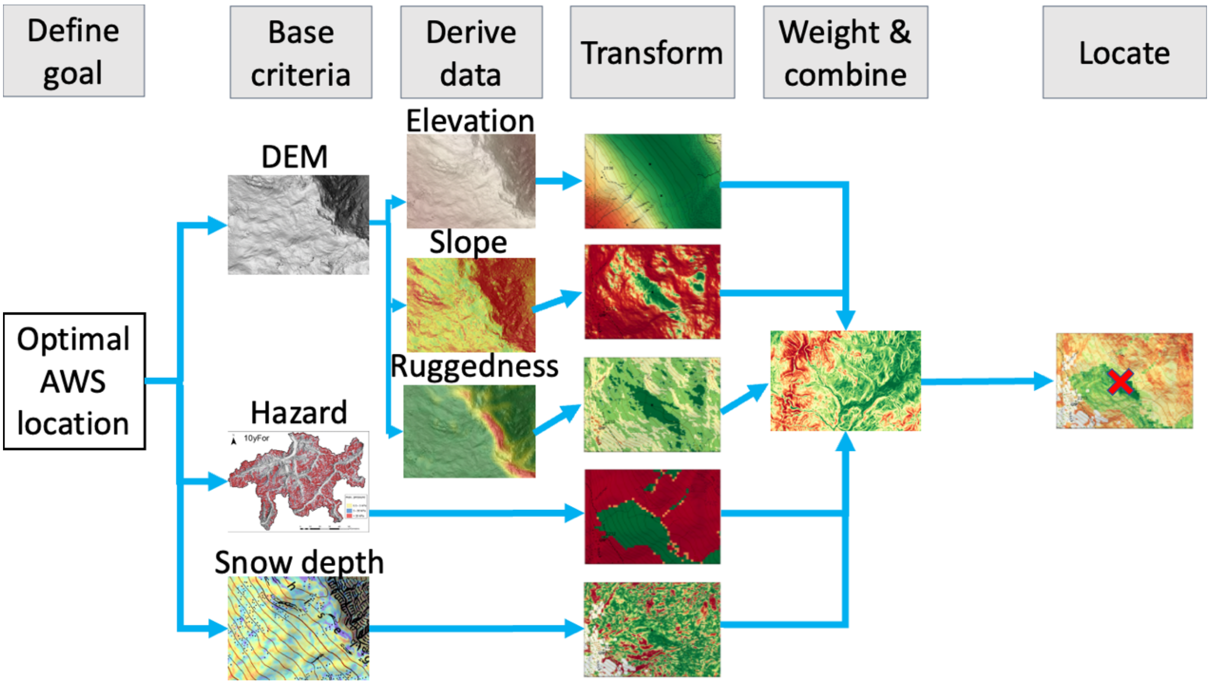

Figure 4: Outline of the suitability model combining the input information described above.

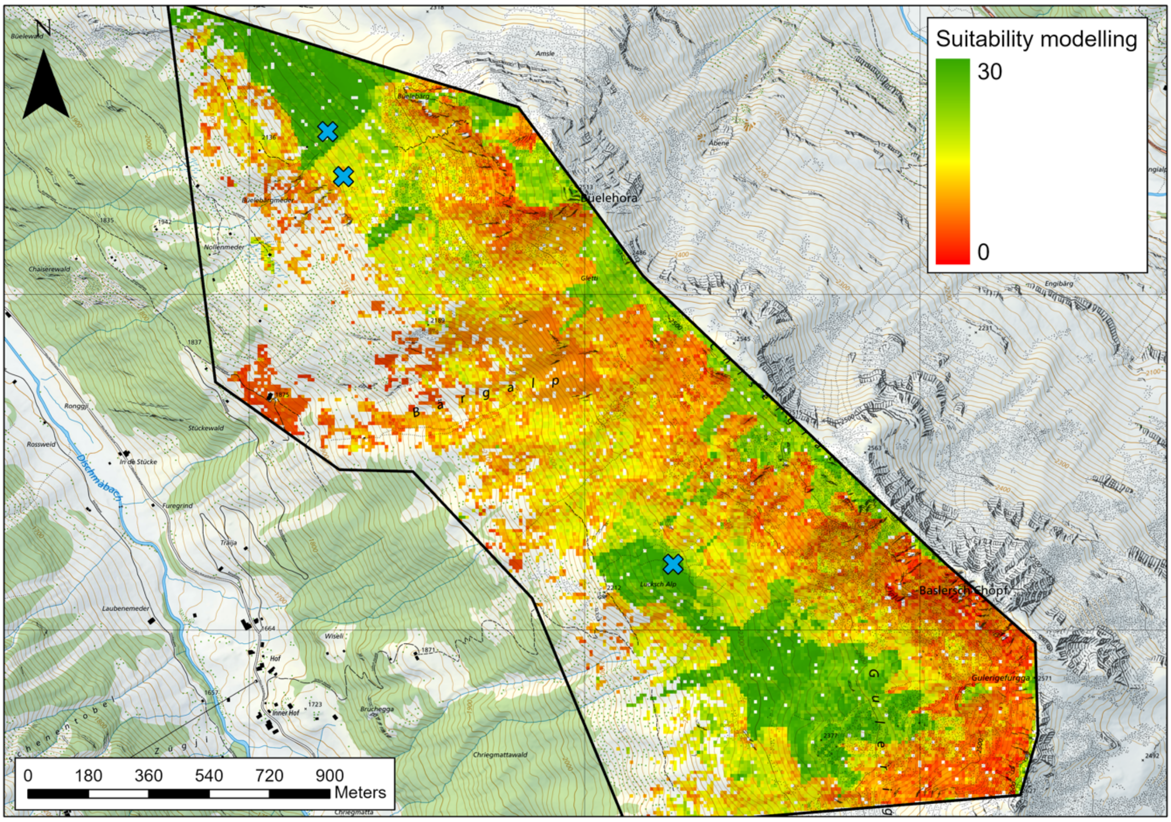

Figure 5: Result of the suitability model for the region Büelenberg. The potential positions identified by the experts from the community of Davos are depicted as blue crosses. Based on the model results and the expert judgment, the southernmost location was finally selected.

6. LIMITATIONS

The method described here provides an automated and structured approach for the evaluation of a new AWS site. Special focus should be given to the implementation of the transformation, weighting and combination steps. Nevertheless, it is advisable to make additional field investigations before the final decision for the construction of a new station.

It is highly recommended to visit the locations evaluated by the above-described method in advance without snow. During an on-site inspection, the vegetation and the condition of the ground can be assessed in detail. For snow depth measurement, high vegetation under the sensor, such as bushes, is not ideal. Especially at the beginning of winter, the measured snow depths are not useful with high vegetation. Grass or rock under the sensor is more favorable. The ground's composition also plays a crucial role in the station's installation. A rock installation using rock anchors is much cheaper than building a concrete foundation.

Another limitation of the described method is the fact that the snow depth distribution is based on a single point in time during the winter. The expected amount of new snow can vary greatly at the evaluated locations depending on the weather conditions. For example, it may be that, with a certain wind direction, no snow remains at a location or, conversely, too much snow is deposited. Therefore, in practice, it is highly recommended to operate a test station for one winter before constructing a permanent station or at least surveying snow depth maps over more than one winter and after snowfalls with differing main wind directions. This way, the snow depth profile can be analyzed under varying weather conditions and compared with data from neighboring stations.

7. CONCLUSIONS

The integration of remotely sensed snow depth mapping with avalanche hazard indication modeling and terrain characteristic assessment offers a systematic approach to optimizing the placement of automated weather stations (AWS). By ensuring that future AWS are positioned in representative and safe locations, the reliability and significance of snow measurements in mountainous terrain are enhanced. This is crucial for accurate avalanche warnings and the timely initiation of temporary mitigation measures. Furthermore, the proposed approach can be utilized to reevaluate the locations of existing AWS.

The application of this method in the Dischma Valley near Davos demonstrates its potential to improve decision-making processes and facilitate data-driven discussions among experts. As digital elevation models and remote sensing capabilities for snow depth mapping continue to advance, this approach can be implemented globally, providing a robust and systematic tool to complement expert judgment and improve the overall safety and effectiveness of avalanche warning systems.

Additionally, by adapting the model and incorporating avalanche release information, this methodology could be applied in the future for the optimized positioning of artificial avalanche release towers.

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