# D17 ESTIMATION OF POTENTIAL SNOW AVALANCHE HAZARD PROBABILITY IN AREAS BELOW PROTECTIVE FORESTS IN AUSTRIA

« BACK TO CONTENT

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## ABSTRACT

The hazard maps available in Austria do not provide information on the areas potentially protected by forest and the probability of hazard occurrence. Furthermore, the protective function mapping of forests is based on ordinal scales of the hazard potential and the vulnerability of the assets to be protected. A finer scale level improves risk-based prioritisations of measures required to maintain and quantifications of the provided ecosystem service. We developed a method to quantify the potential spatio-temporal occurrence of snow avalanches in terms of hazard probability in potential release and transit areas on a continuous scale and implemented the method to areas potentially protected by forests. The potential probability of hazard occurrence does not consider forest effects but is a key component of protective forest management. The method was developed to highlight the importance of protective forests by including the effects of forest in avalanche zones in a next step.

## INTRODUCTION

Forest disturbances, which negatively impact the protective effects of forests are expected to occur more frequently and widespread in the coming decades due to climate change. Therefore, a more detailed and risk-oriented evaluation of natural hazard probabilities in forests and areas potentially protected by object-protective forests (potentially protected areas, PPAs) is required. Now that the first "Indication map of protective forests in Austria" (IMPFA) considering the direct object-protective function is available (Perzl and Starsich, 2024), the question about the economic value of the protective effects of forests within the federal territory arose. Regardless of the current conditions and effects of forests, their protective potential (Brang et al., 2001) is a resource and a green investment in the safety of human settlements and facilities ("objects"). The potential probability of hazard occurrence (pplocal) in PPAs as well as the economic value of the objects located therein determine the significance of this resource in the context of natural hazard risk management. pplocal refers to a generic view without considering the current protective effects of the forest, whereas plocal denotes the actual probability accounting for forest's protective effects against natural hazards.

By combining pplocal with the exposed objects and their respective values and vulnerabilities, the risk of damages as well as the natural and produced forest ecosystem service (Tromp, 1971) can be estimated. These issues are currently addressed by the on-going ÖKO-SCHU-WA project. Our next step is the identification of priority areas for technical and/or silvicultural interventions by estimating the actual probability plocal and, therefore, accounting for forest's protective effects against natural hazards, which will be addressed in the recently started Prio-SCHU-WA project.

The hazard (indication) maps available in Austria do currently not provide information on the PPA and the expected pplocal of locations inside these areas. The methods to create the IMPFA (Perzl et al., 2019) used by Perzl et al. (2015) and Huber et al. (2017) were designed to model the forest use areas with a direct object-protective function by tracking potential hits on the objects but not to identify the entire PPA. According to the official guidelines, the protective function mapping of forest in Austria is based on ordinal assessments of the hazard potential and the vulnerability of the objects to be protected. To contain consistency with existing maps, and to keep data and computational time manageable, topographic hazard propagation models are used.

One of our tasks in ÖKO-SCHU-WA was to determine the PPA of forests with direct object-protective functions according to the IMPFA and to provide estimates for pplocal for locations inside these areas. This information is the foundation for subsequent analysis of the regional socio-economic relevance of protective forests. While the delineation of PPAs is an elaborate process, this paper focuses on the estimation of pplocal in PPAs for snow avalanches based on outputs of topographic mass flow models.

## METHODS

Estimates of hazard occurrence probabilities, especially at regional scales, are subject to uncertainties and model assumptions. Simplified, the spatio-temporal probability of hazard occurrence pplocal at a point in space can be expressed after Hantz et al. (2021) as pplocal = pprelease x ppreach, where pprelease refers to the (potential) release probability of avalanches in potential release areas (PRAs) and ppreach to the probability that the avalanche may reach a point along its path.

The used PRAs originate from the modelling of avalanche hazard zones with a damage potential by back-tracking potential object hits (Perzl et al., 2015), which is one of the inputs of the IMPFA. This approach was cell-based without separating the areas prone to avalanche release into polygons, which is only necessary when using physically based runout models (Bühler et al., 2018, 2022). We selected two types of PRA-cells to model the PPAs: 1) cells within forests with a direct-protective function, and 2) cells above this forest areas from which avalanches might impact assets running through them. Snow depth and slope gradient are two key criteria for assessing locations susceptibility for avalanche release (Schaerer, 1981). Perzl et al. (2015) used the average maximum snow depth (MMXHS) of the 30-years period 1961-1990 and the slope gradient (Slope) at 10-m raster resolution for estimating pprelease on an ordinal scale. Jamieson and Brooks (1998) as well as Perzl et al. (2015) identified a MMXHS of 50 cm as a minimum climatic snow depth of terrain prone to avalanche initiation in humid-temperate climates. Table 1 lists the criteria for the absolute lower limit and three levels of basic avalanche susceptibility used by Perzl et al. (2015). Therein MMXHS can be considered a regionally adapted altitude criterion and might be interpreted as a location's snowiness.

| Level of susceptibility | Altitudinal criteria | Operator | Slope criteria |
|---|---|---|---|
| **very low** | MMXHS < 50 cm | or | Slope > 55° |
| **low** | 50 cm ≤ MMXHS < 80 cm | and | 27.6° + 409.8/MMXHS ≤ Slope ≤ 55° |
| **medium** | 80 cm ≤ MMXHS < 171 cm | and | 33.9° + 256.1/MMXHS ≤ Slope ≤ 55° |
| **high** | MMXHS ≥ 171 cm | and | 37.7° + 117.9/MMXHS ≤ Slope ≤ 55° |

*Table 1: levels of the basic avalanche release susceptibility and their criteria, the average maximum snow depth (MMXHS) and slope (Perzl et al., 2015).*

The criteria presented in Table 1 are based on descriptive statistics of about 1,500 observed avalanche initiations. This concept may be sufficient for the protective function mapping of forests; however, the provided classes cannot be directly translated into avalanche release return periods or probabilities. The probability of occurrence of natural hazards can be estimated with probability density functions (pdf) (Smith, 1995). This also applies to temporally variable critical factors of avalanche initiation such as snow depths or the influence of constants such as Slope. The pdf is the derivative of the cumulative density function (cdf), which can be estimated from the empirical (ecdf). The cdf indicates the probability that a value is equal or less than a certain limit. To identify critical values for snow depth and Slope for avalanche initiation, we reviewed existing literature and data.

The threshold of the total snow depth (HS) above which there is a considerable probability of an avalanche release is referred to as critical snow depth (HScrit). Below this threshold proportionally fewer avalanche releases might be expected. To obtain HScrit and to check it for plausibility, we analysed documented avalanches for which HS was reported (Fig. 1) along with values reported in literature (Tab. 2). The limit for a low cumulative probability of HS values in avalanche releases was set at 0.3 as small probability of hazard occurrence according to BUWAL (1999).

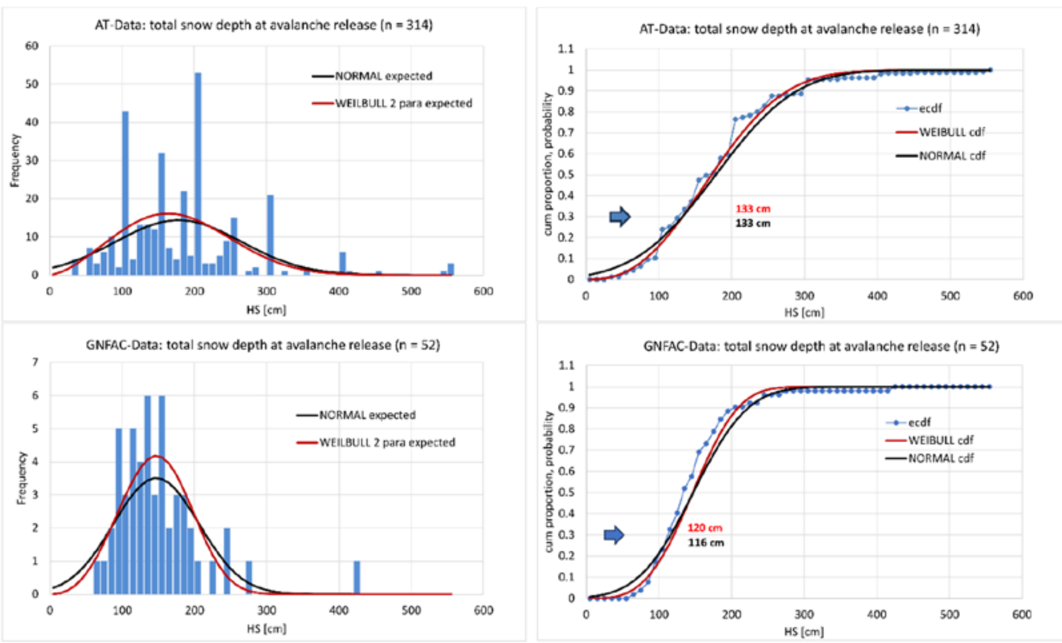


*Figure 1: histograms and cumulative density functions of total snow depths HS from avalanche hazard documentations.*

For our analysis we could utilize 314 documented avalanche releases with reported HS in Austria (AT), which we compiled from diverse sources and a dataset of 52 snow-profiles collected at skier-triggered slab fractures in Montana by the Gallatin National Forest Avalanche Centre (GNFAC, 2023), also reporting HS (see Fig. 1). While an observer-bias (rounding HS to half and full metres) is visible in the AT data, the GNFAC data appears less biased.

The AT and the GNFAC data do not indicate normal distributions, but the GNFAC data may follow a 2-parameter Weibull distribution. The corresponding cdfs give HScrit from 116 to 133 cm at the limit of 0.3. These values are in the range from 100 to 177 cm found in literature (Tab. 2) except for 47 cm (prelease = 0.77) at a low 3-day sum of new snow depth (HN3d) for slab avalanches reported by Součková et al. (2022).

| Source | HN3d [cm] | HS [cm] | ADL or $p_{release}$ | Notes |
|---|---|---|---|---|
| Stoffel et al. (1998) | 50 | 100 | $p_{release} \geq 0.75$ | |
| EISLF (2000) | 50-200 | > 150 | ADL > 3 | |
| Schweizer et al. (2003) | 103 | | ADL = 5 | |
| Schweizer et al. (2003) | 40 | | ADL > 3 | |
| Rousselot et al. (2017) | | > 120 | ADL > 3 | |
| Bründl et al. (2019) | > 100 | > 120 | ADL > 3 | |
| Milian & Cheval (2019) | | > 100 | | |
| Medeu et al. (2022) | | 168 | $p_{release} \geq 0.75$ | |
| Součková et al. (2022) | | 177 | $p_{release} = 0.79$ | wet snow |
| Součková et al. (2022) | 3.8 | 47 | $p_{release} = 0.77$ | slabs |
| Blagovechshenskiy et al. (2023) | 30 | 100 | ADL > 3 | |

*Table 2: examples of critical snow depths (release probability prelease ≥ 0.7 or avalanche danger level ADL > 3) from literature.*

All data referring to incipient or high activity of spontaneous avalanches threating settlement areas (e.g., EISLF, 2000; Rousselot et al., 2019; Bründl et al., 2019) refer to HScrit of more than 120 cm. The return period of HScrit indicates the hazard probability and can be determined with extreme value distributions. We used the Gumbel method for that. Our analyses showed that return periods of HScrit depend on the time series used and cannot be determined with the same reliability for lower and higher levels of snowiness (altitude). Lower values of HScrit reduce the differences between time series of different lengths and at lower altitudes. Therefore, a HScrit of 130 cm was set and the return periods were determined referring to the climatic normal period 1981-2010 as a reference suitable for forest function mapping. Since MMXHS is an indicator of snowiness and thus of the frequency of higher or smaller maximum snow depths, MMXHS is closely related to the return period showing an L-shaped correlation (Fig. 2). At the minimum climatic snow depth of 50 cm, the L-shaped curve is almost vertical and confirms this limit.

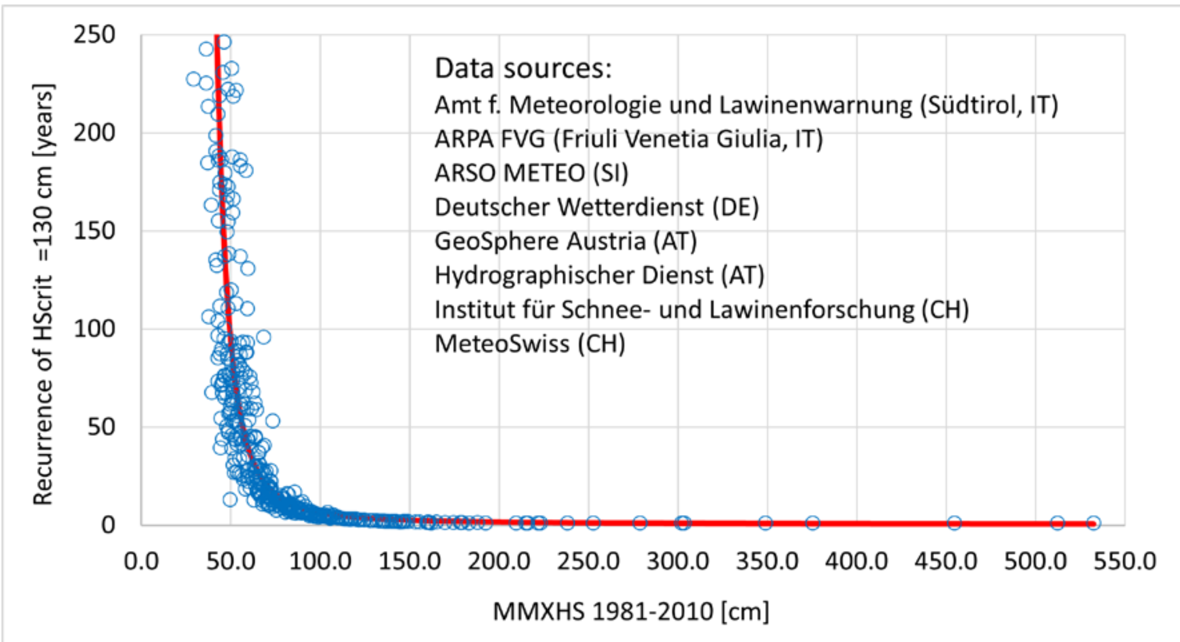


*Figure 2: relationship between the return period of the critical total snow depth (HScrit) and the average maximum snow depth (MMXHS) of the period 1981-2010 based on 811 station observations.*

To calculate the return period of HScrit for each pixel of the PRAs based on Fig. 2, we used a MMXHS-map of the period 1961-1990 created by Perzl and Kammerlander (2010). We adapted the map to snow conditions in 1981-2010 by analysing the MMXHS differences of 436 observation stations.

Besides snow conditions, Slope is a key factor in the probability of avalanche release (Gleason, 1996). PRA-mappings implement different thresholds of Slope. However, we found little information on the influence of Slope on the return period of avalanche release on a ratio scale in the reviewed literature. Therefore, we adapted a Cauchy function introduced by Veitinger et al. (2016) with the maximum probability at 40 to 42 degrees. Results from Schaerer (1977) and Gleason (1996) indicate this turnaround of slab formation. We calculated the pprelease of the PRAs by multiplying the frequencies of HScrit with the Cauchy probabilities of Slope.

To obtain pplocal at each location in the hazard zone potentially influenced by forest, also ppreach, the probability that a certain point along the track will be affected by a released avalanche, must be estimated. For this step we utilized Flow-Py (D'Amboise et al., 2022), a simple empirically motivated avalanche runout model, with a global angle of reach (α) of 24 degrees and without considering the effects of the forest to model potential hazard zones that might potentially be affected if no forests were present. Starting from each single PRA-pixel, Flow-Py calculates the area that is affected by an avalanche released from this point by a combination of an angle of reach approach with a cell-based routing routine (D'Amboise et al., 2022).

One output of the mass flow model Flow-Py is the angle of reach αlocal at each point along the avalanche path. This angle can be interpreted as the likelihood that a released avalanche will also reach this point (ppreach). As a basis for establishing a relation between αlocal and ppreach we utilized a dataset of 18,492 documented avalanches with reported α angles from the Swiss (Bühler et al., 2019; Toft et al., 2023) and Austrian Alps. The distribution of observed α can be approximated by a normal distribution and we utilized the cdf of this distribution to obtain ppreach from modelled αlocal (Figure 3).

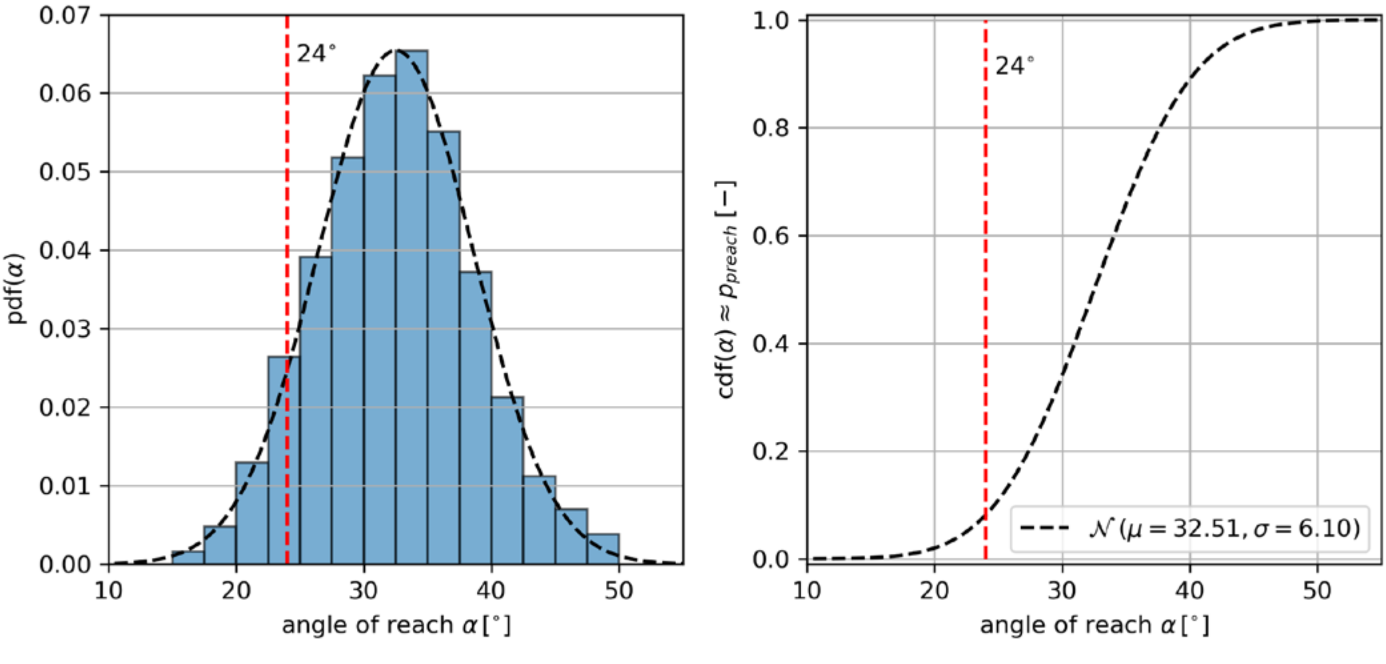


*Figure 3: histogram and cumulative density function of the angle of reach. The global α-angle of 24 degrees is located between the 5th and the 10th percentile of observations.*

To transfer pprelease of the PRAs to each pixel of the avalanche runout as well as to calculate pplocal, the PRAs can be classified by pprelease. We used three classes of pprelease and applied the arithmetic mean to each class. However, more classes may be appropriate depending on resolution and computing time requirements.

## RESULTS AND DISCUSSION

We developed a method for estimating potential occurrence probabilities for snow avalanches (pplocal) in PPAs according to the IMPFA, comprising steps to estimate pprelease and ppreach. The presented method was developed in the context of protective forest management and to provide a gradation of modelled PPAs to subsequently prioritise silvicultural interventions in PRAs in case of low protection by forest. However, a similar approach might also be useful in more general regional-scale hazard indication mapping applications using topographic runout models to minimise computing efforts. Despite an overlap in content, the presented concept cannot be directly compared to approaches for hazard zone mapping, since hazard zone mapping is not the same as mapping the PPAs of forests based on already identified forests with an object-protective function.

Based on 10 x 10 m raster representation, forest with direct object-protective functions potentially protect an area of 235,371 ha outside of forest use land (PPA) from impact by snow avalanches in Austria, which corresponds to 2.8% of the federal territory. Depending on the federal state shares vary between 0 and 7.8%. The largest total PPA of 83,888 ha is in Tyrol. The average pplocal within the PPAs is 0.04 which indicates an average potential avalanche return period of about 25 years without protection by forest. The results are difficult to validate, as the hazard zone maps of the Austrian Service for Torrent and Avalanche Control (WLV) primarily show hazard zones in settlement areas where avalanche activity has already been observed, e.g., due to the insufficient protective effect of the forest. 11,870 ha (95%) of the avalanche hazard zone area mapped by the WLV is located below forests with direct-object protective functions.

Regarding estimations of pplocal, established approaches for snow avalanche hazard zoning often neglect the initiation component of the hazard probability. They focus on the expected hazard runout based on a design magnitude of new snow depth (HN) as a trigger of snow avalanches. That is, the 3-day sum of new snow depth (HN3d) is often used as an indicator of avalanche probability and expected fracture depths at return levels. However, the consensus in the literature we reviewed, which resonates with insights from Schaer (1995) and Stoffel et al. (1998), is that HN alone cannot consistently explain avalanche activity and thus the likelihood of avalanche initiation. While total snow depth (HS) can be considered a factor relevant to all types of avalanche release mechanisms, HN might solely be linked to avalanches released in response to loading of the snowpack by recent snowfalls. Therefore, hazard zone mapping based on HN only is an over-simplification since avalanche activity is clearly influenced by HS and other snowpack and weather conditions, and a combination of HS and HN would be desirable. However, avalanche hazard documentations provide much less information on HS than on fracture depths. Generally, data on snow conditions from avalanche hazard documentations can be heavily biased.

In addition, the modelling to create the MMXHS map revealed a significant average decrease of about 8 % from the period 1961-1990 to 1981-2010. Surprisingly, the strongest relative decrease occurred at medium and not low altitudes. However, area-wide datasets on HN linked to HS over specified periods at different recurrence levels also taking these trends into account are lacking. Consequently, we focused on the occurrence of a critical HS in our estimation of pprelease.

Moreover, established hazard zoning concepts do not consider issues like the influence of Slope on the release probability and the effect of topography on the position and size of release areas. Estimating the return period of avalanche initiation is treated as a question of snow depths rather than geomorphological conditions. Concepts to transfer the size of release and the avalanche activity from well documented avalanche catchments matching the topography of the PRAs may require much more data as well as the consideration of snowpack characteristics (Maggioni, 2004). This is why such a more sophisticated approach – especially in forested terrain – is currently not applicable and existing concepts of avalanche hazard zone and forest function mapping implement considerable simplifications of the release probability and thus introduce uncertainty because of methodical constraints. The presented method can be a contribution towards resolving these methodical issues in hazard and risk assessments.

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