https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

Probabilistic modelling for avalanche hazard and risk assessment

Jan Kleinn[1,2], Dörte Aller[3], Yves Bühler[1,2], Julia Glaus[1,2], Adrian Peter[4], Nils Hählen[4]

[1] WSL Institute for Snow and Avalanche Research SLF, 7260 Davos Dorf, Switzerland
[2] Climate Change, Extremes and Natural Hazards in Alpine Regions Research Centre CERC, 7260 Davos Dorf, Switzerland
[3] Aller Risk Management, 8052 Zurich, Switzerland
[4] Office for Forests and Natural Hazards, Canton of Berne, Interlaken, Switzerland

Correspondence to: Jan Kleinn (jan.kleinn@slf.ch)

Abstract

The number of requirements for hazard and risk assessment of mass movements like avalanches has increased over time. We are presenting a feasibility study of applying the approach of probabilistic hazard and risk assessment, which was originally developed for seismic hazards and risks, to avalanches. This modelling approach is based on the idea of simulating a large range of possible events and associate probabilities or rates to these events. The aim of such a probabilistic modelling approach is to provide more nuanced modelling results as a basis for consistent hazard and risk management. It allows to derive continuous intensity frequency curves for any location in the affected area. Furthermore, continuous loss frequency curves can be derived by combining the simulated event intensities with affected objects and their vulnerabilities. The probabilistic modelling approach is enabling several products and applications, which are not possible with the current Swiss approach of hazard and risk assessment for avalanches. This first attempt of the probabilistic modelling approach to avalanches provides plausible results, which are in line with existing hazard assessments. Furthermore, it provides more differentiated results by enabling hazard maps for any given return period, and it enables the generation of maps depicting the probabilities of being affected by avalanches of a certain avalanche intensity. These types of products are not possible with the current Swiss hazard assessment approach.

1 Introduction

The first avalanches hazard map in Switzerland was developed in 1954, based on observations of past avalanches and expert judgement. Guidelines for taking avalanche hazard into account in spatial planning were published in 1984 (Federal Office of Forestry and Swiss Federal Institute for Snow and Avalanche Research, 1984) and are still in force today. Further guidelines, including risk assessment, were developed in the late 1990s (Heinimann et al., 1998, Borter, 1999). The latest guidelines by the Swiss Federal Office for the Environment on risk assessment for gravitational natural hazards highlights, that the probabilities in the affected area are the relevant probabilities to be considered, not those at release (FOEN, 2025).

The current approach for avalanche hazard assessment in Switzerland is following the approach as described in Rudolf-Miklau et al. (2014). It is based on the analysis of the general situation (topography, climate, vegetation, etc.), the assessment of past

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

events, and on avalanche simulations. Avalanche simulations are conducted for release return periods of 30, 100, and 300 years. An extreme case of a return period of more than 300 years (e.g. 1'000 years) should also be considered according to the Swiss Federal Office for the Environment. Fracture depth, size and location of the release area, friction coefficients, snow characteristics, wind drift, and the impact of protective measures or vegetation are determined for each of the return periods. The fracture depth in the avalanche release zone is determined by using statistical estimates of 3-day snow depth increase (ΔHS3d, also called snow accumulation) for selected return periods. Based on expert judgement, the most relevant possible avalanches are simulated for the fracture depth of a specific return period, e.g. 1 in 100 years, using an avalanche dynamics model (e.g. RAMMS, Christen et al. 2010). Simulation results are validated with past events and adjusted, if needed. Maps of hazard intensity (avalanche pressure and flow height) are generated based on these simulations. Where simulations overlap, the maximum of the simulated intensities is taken. The return period of the fracture depth is finally assigned to the map of avalanche intensity. This approach does not account for the probability of a location being hit by an avalanche and is neglecting the different probabilities in space of being hit by an avalanche.

The current approach is a well-established concept. The decline in fatalities in buildings and on transportation corridors (including ski resorts) due to avalanches since the 1950s and 1960s can be partly attributed to the introduction of avalanche hazard maps in Switzerland and the subsequent construction of protective measures (Fig. 1). The question arises though, whether the current approach might not be overly conservative in order not to miss any potential avalanche and hence define hazardous areas rather generously.

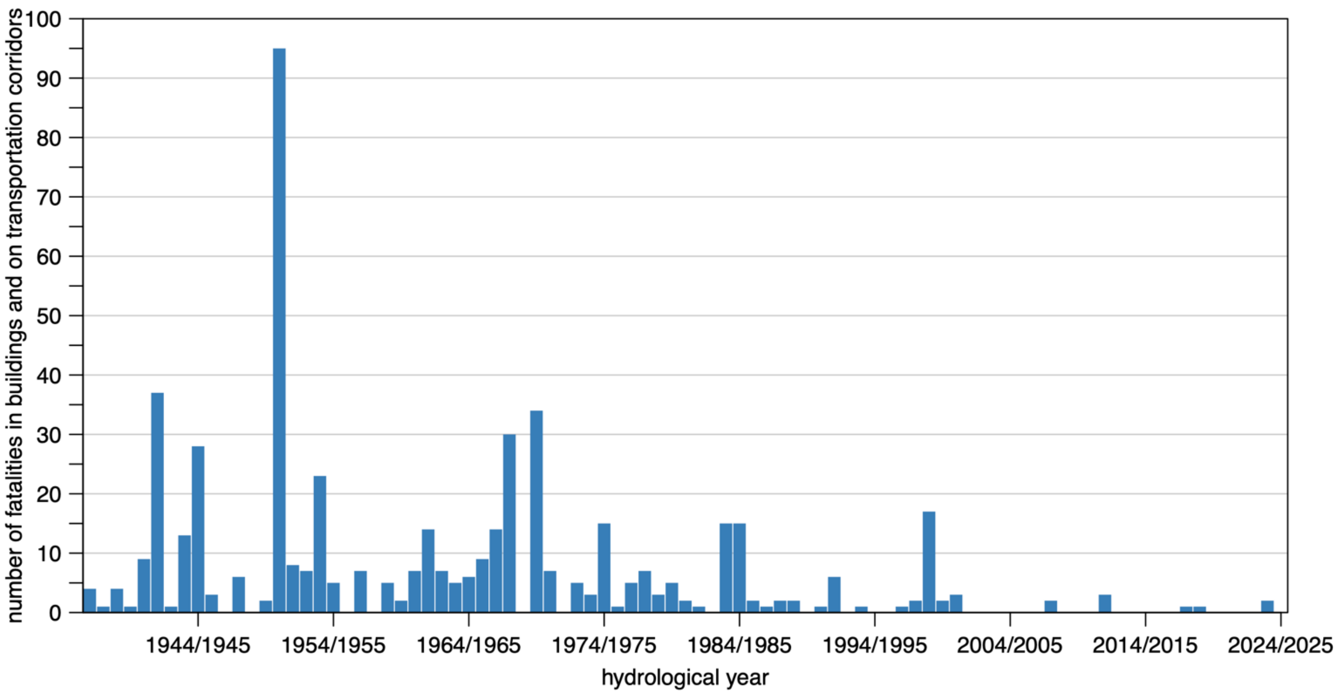


Figure 1: Number of fatalities in buildings and on transportation corridors since the 1930s (data source: WSL, 2023).

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

As resources for mitigation measures are limited prioritization is needed. Many stakeholders (e.g. people affected as well as people and organisations having to assume the risk) expect to be able to raise their concerns at an early stage in the decision-making process. Integrated risk management takes these requirements into account.

Integrated risk management (PLANAT, 2018) is a holistic concept, meaning that risks are assessed as a whole and the need for action is prioritised accordingly. The aim is to limit risks to an acceptable level for the population and their livelihoods. This involves weighing up what we as a society can accept and how much we are willing to spend on safety. Furthermore, all aspects of sustainability (ecological, economic, and social) should be considered when deciding on measures.

Integrated risk management in Switzerland was introduced following the damaging flood events of 1987 (Rickenmann and Zimmermann, 1993). This flood event has revealed that absolute protection would not be cost-effective. A paradigm shift was started, away from purely hazard-based protection towards a risk-based approach (PLANAT, 2004).

The integrated risk management has been propagated in Switzerland by federal offices and strategic organisations (e.g. PLANAT, 2004). New federal laws and regulations on hydraulic engineering and forestry, which are based on PLANAT (2018) are in force since 2025 (Swiss Federal Act on Hydraulic Engineering, 2025, and Swiss Federal Act on Forests, 2025). These laws require a more consistent implementation of the integrated risk management for gravitational natural hazards. They require the inclusion of climate change in hazard and risk assessment, the consideration of a wide range of possible measures (spatial planning, maintenance, technical measures, operational planning/organisational measures, large scale mitigation measures, nature-based solutions, etc.) to find an optimum combination. Decisions on mitigation measures must be taken using risk-based approaches. Such a risk-based focus requires tools for hazard and risk assessment of natural hazards, which provide more differentiation in the results compared to the current approach of using selected return periods of release. Such a need for more differentiated information has also been recognized by Argue, et al. (2024).

Nowadays, the management of natural hazards and their risks mainly rely on the same approach of hazard assessment which was originally developed for spatial planning several decades ago. Furthermore, technology has advanced significantly over the last decades, making it possible to pursue new approaches: modelling capabilities have increased, improved input data is available for driving and validating models, and tools for analysing and visualising large datasets are now readily available.

The probabilistic modelling approach presented here aims at providing information on intensities (pressure, flow height, and velocity) for the entire range of return periods at any given location in the affected area, i.e. in the avalanche runout zone. The modelling approach is comparable to the one which is commonly used for seismic hazard and risk assessment (e.g. Silva et al., 2020, or Gerstenberger, et al. 2020) and which is based on Cornell (1968). Since then, similar approaches have been developed for tropical cyclone hazard assessment, including climate change impacts (Bloemendaal et al., 2020, Emanuel et al., 2006, Hall and Jewson, 2007, Hall et al., 2021, Lee et al. 2020), for floods (Bates et al., 2023), for more localized hazards like hail (Schröer et al., 2022), and for tsunamis (Sørensen et al., 2026), among others.

The results of such probabilistic modelling approach allow to conduct comprehensive assessments of hazards and risks and therefore provide a basis for risk management and risk-based decision making. The aim is to derive the relationship of hazard intensities and probabilities, i.e. so-called intensity-frequency-curves, for any location in the affected area. Furthermore,

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

comprehensive risk analyses require continuous loss frequency curves (Kleinn et al., 2022), i.e. the relationship of event losses and event return periods. These can be derived from probabilistic event-based modelling, as suggested in this study. This is also the reason, why this probabilistic modelling approach is commonly used in the global insurance and reinsurance industry for various hazards and for climate adaptation studies (Aznar-Siguan and Bresch, 2019).

The main aim of our study is to demonstrate the feasibility of the probabilistic modelling approach for alpine mass movements as this approach provides a wide range of advantages compared to the current Swiss approach of hazard assessment. These advantages include more differentiated information on the hazard as well as additional products, which are not possible with the current approach. The results of the probabilistic modelling approach support risk management and risk dialogue related to avalanche hazards.

While other studies have been conducted on probabilistic modelling of avalanches (Fischer et al., 2014, and Glaus et al., 2026) and their risks (Straub and Grêt-Regamey, 2006, and Grêt-Regamey and Straub, 2006), their focus was not on providing continuous intensity frequency curves and loss frequency curves for comprehensive hazard and risk assessment.

In this study, we concentrate on cold slab avalanches. A similar approach can also be used for powder snow or wet snow avalanches. Possible improvements in the modelling chain for improving the overall results are discussed in section 5.

2 Pilot study region

The modelling approach is implemented and tested in the region of Adelboden in the Canton of Berne, Switzerland. This pilot region, shown in Fig. 2, covers an area of 4 km by 7 km and ranges in altitude from about 1’200 meters to about 3’000 meters above sea level (a.s.l.). This region was chosen because it is prone to avalanches, especially in the southern half of the pilot region and along the slopes north of Adelboden. Furthermore, the region also covers the other hazards of the pilot study, namely rockfall and shallow landslides.

The Jaunpass snow measurement station is used for this study. It is located about 20 kilometers to the northeast of Adelboden at about 1’500 meters a.s.l. The Jaunpass station is outside the settlement area and therefore matches the snow climatology of the release areas better than the station in Adelboden itself, which is located in the center of the populated area of Adelboden. Furthermore, data at the Jaunpass station is available for a longer period of time. Daily snow data is available at the Jaunpass station since 1941. The exact station being used for defining the input data is of minor relevance to our study as we concentrate on highlighting the feasibility of the modelling approach per se.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

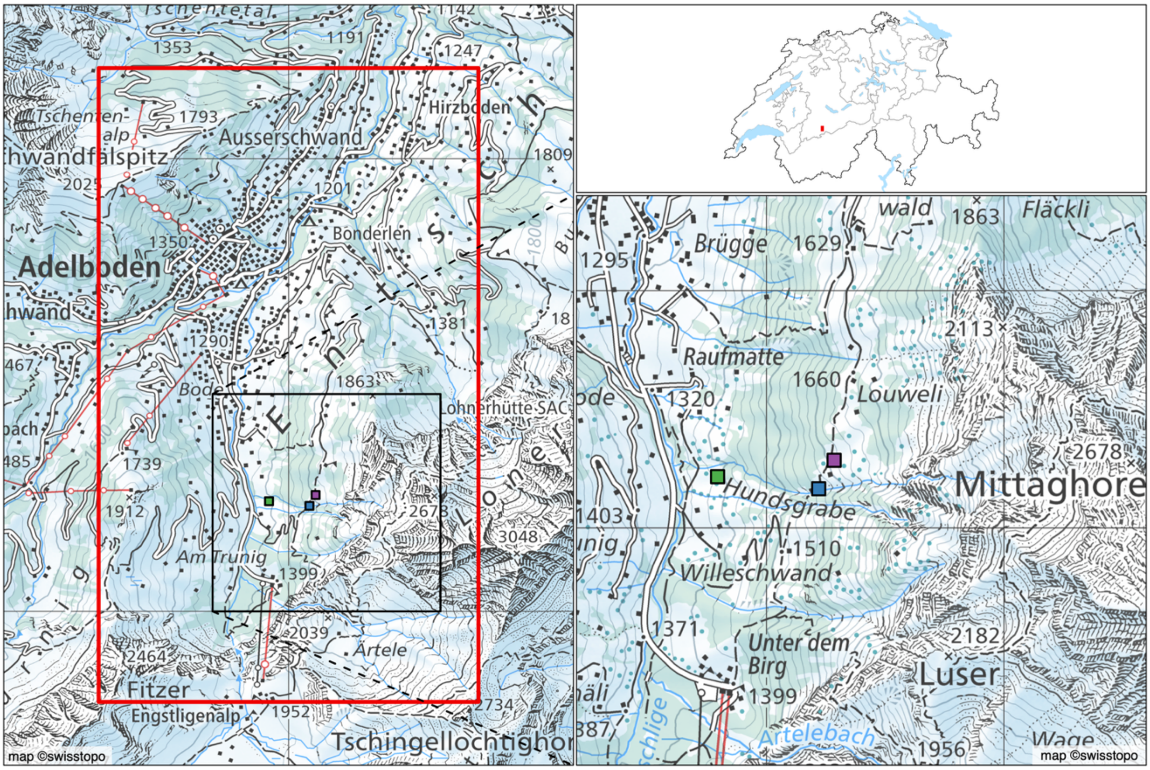


Figure 2: Pilot region used for this study (panel to the left) and its location in Switzerland (top-right). The three coloured points in the southern half of the domain represent locations, for which detailed results are shown in section 4. The panel to the bottom right is zooming in on the three locations.

3 Modelling approach

3.1 Basic concept

Probabilistic hazard and risk analysis is based on the concept of taking the entire range of possible events into account, including their probabilities or rates. We consider an event to be a single simulated avalanche. Both, annual probabilities as well as annual rates of occurrence can be attributed to the events and used for the probabilistic analyses. The combination of the simulated events with their respective probabilities or rates results in comprehensive hazard information in the impact area. The probabilistic hazard and risk modelling, as we apply it here, consists of three components (Fig. 3), which we will explain in more detail in sections 3.2, 3.3, and 3.4.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

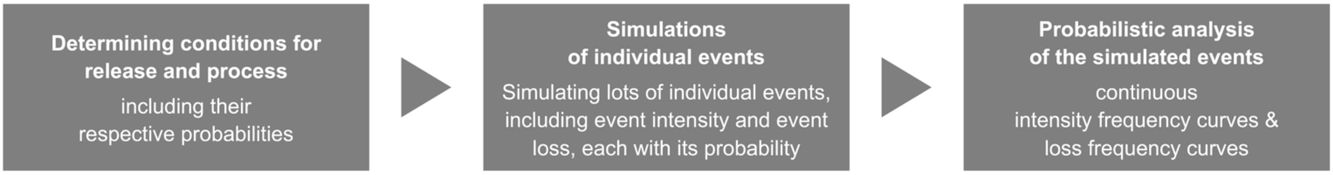


Figure 3: The three components of probabilistic hazard and risk modelling.

3.2 Determining event probabilities, event rates, and event conditions

The probabilistic approach can be implemented with either annual event probabilities or annual event rates. Event probabilities describe the probability that such an event occurs within a year (or season) and is limited to the range of zero to one. Event rates describe the average number of events per year and can exceed the value of one.

We define the annual event probability as the product of release probability and process probability, as shown in Eq. (1):

$$P_{event} = P_{release} \cdot P_{process} \quad (1)$$

The release probability is the probability of a certain avalanche release with its corresponding release properties, in our case release location and fracture depth. The process probability is the probability that an avalanche takes a certain course.

When working with rates of occurrence instead of probabilities, we replace the annual release probability with an annual release rate of occurrence, in order to calculate annual event rates. The advantage of using rates instead of probabilities is that frequent events, which are occurring multiple times per season, can be considered whereas the annual probability cannot exceed the value of one. Taking events into account, which can occur multiple times per season can have a significant impact on the risk assessment and hence on risk-based planning of mitigation measures.

3.2.1 Determining release probabilities and release conditions

The release probabilities (or rates) can be defined as the combination of the probabilities of the physical properties of release and a spatial component, as shown in Eq. (2).

$$P_{release} = P_{phys} \cdot P_{spatial} \quad (2)$$

Fracture depth is used as the physical property of release. We define the probability of the physical properties, i.e. probability of a fracture depth, as a combination of the probability of the 3-day snow accumulation and the probability of release given such a 3-day snow accumulation. Probabilities as well as rates for 3-day snow accumulation are determined based on daily snow data from a station in the vicinity (Jaunpass, see section 2), adjusted by altitude to a reference altitude of 2’700 meters a.s.l., which corresponds to the altitude of the higher potential release areas in the region. An adjustment of 5 cm per 100 meters of altitude difference is applied. This is a common altitude adjustment in the Swiss hazard mapping approach (Salm, 1990, and Bühler et al. 2022).

For the probability of the 3-day snow accumulation, we derive the 3-day snow accumulation from the daily data at the Jaunpass station (section 2) by using the 3-day difference in daily snow height and fit a general extreme value distribution (GEV) to the historic data of 3-day snow accumulation (Figure 4, panel (a)). Extreme value fits of either a GEV or a Gumbel distribution

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

(which is a special case of the GEV) are usually used in the current Swiss hazard assessment approach for defining 3-day snow accumulation at specific return periods (typically 30, 100, and 300 years). Here we convert the fitted extreme value distribution into exceedance probability dependent on 3-day snow accumulation (Figure 4, panel (b)). We define bins of snow accumulation and consider the centre of these bins to be the snow accumulation representative for each category. Numerical avalanche simulations will be performed for each of these representative snow accumulations. Exceedance probabilities can be derived for the boundaries of the snow accumulation bins (Figure 4, panel (b)). The probabilities for each of the snow accumulation bins is derived from the differences in exceedance probability at the bin boundaries (Figure 4, panel (c)). We have chosen equally sized bins of snow accumulation with a bin size of 20 centimeters. This is a compromise between fine-grain differentiation of release conditions and computational effort.

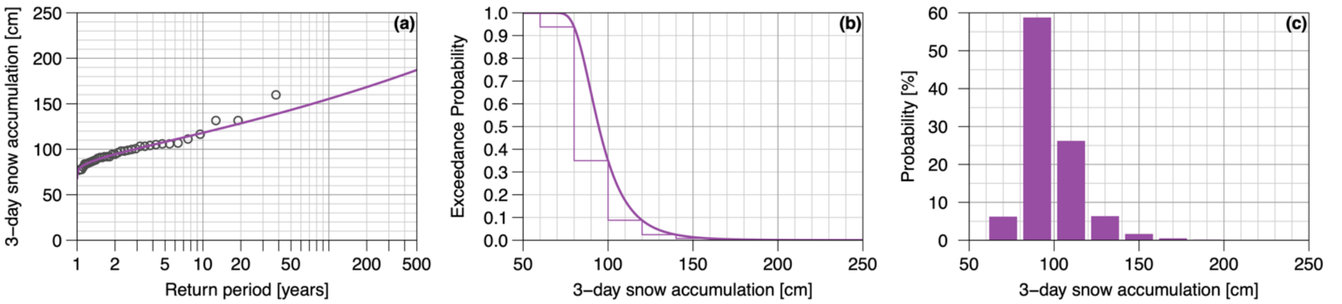


Figure 4: Probabilities of 3-day snow accumulation bins derived from an extreme value fit of historic 3-day snow accumulation data.

Similarly, we derive yearly exceedance rates of 3-day snow accumulation from historic data. A fit is applied to yearly exceedance rates (Fig. 5, panel (a)), similar to the magnitude-frequency distributions used in seismic hazard assessment (Kagan, 2002). Yearly rates for the bins of snow accumulation can be derived from the fitted exceedance rates at the boundaries of the snow accumulation bins (Fig. 5, panels (b) and (c)).

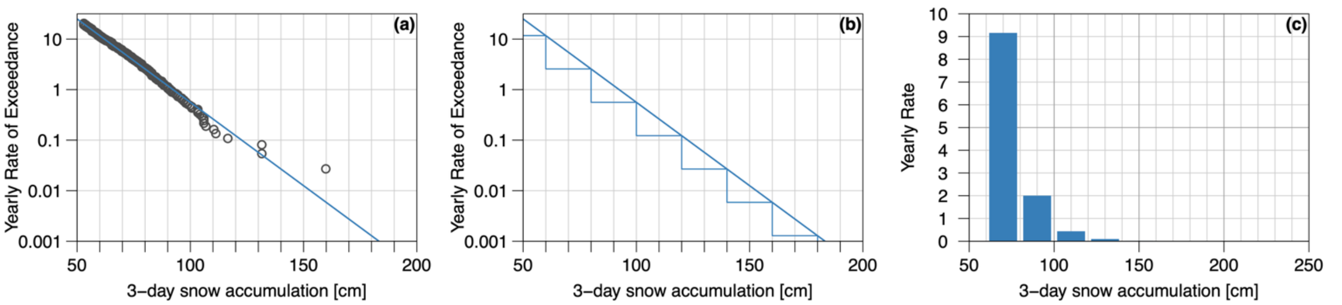


Figure 5: Yearly rates of 3-day snow accumulation bins derived from a fit of yearly exceedance rates to historic 3-day snow accumulation data.

The impact of wind drifted snow or weak layers leading to fracture depths of more than the amount of 3-day snow accumulation are not taken into account in this study. Both can be integrated in the probabilistic framework at a later stage.

Not all potential release areas will lead to an avalanche release at a given fracture depth. We therefore introduce an adjustment for the release probability for each fracture depth. In this first implementation of the probabilistic modelling approach, this

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

adjustment is based on the estimates of number of avalanches per path from Evin et al. (2021) for return periods of 100 and 300 years. We interpolate and extrapolate from the two values by Evin et al. (2021) and limit the probability adjustment to 1 for return periods of more than about 2'250 years (Fig. 6).

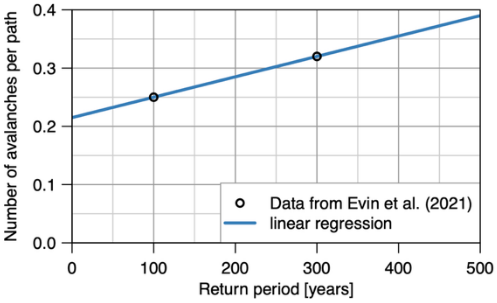


Figure 6: Interpolation and extrapolation of the number of avalanches per path depending on return period of snow accumulation, which capped at 1.0 and used as probability adjustment in the definition of the release probability.

Potential release areas were derived for each of the snow accumulation bins using the algorithm by Bühler et al. (2013, 2018). Since the algorithm has been developed to derive potential release areas for given return periods, the return periods were extracted for each of the snow accumulation bins from the exceedance probability distribution. A total of 14'063 potential release areas was derived for the 13 categories of fracture depth in the pilot study region, ranging from about 1'160 meters to about 2'890 meters of altitude. The number of potential release areas varies with fracture depth (Table 1 and Fig. 7).

Table 1: Probabilities, rates and number of potential release areas for the different values of 3-day snow accumulation used as fracture depths.

3-day snow accumulation	Yearly Probability	Yearly Rate	Number of potential release areas
70	0.0622	9.1624	3'398
90	0.5877	2.0041	3'319
110	0.2622	0.4384	2'230
130	0.0636	0.0959	1'058
150	0.0166	0.0210	639
170	0.0050	0.0046	499
190	0.0017	0.0010	448
210	6.34E-04	2.19E-04	423
230	2.60E-04	4.80E-05	412
250	1.15E-04	1.05E-05	408
270	5.41E-05	2.30E-06	411
290	2.66E-05	5.02E-07	409
310	1.37E-05	1.10E-07	409

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

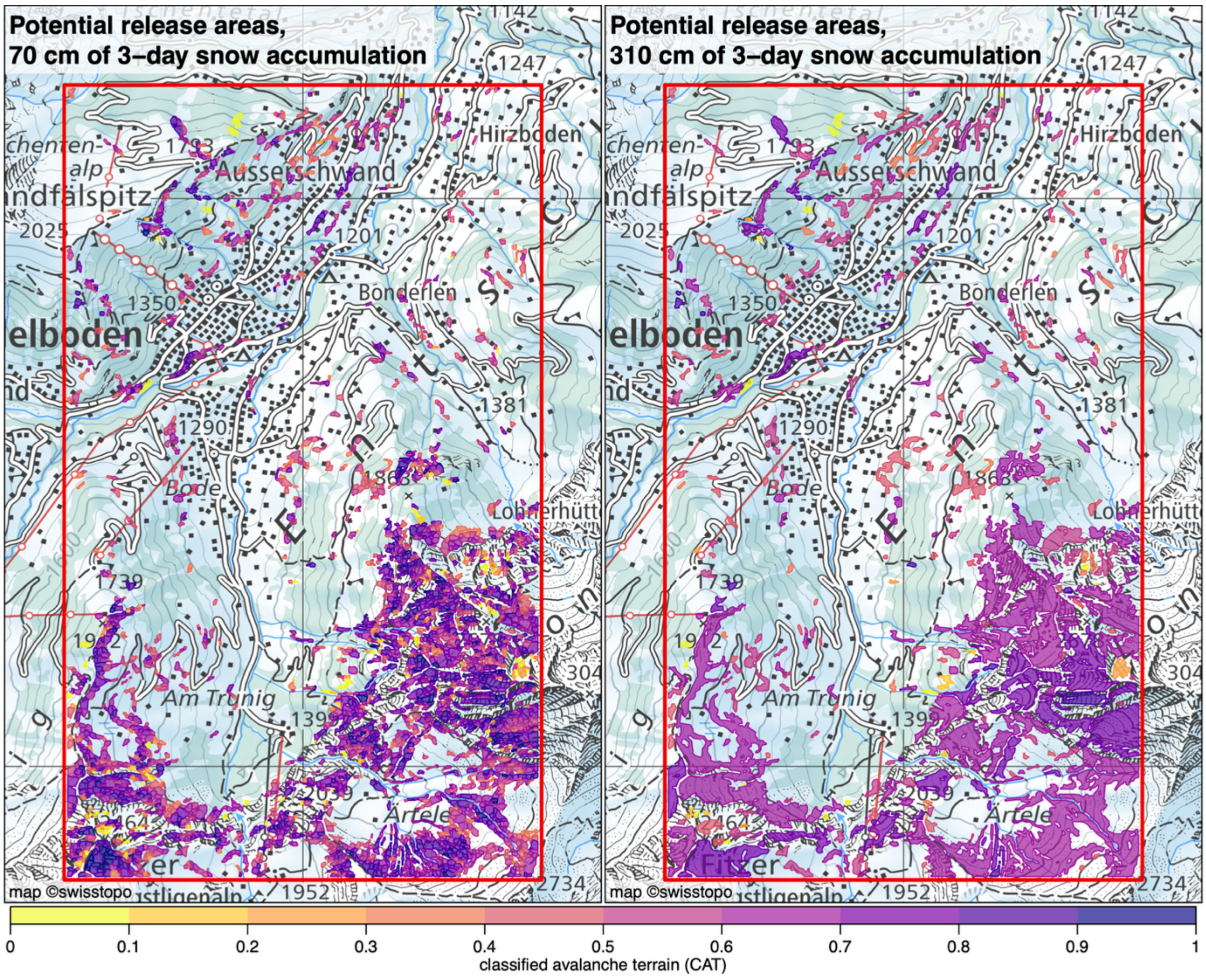


Figure 7: Potential release areas for the lowest and the highest value of fracture depth defined by the 3-day snow accumulation. Colour coding is highlighting the different values of the classified avalanche terrain (CAT), which are used for the spatial component of the release probability.

For each potential release area, the representative fracture depth from the 3-day snow accumulation bins were adjusted to account for the altitude of each potential release area.

To account for different avalanche release susceptibilities of different slopes, we introduced a scaling to the release probabilities based on the classified avalanche terrain CAT (Harvey et al., 2018, 2024). The CAT is an automatic classification of avalanche terrain, including the potential for avalanche release. The average value of CAT was calculated for each release area (Fig. 7). The release probability of each potential release area was adjusted with the release susceptibility based on the CAT value of the given release area divided by the average of all CAT values of the release areas for a given fracture depth (Eq. (3)). We call this the spatial component of the release probability:

$$P_{spatial} = \frac{P_{CAT,a}}{\frac{\sum_{a=1}^{n} P_{CAT,a}}{n}} = \frac{P_{CAT,a}}{\sum_{a=1}^{n} P_{CAT,a}} \cdot n \quad (3)$$

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

The spatial component is not a probability. Due to the normalization with the average, it can reach values larger than one.
The overall release probabilities are now defined as the combination of the probability of fracture depth (3-day snow accumulation, ΔHS3d), the probability of release given the fracture depth (based on Evin et al., 2021), and the spatial component (based on CAT):

$$P_{release} = P_{\Delta HS3d} \cdot P_{release@\Delta HS3d} \cdot P_{spatial} \quad (4)$$

3.2.2 Process probabilities and process conditions

Different conditions of process modelling can be taken into account in probabilistic hazard modelling, e.g. by using different model parameters for the numerical simulations. The probabilities for each of the different modelling sets need to be determined for the analysis of the results. In a first step, we focus on varying avalanche release conditions. The parameters for the process simulations are therefore kept constant for now. Hence, the process probability is equal to one.
Numerical simulations with varying process parameters were performed at a later stage. The results of these simulations are presented in section 4.5.
Different process simulations can also be achieved by performing simulations with different process models such as com1DFA (Tonnel et al. 2023), material point method MPM (Gaume et al. 2019), or r.avaflow (Mergili et al. 2017). Such an approach would be comparable to using different ground motion prediction equations in probabilistic seismic hazard analyses (e.g. Silva et al. 2015). A probability will have to be assigned to each of the different process models and the sum of these probabilities needs to be 1.

3.3 Avalanche modelling

Our modelling approach is principally independent of the model used for numerically simulating single independent avalanches. It can be applied to simulations with any avalanche model which is capable of storing each simulated avalanche event for further analyses and which allows to link the event probability or event rate to the simulation output. Different avalanche models are available nowadays. For a detailed description of current depth-averaged models, see Wirbel et al. (2026).
We used the large-scale hazard indication modelling LSHIM version of RAMMS::Avalanche (Christen et al. 2010, Bühler et al., 2018 & 2022). RAMMS::Avalanche is a deterministic model, i.e. there is no probabilistic component within the model itself. Two simulations of the same avalanche release will yield the same results. It is a depth-average avalanche model, which is implementing a quasi Voellmy friction approach. The friction parameters μ (Coulomb friction) and ξ (velocity dependent friction) are dependent on the release volume. We have introduced two minor modifications to the standard version of RAMMS::Avalanche regarding the definition of the friction parameters. The friction parameters μ and ξ are usually set in categories dependent on altitude, slope normal fracture depth return period, fracture volume, and terrain properties (steepness and terrain shape). We have defined the dependency of the friction parameters to altitude and fracture depth return period

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

continuously. The dependency of the friction parameters to the fracture volume of the avalanches and the terrain properties remains defined in predefined categories. The categories of fracture volume and terrain properties correspond to the categories in the standard version of RAMMS::Avalanche: tiny (< 5'000 m^3), small (5'000 – 25'000 m^3), medium (25'000 – 60'000 m^3), and large (> 60'000 m^3) for the fracture volume and the classes unchannelled, channelled, gully, and flat for the terrain properties. The forest cover is considered in the same way as in the standard version of RAMMS::Avalanche, i.e. by increasing μ and by setting ξ to a fixed forest value (Christen et al. 2010).

14'063 avalanches with 13 different fracture depths have been simulated in the pilot project domain, and the output (maximum avalanche pressure, maximum avalanche height, and maximum flow speed) has been stored individually for each of these simulated avalanches.

The simulation results are limited to grid cells with maximum pressure larger than 0.5 kPa and maximum flow height larger than 20 centimeters. This is based on expert judgement that RAMMS is continuing simulating very shallow avalanches, which would most probably stop in reality. Fig. 8 shows that grid cells in the most affected regions are affected by more than 100 simulated avalanches.

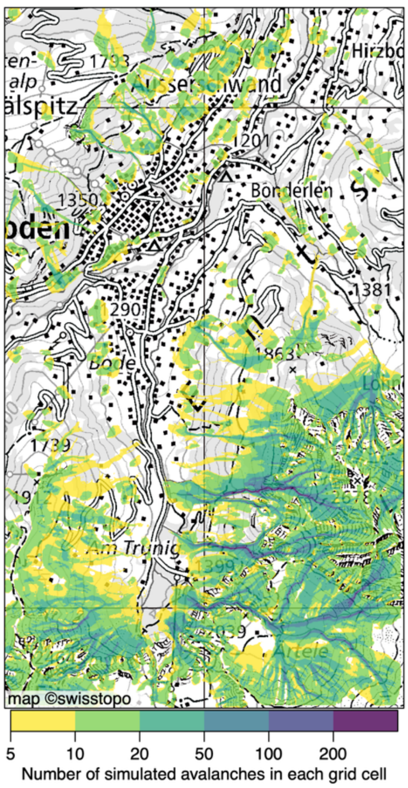


Figure 8: Number of simulated avalanches affecting each grid cell with more than 0.5 kPa of maximum pressure and more than 20 centimeters of flow height.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

3.4 Analyses of avalanche simulations

The analyses of the simulated avalanche events and their respective probabilities or rates are based on intensity frequency curves, which are computed for each grid cell of the simulation domain. To compute such an intensity frequency curve, all events affecting an individual grid cell are considered with their intensity at the grid cell and their respective probability or rate. Intensity frequency curves can be calculated for any intensity resulting from the event simulations. In the case of RAMMS, we can use avalanche pressure, avalanche height, and flow velocity to derive intensity frequency curves. The exceedance probabilities (EP) for the intensity frequency curves can be computed from the event probabilities (P_{event} in Eq. 5) or event rates (λ in Eq. 6) of the events ranked by decreasing intensity. The formula based on event rates (Eq. 6) is assuming a Poisson distribution of the events and λ to be the average frequency of the Poisson distribution. The concept of computing the exceedance probability is that we first compute the non-exceedance probability using the non-occurrence probabilities of the events and their cumulative product.

$$EP_i = 1 - \prod_{max}^{i}(1 - P_{event,i}) \quad (5)$$

$$EP_i = 1 - \prod_{max}^{i} e^{-\lambda_i} \quad (6)$$

Having calculated the intensity frequency curves at each grid cell, the results can be visualised either as intensity frequency curve for single locations, maps of intensities at given return periods or maps of probabilities for given intensities. Examples of these visualisations are shown in sections 4.1 (Fig. 9), 4.2 (Fig. 10), and 4.3 (Fig. 11).

4. Results

4.1 Intensity frequency curves

Intensity frequency curves can be calculated for each grid cell in the pilot study region, as described in section 3.4. For this purpose, all avalanches affecting a grid cell are combined with their probabilities or rates, respectively, to compute the exceedance probability and hence the return period of each event intensity. The three intensity frequency curves in Fig. 9 are derived for three different locations in a gully in the southern part of the pilot study region (Fig. 2) and show distinctly different characteristics of the hazard at these three locations. The three points are affected at different return periods and the increase of intensity with increasing return period is very different. Using event rates compared to event probabilities results in significantly different intensity frequency curves. This is probably due to the differences in the fit of the exceedance rates compared to the fit to an extreme value distribution for event probabilities, especially for values of 3-day snow accumulation larger than any historic value in the time series.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

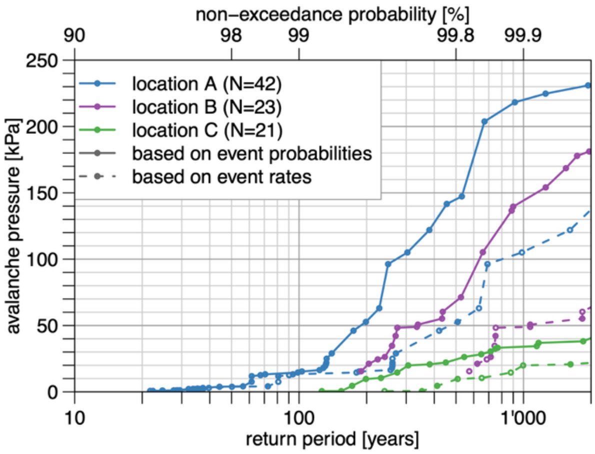
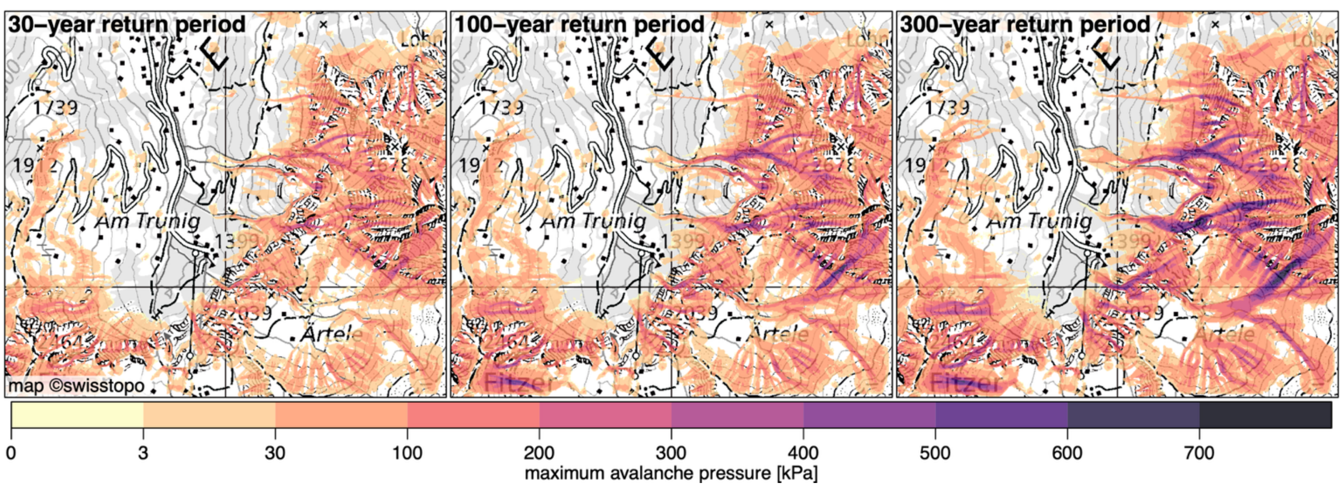


Figure 9: Intensity frequency curves at three different locations in the pilot study region using event probabilities and event rates. The number of avalanches used for computing each of the intensity frequency curves is mentioned in the legend. The colours correspond to the colours of the three points in Fig. 2.

4.2 Intensity maps for given return periods

From the intensity frequency curves at each of the grid cells, the intensity at any given return period or exceedance probability can be extracted and displayed on a map. Figure 10 shows such maps of intensities at 30, 100, and 300 years of return period. These return periods are common in the current Swiss hazard assessment approach. Maps for any other return periods (e.g. 20, 50, or 200 years) can be easily generated, even for very extreme return periods of 1'000 or even 5'000 years, as they are applied in Norway or Iceland. These maps depict the intensity for a return period specific to every location. This contrasts with the current hazard mapping approach in Switzerland, for which several possible avalanches of a return period of fracture depth are combined, without considering whether a specific location is more likely to be affected by an avalanche or less.

As expected, the avalanche pressure is increasing with increasing return period, and the highest values of avalanche pressure can be found in the centre of the couloirs with lower values at the edges.



https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

Figure 10: Maps depicting the intensity at 30 (left), 100 (centre), and 300 (right) years of return period in the southern part of the pilot study region.

4.3 Probability maps for given intensities

From the intensity frequency curves at each grid cell, we can also derive the probability, that a grid cell is affected by an avalanche or an avalanche of a certain intensity, i.e. avalanche pressure. This results in maps showing the probability of being affected by an avalanche or by an avalanche of a selected minimum intensity (Fig. 11). These maps provide a different view of the hazard compared to the intensity maps for given return periods and can be more useful in outreach and risk dialogue applications. Such maps can also be produced for the probability within longer time periods than a year or a season, e.g. within the average lifetime of a building of 50 years.

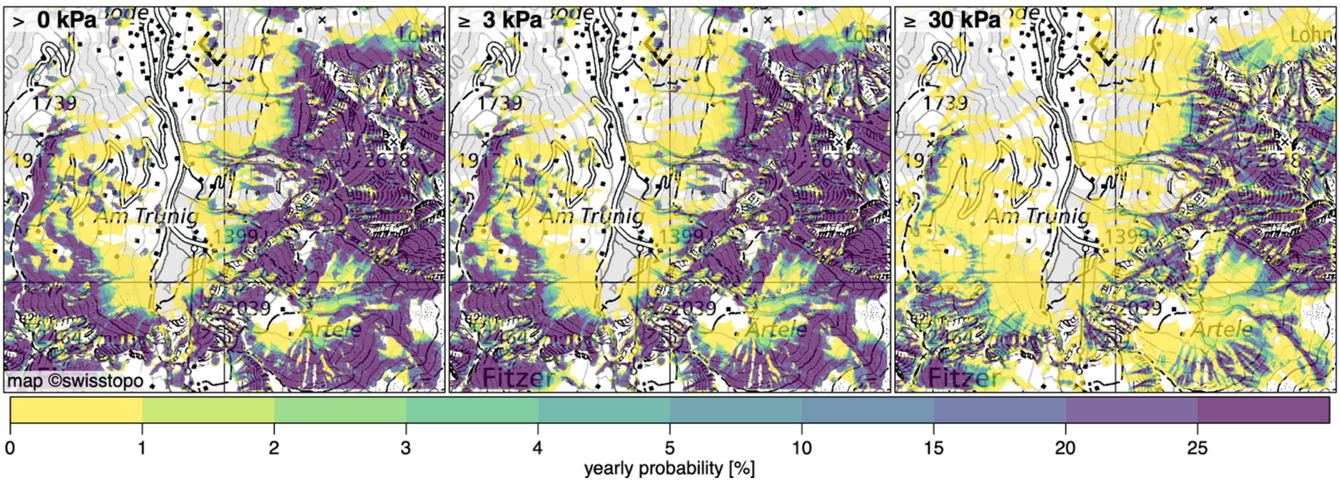


Figure 11: Maps depicting the probability at each grid cell of being affected by an avalanche at all (left), an avalanche pressure of 3 kPA or more (centre) and an avalanche pressure of 30 kPa or more (right) in the southern part of the pilot study region.

4.4 Loss-frequency-curves

For risk analyses, the intensity frequency curves can be combined with the values and vulnerabilities of the objects to derive loss frequency curves. Such loss frequency curves are an essential component for characterizing risks (Kleinn et al., 2022). The annual expected loss, which is used for benefit-cost analyses, is only one of several characteristics of risk. The probability of a loss and the loss at different return periods are other characteristics.

Event based simulations are essential for risk analyses, especially when considering a group or portfolio of objects. The sum of the losses can be calculated for each of the events so that a loss frequency curve can be derived for a group of objects. For illustration, we assigned monetary values to the three locations (Fig. 2) with the purple object having double the value of the blue and the green having triple the value of the blue. We used the same vulnerability function (damage ratio dependent on avalanche pressure) for all three locations. The combination of the intensities at the three locations with the monetary value and the vulnerability function allows to compute the monetary loss to each object for each event. In combination with the event probabilities or event rates, loss frequency curves can be derived for each of the objects individually and for the combined loss

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

for all locations together (Figure 12). For the loss-frequency-curve of all objects together, the losses were summed up for each event before sorting the events by their total loss and deriving the loss-frequency-curve.

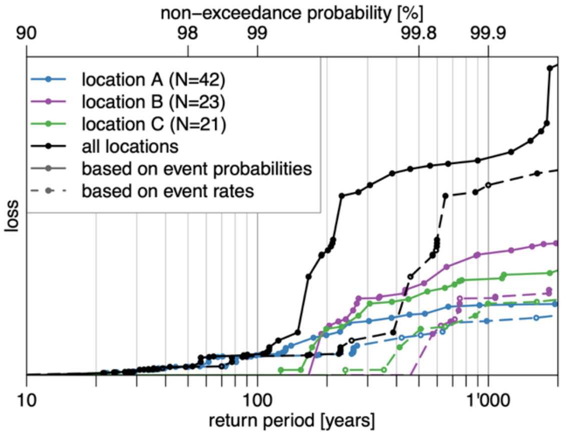


Figure 12: Loss frequency curves for objects at three locations and for their total (black) in the pilot study region using event probabilities and event rates. The number of avalanches used for computing each of the loss frequency curves is mentioned in the legend. The colours correspond to the colours of the three points in Fig. 1.

4.5 Variations of process model parameters

The two friction parameters used in the avalanche simulations of RAMMS::Avalanche were modified to analyse their influence on the intensity frequency curves. Furthermore, we analysed the impact of including all variations of the model parameters in a single intensity frequency curve for including a probabilistic component to the process modelling of avalanches. Four additional sets of about 14'000 avalanche simulations were performed. Two sets of simulations in which μ was changed by plus and minus 10% and two sets in which ξ was changed by plus and minus 20%. These changes approximately match the changes from one category to another in the friction parameter categories in the standard version of RAMMS::Avalanche. Depending on the avalanche model used for the probabilistic simulations, different parameters can be modified.

For analysing the sensitivity of the hazard to the variations of the friction parameters, we have calculated intensity frequency curves for all parameter combinations (Fig. 13). Different parameter combinations result in different intensity frequency curves. Differences are stronger for variations of ξ by plus and minus 20% than for variations in μ by plus and minus 10%. Increasing μ leads to lower values of avalanche pressure whereas increasing ξ leads to higher values of avalanche pressure.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

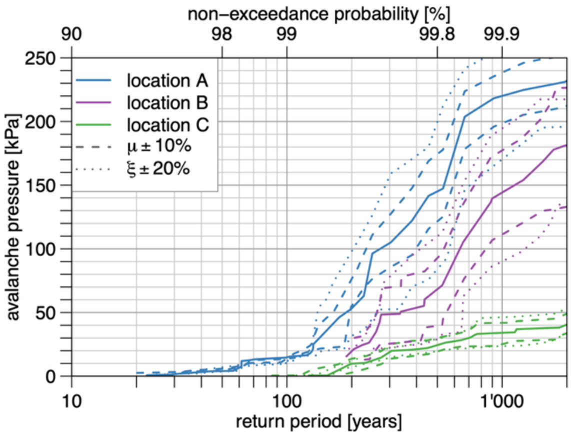


Figure 13: Intensity frequency curves at three different locations in the pilot study region with variations in the friction parameters in the avalanche simulations, all using event probabilities.

In a further step, we integrated all parameter variations in a single intensity frequency curve. Each parameter variation can be considered a separate process condition (section 3.2.2). We assigned equal probabilities to all five parameter combinations, hence reducing the overall event probabilities by a factor of five. This results in five times as many events for computing intensity frequency curves. The resulting intensity frequency curves at the three locations (Fig. 2) including all parameter combinations are compared to the original intensity frequency curves with a single set of parameters (Fig. 14). The differences in the different versions of the intensity frequency curves are small. It is therefore questionable, whether different parameter combinations for depicting different process conditions are worth the additional computational effort.

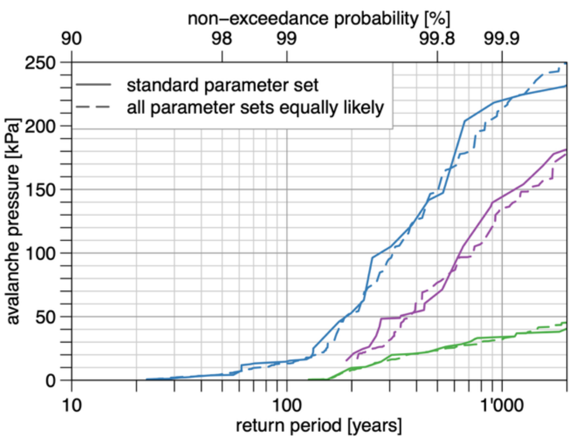


Figure 14: Intensity frequency curves at three different locations in the pilot study region (Fig. 2) with a single set of friction parameters and using all five variations in the friction parameters for each intensity frequency curve, all using event probabilities.

5 Discussion

In this section, we discuss differences to the current Swiss approach of hazard assessment, and the advantages of the approach of probabilistic hazard and risk assessment, as well as potential improvements in the probabilistic approach. The probabilistic modelling approach should also be applicable to other mass movement hazards than avalanches, e.g. rockfall or debris flow. Most differences to the current Swiss approach of hazard assessment and advantages of the probabilistic modelling approach will most likely also apply to these other hazards.

5.1 Probabilistic modelling approach in comparison to the current approach

The modelling part of the current approach for avalanche hazard assessment in Switzerland consists of numerical simulations of the most relevant possible avalanches, based on historical avalanche records, field investigations, and expert judgement, for fracture depths of selected return periods. The maximum at any given location of the simulations of each fracture depth are used as hazard output. The return period of the fracture depth is assigned to this combined hazard output. This is usually done for fracture depth return periods of 30, 100, and 300 years. The hazard at locations being hit by many avalanches or by few avalanches cannot be distinguished in the current approach of hazard assessment for several reasons. Determining the hazard by the maximum intensity of selected simulations does not account for the probability of a location of being hit by an avalanche. Assigning the return period of the fracture depth to the maximum intensity of selected simulations is neglecting the different probabilities in space of being hit by an avalanche. For representing the probability of every location in the affected area of being hit by an avalanche, the number of simulations needs to be larger compared to the current approach and each event needs to have an event probability. Due to the large number of simulations, the source region of the most damaging avalanches can be identified. This information is helpful for targeted planning of protection measures.

The probabilistic hazard and risk assessment approach presented in this study is not meant to directly replace the current approach of creating legally binding hazard maps. First of all, the approach of probabilistic hazard assessment has been performed at the scale somewhere in-between those of a hazard indication map (Bühler et al. 2022) and a legally binding hazard map. The probabilistic hazard assessment approach allows the creation of maps in the entire simulation area whereas hazard maps are usually only created for built-up areas. Furthermore, current hazard maps are usually not purely based on numerical simulations but include expert judgement. Such expert judgement has not yet been included in the probabilistic hazard assessment approach. Expert judgement can be included in determining the best estimate of modelling parameters, the validation of simulations, or when determining event probabilities.

The probabilistic modelling approach presented in this study allows to compute continuous intensity frequency curves for various intensities at any given point in the affected area, i.e. in the avalanche runout zone (Section 4.1 and Fig. 9). These intensity frequency curves allow to produce intensity maps for any return period of interest. These hazard maps can be calculated for the entire modelling domain, at municipal or regional level. The return periods in these intensity frequency curves represent the return periods at the location of impact and not the return period of release.

The large-scale hazard indication modelling, which has already been performed for the cantons of Grisons, Valais and Ticino in Switzerland (Bühler et al., 2022) is following the approach of the current hazard assessment. It depicts the maximum of all simulated avalanches given the fracture depth at selected return periods.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

Since we have used bins of 3-day snow accumulation in our probabilistic modelling approach we can reproduce the current Swiss hazard assessment approach for the return periods of these values of 3-day snow accumulation. The hazard maps based on the current Swiss avalanche hazard assessment approach are compared to the results of the probabilistic modelling approach for the same return periods (Fig. 15). We use return periods of 20, 75, and 220 years, as these correspond to return periods of 3-day snow accumulation bins used in the probabilistic approach (section 3.2.1) and are close to the usual return periods of 30, 100, and 300 years. The maximum intensity values for mimicking the current approach are based on about 1'060, 640, and 500 simulated events respectively. These numbers of simulations are way larger than what is commonly used in the current approach. The overall impression of the two approaches is similar with higher intensities in gulleys and lower intensities on ridges. The current approach of avalanche hazard assessment is covering a slightly larger area, and it is showing slightly larger intensities at all three return periods. We assume, that determining the hazard at every location from the large number of simulated avalanches and their probabilities is the main reason for the probabilistic results covering a smaller area and intensities being mainly smaller than with the current approach. It must be noted that the current approach of reaching a legally binding hazard map usually involves less simulations but includes expert judgement and field investigations, which have not yet been included in the probabilistic modelling approach.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

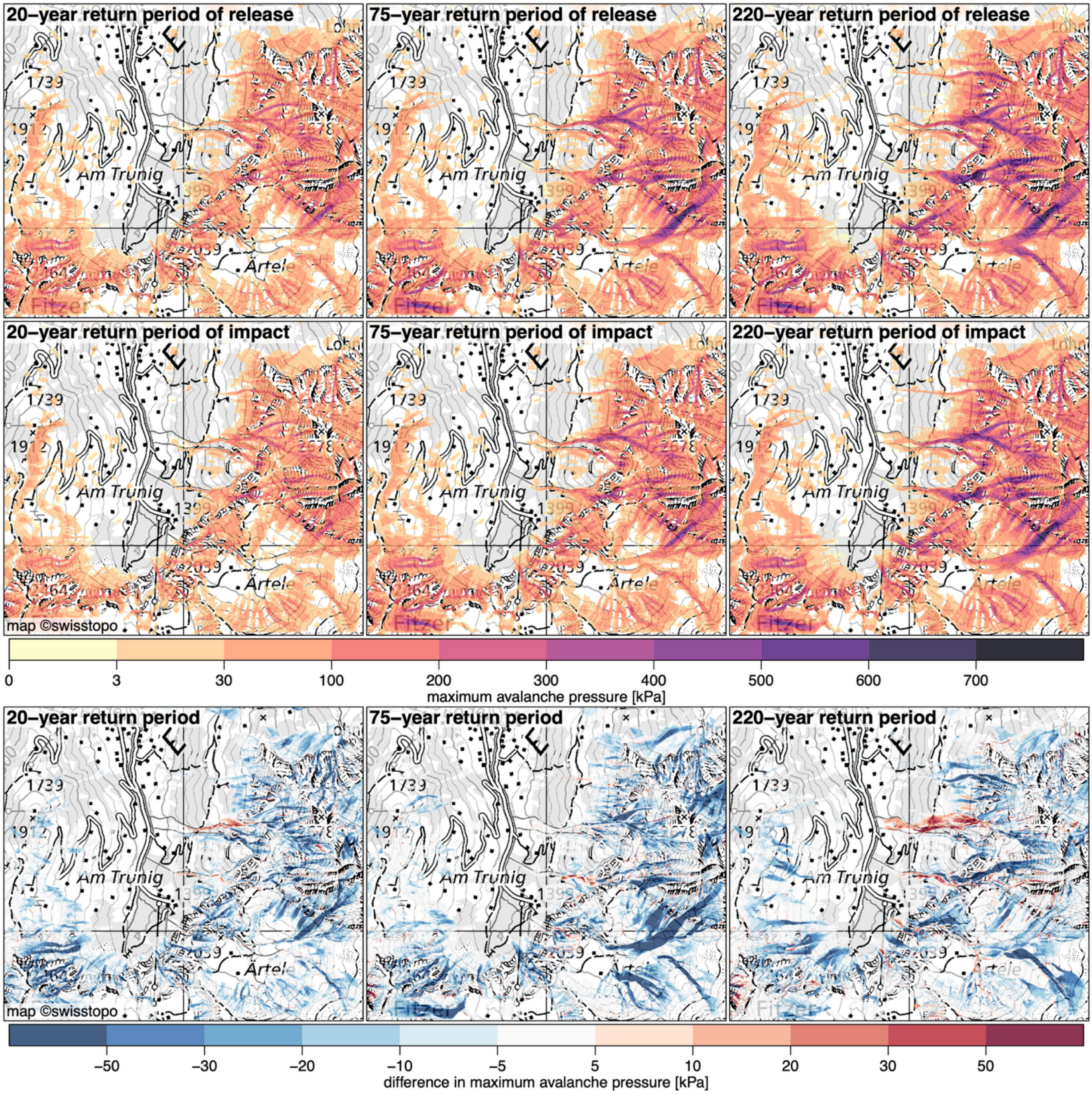


Figure 15: Intensity maps using the probabilistic modelling approach (center) compared to the approach used in the current hazard assessment in Switzerland (top), based on the maximum of all simulations based on the fracture height of a selected return period, and the difference of the two (bottom).

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

5.2 Possibilities beyond the current approach

The probabilistic approach of avalanche hazard assessment is enabling various products and applications, which are not possible with the current Swiss approach of avalanche hazard assessment. We highlight a few of these additional possibilities in terms of products and applications.

Intensity frequency curves at any location

Deriving continuous intensity frequency curves at any location in the affected area is not possible in the current Swiss approach, since it is only considering a limited number of avalanche release return periods. The probabilistic modelling approach allows to derive continuous intensity frequency curves as described in section 4 and shown in Fig. 9. These intensity frequency curves provide more differentiated and comprehensive information for characterizing the hazard. Such characterization consists of the probability of being affected by an avalanche and the different intensities at different return periods. This can be helpful in the design of protective structures for individual objects as it provides intensities for all return periods, analysed at a specific the location.

Intensity maps for any return period

The intensity maps derived from the probabilistic modelling approach (section 4.2 and Fig. 10) look similar to those being derived from the current Swiss hazard assessment approach (section 5.1 and Fig. 14). Intensity maps can be derived for any return period of interest when using the probabilistic modelling approach. Furthermore, the intensity maps derived from the probabilistic modelling approach provide information on the intensities at given return periods in the affected area and not the maximum of intensities for a limited number of return periods at release.

Probability maps of intensities

Probability maps (section 4.3 and Fig. 11) provide information on the probability, that a location is hit by an avalanche of any given intensity. Such maps cannot be produced with the current Swiss hazard assessment approach as they require information on all possible events and their probabilities at the location of impact. Probability maps can also be derived for the probabilities within a longer period of time than a year or a season, e.g. the probability within the average lifetime of a building of 50 years. The probabilities within 50 years highlight that return-periods of e.g. 100 or 300 years are not as unlikely as many people think.

Probability maps are very helpful for risk dialogue and for discussing the hazard with affected stakeholders. They therefore provide a major advantage compared to the current Swiss approach of avalanche hazard assessment.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

Use of selected single events

Single events from the probabilistic simulations can be used for emergency service training or as decision support in the case of strong snowfall events. In the latter case, events matching the snow accumulation of the current snow fall event can be selected. This allows emergency services and those being responsible for safety, to get information on potential impacts of avalanches with the fracture height of this given snow accumulation.

Continuous loss frequency curves

Probabilistic event sets together with object values and vulnerabilities, allow to calculate continuous loss frequency curves for individual objects as well as for groups of objects (section 4.4, Fig. 12), allowing to characterize the risks (Kleinn et al., 2022). Such risk assessments can serve as a basis for risk-based planning. The modelling results can therefore be used as a basis for risk-based decision making, support risk dialogue with stakeholders, and inform the planning of mitigation measures, such as spatial planning, building protection or structural avalanche protection. Measures can therefore be planned more effectively, as the protection can be defined in a more targeted manner.
Such risk assessments are comparable to those being used in climate adaptation studies with CLIMADA (Aznar-Siguan and Bresch, 2019), in probabilistic seismic hazard assessment (PSHA, e.g. Silva et al., 2020) or in the insurance and reinsurance industry. Such comprehensive risk assessment is not possible with the current approach of avalanche hazard assessment in Switzerland. The current approach therefore does not allow risk assessments for gravitational hazards comparable to the one provided in the Swiss earthquake risk model (Wiemer et al., 2023) or for other hazards.

Quantifying Uncertainties

A number of uncertainties exist in the entire modelling chain leading to the hazard and risk assessment, e.g. in the distribution of the snow accumulation or in the modelling friction parameters. The impact of uncertainties from several sources can be visualised in the final results of intensity frequency curves and loss frequency curves. The uncertainties of different friction parameters in the avalanche simulations have been shown in section 4.5 (Fig. 13) and the uncertainty from defining event probabilities versus event rates has been shown in Fig. 8. The uncertainties of the event probabilities or event rates could be visualised by changing these probabilities or rates and would not require additional event simulations.

Inclusion of Climate Change

Climate change should be considered in hazard and risk assessment, so that decisions on mitigation measures can be taken based on information of potential future hazards and risks. These requirements cannot be comprehensively met with the current Swiss approach of hazard assessment, as it is limited to selected return periods of snow accumulation. Recent studies on the climate change impact on avalanche hazard have either been limited to the current Swiss approach of hazard assessment (Ortner et al. 2025a and 2025b) or have been limited to selected aspects of the hazard assessment (Mayer et al., 2024). The probabilistic

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

approach allows a simple inclusion of potential changes by changing event probabilities or event rates, e.g. using snow accumulation information from climate scenarios. Such a simple inclusion of climate change does not require any new avalanche simulations, only an updated analysis of the simulated events with updated probabilities or rates. It therefore allows to include a larger number of climate scenarios to cover the entire range of possible climate impacts. Comprehensive climate change impact analyses can be performed with avalanche models, which take climate variables (e.g. air and snow temperature) into account. Such simulations together with updated probabilities or rates will provide a possibility to derive intensity frequency curves, intensity maps, probability maps, and loss frequency curves including the impact of climate change. They can provide information on changes in hazard at any given return period and can be used for risk assessment including climate change.

Comprehensive risk management compared to pure benefit-cost analyses

Since the introduction of the current approach of avalanche hazard assessment in Switzerland, the requirements to hazard and risk assessments of natural hazards have increased. The decision for mitigation measures should nowadays be taken in a risk-informed manner, which requires comprehensive risk assessments.

The probabilistic modelling approach allows a more comprehensive characterisation of the hazard by allowing the calculation of intensity frequency curves at any given location in the affected area. Furthermore, it allows to derive continuous loss frequency curves for single objects or entire municipalities, which allows to comprehensively characterize risks (Kleinn et al., 2022). The expected annual loss is one of the characteristics of risk, which can be derived from loss frequency curves, and which can be used for benefit-cost analyses.

The tool EconoMe (Bründl et al., 2009) was developed in Switzerland for public authorities. The aim of the tool is to provide comparable benefit-cost information for the decision-making for subsidies of planned measures throughout Switzerland, based on the current Swiss hazard assessment approach. These analyses are therefore based on the existing hazard maps, which are depicting the intensity (e.g. avalanche pressure) for a limited number of return periods only. The characteristics of the loss frequency curve between the limited number of return periods from the hazard maps can have a significant impact on the characteristics of risk, the expected annual loss, and on the benefit-cost analysis. Using continuous loss frequency curves can therefore help in finding the optimum measure (or combinations of measures) for managing risks.

Several assumptions are needed in EconoMe in order to use the existing hazard maps for an approximation of the expected annual loss for benefit-cost analyses: the loss associated with each of the intensity maps is assigned the return period of the release. To account for the fact, that the entire area in the hazard map cannot be affected by a single event, a correction factor (spatial probability of occurrence) has been introduced. In the probabilistic risk assessment, the return period of losses is calculated from the event losses and event probabilities or rates. This takes the spatial extent of the events as well as the number of affected objects into account in the loss calculation. The probabilistic hazard and risk modelling therefore enables a more comprehensive risk assessment compared to the current approach in Switzerland.

5.3 Distinction from previous probabilistic studies

The type of probabilistic modelling presented in this study goes beyond probabilistic sensitivity analyses, which are commonly used to quantify parameter uncertainties in the impact, e.g. Fischer et al., 2014. These studies usually do not assign a probability to each single event and therefore do not allow to compute continuous intensity frequency curves.

Probabilistic hazard and risk models have already been described by Straub and Grêt-Regamey (2006) and Grêt-Regamey and Straub (2006). While their approach focusses on the damage assessment of selected return periods of fracture depth, the probabilistic modelling approach presented in this study allows the calculation of complete intensity frequency curves at any location in the affected area. Furthermore, continuous loss frequency curves for single objects or groups of objects can be computed with the probabilistic approach presented in this study, taking the spatial correlation in damaging events into account in the risk assessment.

5.4 Areas of improvement

This study is a first attempt to implement the probabilistic hazard assessment approach for avalanches. Improvements in the modelling of avalanches as well as in the definition of event probabilities and event rates are likely to improve the results of such an approach of probabilistic hazard and risk assessment.

The definition of event probabilities or event rates (section 3.2) can have a large impact on the results of hazard and risk. Improvements in the definition of event probabilities and event rates are possible and apply to all components of the event probabilities and event rates. We have chosen to use the 3-day snow accumulation for defining fracture height, as this is common practice in Swiss avalanche hazard assessment. Better metrics for defining fracture height and its probabilities might be possible. The altitude correction of station data for estimating the 3-day snow accumulation in the potential release areas is currently set to a fixed value of 5 cm for 100 meters of altitude difference. An update to this altitude correction, maybe even including spatial variability in the Alps, would improve determining of the fracture depth. The probability of release given a certain snow accumulation is currently derived very simply based on Evin et al. (2021). Better estimates for theses probabilities are desirable and require further research. Historic data of 3-day snow accumulation combined with known avalanche releases might enable to provide a better estimation of the probability of release given a certain snow accumulation, possibly even differentiating spatially across the Alps. Lastly, the spatial component of the fracture probabilities is based on CAT (Harvey et al., 2024), which was originally derived from avalanches triggered by skiers. It is therefore rather valid for smaller to medium sized snow accumulations and not necessarily for the extremes. An updated approach for extreme snow accumulations would be desirable.

We have chosen a bin size of 3-day snow accumulation of 20 centimeters in our study. Further sensitivity analyses are needed, whether smaller bin sizes are favourable. Depending on the situation, other bin sizes, even unregular ones, can be used. The bins can also be chosen so that the return periods of 30, 100, and 300 years are included. This would enable the generation of hazard maps according to the current approach from the same set of simulations as is used in the probabilistic approach.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

Several of the potential improvements we were able to identify are related to the modelling of avalanches rather than to the approach of probabilistic hazard and risk assessment. Improvements in the avalanche models themselves can include the computational efficiency, the possibility to include climate parameters like temperature, erosion and deposition, etc. These improvements would be equally beneficial to the current approach of hazard assessment as they would be to the approach of probabilistic hazard assessment.

Sensitivity analyses all the way to the impact on hazard and risk can be performed with this probabilistic modelling approach. These sensitivity analyses can identify, which parameters, assumptions, and processes have the largest impact on the final hazard and risk assessment, and therefore which research and improvements would allow the largest improvement in the hazard and risk assessment output. As long as the sensitivity analyses are limited to changes in the probabilities of avalanche release or process, they can be performed without having to perform additional avalanche simulations.

A possible extension of the probabilistic approach is starting at the precipitation or snowfall field as an event definition and not at the avalanche release. In such a modelling strategy, a snowfall event could include several simulated avalanches. It would therefore enable to capture the spatial dimension of strong snowfall events and hence the spatial correlation of hazard and risks.

6 Conclusions

This study demonstrates that it is possible to apply the probabilistic modelling approach, which was originally developed in seismology, and which is common in other hazards and risk assessments, to snow avalanches. The study provides indications for its applicability to hazard and risk analyses of avalanches and other mass movements as well as research needs for further improvement. Several assumptions and simplifications have been made for this first probabilistic approach to avalanche hazard and risk assessment. These include the omission of wind drift in determining the fracture depth, or the concentration on cold slab avalanches. These assumptions and simplifications can be revised and improved in further studies.

The aim of this probabilistic modelling approach is to model the entire range of possible avalanche events and assign an event probability or an event rate to each of the simulated avalanches. The combination of the numerically simulated avalanches with their probabilities or rates allows to compute intensity frequency curves at any location in the affected area. These intensity frequency curves allow to characterize the hazard at any location. Although the probabilistic modelling approach requires more computational resources and more data storage compared to the current approach of hazard assessment in Switzerland, it provides more differentiated information on hazard and risk and is able to overcome some of the limitations of the current approach. A wide variety of products for a wide range of applications can be derived from the probabilistic modelling results.

The probabilistic modelling approach was conceived with the idea of enabling comprehensive risk assessments. Rather than moving from hazard (maps) to risk, we focused on what is required for comprehensive risk assessments and which information is needed for developing an optimum combination of measures drawn from various categories. We have also considered what

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

is commonly used today and ensured that products currently being generated can also be created using the probabilistic approach.

As the modelling approach is based on individual events, comprehensive risk analyses can be performed for individual objects or for groups of objects. By calculating the loss to each event, continuous loss frequency curves can be generated using the event losses and event probabilities or event rates. Loss-frequency-curves are an essential component for characterizing risk (Kleinn et al., 2022), for comprehensive risk management, and for risk-based decision making.

Hazard and risk analyses with changes in event probabilities, e.g. due to climate change, can be easily implemented in this modelling framework and do not require additional avalanche simulations. Comprehensive climate change analyses can be performed, if avalanche models are used, which include the most relevant climate parameters (most likely snow temperature). This will allow to conduct differentiated climate change analyses of avalanche hazard and risks.

For implementing the approach of probabilistic hazard assessment for avalanches, we were able to use existing data, models, and tools. The way these data, models, and tools were combined and used is new to mass movements though. The approach presented in this study is not tied to a specific avalanche model. Any avalanche model currently being available can be used for this modelling approach, if simulation results of individual events can be stored and combined with their respective probability or rate for the analyses of the probabilistic modelling results (as described in section 3.6).

Code availability

The code for deriving input data for the simulations as well as the code for the analyses will be made available after publication.

Author contribution

JK, DA, AP, and NH designed the study. JK performed the simulations and analyses. YB and JG provided support in setting up the simulations. JK and DA wrote the manuscript draft. YB, JG, AP, and NH reviewed and edited the manuscript.

Acknowledgements

The research to this study is the result of a joint pilot project of the Foundation for Prevention of the Public Insurance Companies for Real Estate (FPPIRE), the office for forests and natural hazards of the Canton of Berne, geo7, Aller Risk Management and the WSL Institute for Snow and Avalanche Research SLF. The authors would like to acknowledge the financial support of the Foundation for Prevention of the Public Insurance Companies for Real Estate (FPPIRE) and the Canton of Berne for this project, as well as the financial support of the Canton of Grisons for the Climate Change, Extremes and Natural Hazards in Alpine Regions Research Centre CERC at the WSL Institute for Snow and Avalanche Research SLF.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

The authors would like to thank all members of the pilot project team, namely Catherine Berger, Michael Rinderer, and Ursin Caduff from geo7, as well as Martin Jordi and Corinne Singeisen from the Foundation for Prevention of the Public Insurance Companies for Real Estate (FPPIRE).

We are grateful for the support provided by the development team of RAMMS AG, namely Marc Christen and Perry Bartelt, for implementing adjustments to the RAMMS model needed for this study.

Many thanks to Michael Bründl, Stefan Margreth, Matthias Spieler, and Pia Echtler, for their comments and feedback to an earlier version of the manuscript.

References

Argue, C., D. Gauthier, P. LeSueur, D., Rohn, S. Zubrycky. 50 Shades of Blue: Risk Gradients Within Avalanche Hazard Zones. Proceedings of the 2024 International Snow Science Workshop, Tromso, Norway. pp. 853 – 859, 2024.

Aznar-Siguan, G. and Bresch, D. N., CLIMADA v1: a global weather and climate risk assessment platform, Geosci. Model Dev., 12, 3085–3097, https://doi.org/10.5194/gmd-12-3085-2019, 2019.

Bates, P. D., Savage, J., Wing, O., Quinn, N., Sampson, C., Neal, J., and Smith, A.: A climate-conditioned catastrophe risk model for UK flooding, Nat. Hazards Earth Syst. Sci., 23, 891–908, https://doi.org/10.5194/nhess-23-891-2023, 2023.

Bloemendaal, N., Haigh, I.D., de Moel, H. et al. Generation of a global synthetic tropical cyclone hazard dataset using STORM. Sci Data 7, 40, https://doi.org/10.1038/s41597-020-0381-2, 2020

Borter, P., Risikoanalyse bei gravitativen Naturgefahren, Umwelt-Materialien Nr. 107/I, Naturgefahren, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, 115 p, 1999.

Bründl, M., Romang, H. E., Bischof, N., and Rheinberger, C. M.: The risk concept and its application in natural hazard risk management in Switzerland, Nat. Hazards Earth Syst. Sci., 9, 801–813, https://doi.org/10.5194/nhess-9-801-2009, 2009.

Bründl, M., Hafner, E., Bebi, P., Bühler, Y., Margreth, S., Marty, C., Schaer, M., Stoffel, L., Techel, F., Winkler, K., Zweifel, B., and Schweizer, J.: Ereignisanalyse Lawinensituation im Januar 2018. WSL Bericht, 76. 162 S., 2019.

Bühler, Y., Kumar, S., Veitinger, J., Christen, M., and Stoffel, A.: Automated identification of potential snow avalanche release areas based on digital elevation models, Natural Hazards and Earth System Sciences, 13, 1321–1335, https://doi.org/10.5194/nhess-13-1321-2013, 2013.

Bühler, Y., von Rickenbach, D., Stoffel, A., Margreth, S., Stoffel, L., and Christen, M.: Automated snow avalanche release area delineation – validation of existing algorithms and proposition of a new object-based approach for large-scale hazard indication mapping, Nat. Hazards Earth Syst. Sci., 18, 3235–3251, https://doi.org/10.5194/nhess-18-3235-2018, 2018.

Bühler, Y., Hafner, E. D., Zweifel, B., Zesiger, M., and Heisig, H.: Where are the avalanches? Rapid SPOT6 satellite data acquisition to map an extreme avalanche period over the Swiss Alps, The Cryosphere, 13, 3225–3238, https://doi.org/10.5194/tc-13-3225-2019, 2019.

https://doi.org/10.5194/egusphere-2026-3799
Preprint. Discussion started: 12 August 2026

Bühler, Y., Bebi, P., Christen, M., Margreth, S., Stoffel, L., Stoffel, A., Marty, C., Schmucki, G., Caviezel, A., Kühne, R., Wohlwend, S., and Bartelt, P.: Automated avalanche hazard indication mapping on a statewide scale, Nat. Hazards Earth Syst. Sci., 22, 1825–1843, https://doi.org/10.5194/nhess-22-1825-2022, 2022.

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

Cornell, C.A., Engineering seismic risk analysis, Bulletin of the Seismological Society of America 58 (5): 1583–1606, https://doi.org/10.1785/BSSA0580051583, 1968.

Emanuel, K., Ravela, S., Vivant, E., and Risi, C., A Statistical-Deterministic Approach to Hurricane Risk Assessment. Bull. Amer. Meteor. Soc., 87, 299–314, https://doi.org/10.1175/BAMS-87-3-299, 2006.

Evin, G., Dkengne Sielenou, P., Eckert, N., Naveau, P., Hagenmuller, P., Morin, S., Extreme avalanche cycles: Return levels and probability distributions depending on snow and meteorological conditions, Weather and Climate Extremes, Vol. 33, 100344, ISSN 2212-0947, https://doi.org/10.1016/j.wace.2021.100344, 2021.

Federal Office of Forestry and Swiss Federal Institute for Snow and Avalanche Research, Richtlinien zur Berücksichtigung der Lawinengefahr bei raumwirksamen Tätigkeiten, 1984.

Federal Office for the Environment, Guidelines on risk assessment for gravitational natural hazards, in accordance with the Ordinances on Hydraulic Engineering and Forestry, Vollzugshilfe Gefahrenbeurteilung bei gravitativen Naturgefahren nach Wasserbau- und Waldverordnung, 2025.

Fischer, J.-T., Fromm, R, Gauer, P., Sovilla, B., Evaluation of probabilistic snow avalanche simulation ensembles with Doppler radar observations, Cold Regions Science and Technology, Vol. 97, 151-158, https://doi.org/10.1016/j.coldregions.2013.09.011, 2014.

Gaume, J., van Herwijnen, A., Gast, T., Teran, J., and Jiang, C.: Investigating the release and flow of snow avalanches at the slope-scale using a unified model based on the material point method, Cold Regions Science and Technology, 168, https://doi.org/10.1016/j.coldregions.2019.102847, 2019.

Gerstenberger, M. C., Marzocchi, W., Allen, T., Pagani, M., Adams, J., Danciu, L., et al., Probabilistic seismic hazard analysis at regional and national scales: State of the art and future challenges, Reviews of Geophysics, 58, e2019RG000653, https://doi.org/10.1029/2019RG000653, 2020.

Glaus, J., Kleinn, J., Stoffel, L., Ruttner, P., Wikstrom Jones, K., Gaume, J., and Bühler, Y.: Probabilistic avalanche runout modelling for daily risk management of traffic routes, EGUsphere, 2026, 1–29, https://doi.org/10.5194/egusphere-2026-999, 2026.

Grêt-Regamey, A., Straub, D., 2006. Accommodating uncertainties in avalanche risk assessment by linking Bayesian networks to a GIS. Natural Hazards and Earth System Sciences, Nat. Hazards Earth Syst. Sci., 6, 911–926, https://doi.org/10.5194/nhess-6-911-2006, 2006.

Hall, T.M., and S. Jewson, Statistical modeling of North Atlantic tropical cyclone tracks, Tellus A, 59A, 486-498, https://doi.org/10.1111/j.1600-0870.2007.00240.x, 2007.

Hall, T.M., J.P. Kossin, T. Thompson, and J. McMahon, US tropical cyclone activity in the 2030s based on projected changes in tropical sea-surface temperature, J. Climate, 34, no. 4, 1321-1335, http://dx.doi.org/10.1175/JCLI-D-20-0342.1, 2021.

Harvey, S., Schmudlach, G., Bühler, Y., Dürr, L., Stoffel, A., and Christen, C.: Avalanche terrain maps for backcountry skiing in Switzerland, International Snow Science Workshop ISSW, Innsbruck, Austria, 2018.

Harvey, S., Christen, M., Bühler, Y., Hänni, C., Boos, N., & Bernegger, B., Refined Swiss avalanche terrain mapping CATv$_2$ / ATHv$_2$. In K. Gisnås, P. Gauer, H. Dahle, M. Eckerstorfer, A. Mannberg, & K. Müller (Eds.), Proceedings of the international Snow Science Workshop 2024 (pp. 1637-1644), Norwegian Geotechnical Institute, 2024.

Heinimann, H. R., Hollenstein, K., Kienholz, H., Krummenacher, B., Mani, P., Methoden zur Analyse und Bewertung von Naturgefahren. Umwelt-Materialien Nr. 85, Naturgefahren, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, 248 p, 1998.

Kagan, Y. Y., Seismic moment distribution revisited: I. Statistical results. Geophysical Journal International, 148, 520–541. https://doi.org/10.1046/j.1365-246x.2002.01594.x, 2002.

Kleinn, J., Aller, D., and Oplatka, M.: Characteristics of Risk, in: Collins, J.M., Done, J.M. (eds) Hurricane Risk in a Changing Climate. Hurricane Risk, vol 2. Springer, Cham, https://doi.org/10.1007/978-3-031-08568-0_2, 2022.

Lee, C.-Y., Camargo, S. J., Sobel, A. H., and, Tippett, M. K., Statistical-dynamical downscaling projections of tropical cyclone activity in a warming climate: Two diverging genesis scenarios. J. Climate, 33, 4815–4834, https://doi.org/10.1175/JCLI-D-19-0452.1, 2020.

Mayer, S., Hendrick, M., Michel, A., Richter, B., Schweizer, J., Wernli, H., and van Herwijnen, A.: Impact of climate change on snow avalanche activity in the Swiss Alps, The Cryosphere, 18, 5495–5517, https://doi.org/10.5194/tc-18-5495-2024, 2024.

Mergili, M., Fischer, J.-T., Krenn, J., and Pudasaini, S. P.: 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, 2017.

Ortner, G., Michel, A., Kropf, C.M., Bründl, M., and Bresch, D. N.: Assessing the impacts of climate change on snow avalanche-induced risk in alpine regions. Nat Hazards 121, 10877–10904. https://doi.org/10.1007/s11069-025-07229-9, 2025.

Ortner, G., Michel, A., Spieler, M. B. A., Christen, M., Bühler, Y., Bründl, M., and Bresch, D. N., A novel approach for bridging the gap between climate change scenarios and avalanche hazard indication mapping, Cold Regions Science and Technology, Vol. 230, 104355, https://doi.org/10.1016/j.coldregions.2024.104355, 2025.

PLANAT, 2004. Sicherheit vor Naturgefahren-Vision und Strategie. Report 7/2004, National Platform for Natural Hazards (PLANAT), Switzerland. www.planat.ch. Available online.

Rudolf-Miklau, F., Sauermoser, S., and Mears, A.: The Technical Avalanche Protection Handbook, Wiley-VCH, Berlin, Germany, 430 pp., 2014.

Salm, B., Burkard A., and Gubler H.U. Berechnung von Fliesslawinen. Eine Anleitung für den Praktiker. Mit Beispielen. Mitteilungen Eidg. Institut für Schnee- und Lawinenforschung, Nr. 47, 1990.

Schröer, K., Trefalt, S., Hering, A., Germann, U., Schwierz, C., Hagelklima Schweiz: Daten, Ergebnisse und Dokumentation Fachbericht MeteoSchweiz, 283, 1-82, http://dx.doi.org/10.18751/PMCH/TR/283.HagelklimaSchweiz/1.0, 2022.

Silva, V., Amo-Oduro, D., Calderon, A., et al.: Development of a global seismic risk model, Earthquake Spectra, 36 (1_suppl): 372-394. https://doi.org/10.1177/8755293019899953, 2015.

Sørensen, M. B., Behrens, J., Jalayer, F., Løvholt, F., Lorito, S., Rafliana, I., Salgado-Gálvez, M. A., Selva, J. (eds.): Probabilistic Tsunami Hazard and Risk Analysis, Springer, Cham, https://doi.org/10.1007/978-3-031-98115-9, 2026.

Straub, D. and Grêt-Regamey, A.: A Bayesian probabilistic framework for avalanche modeling based on observations, Cold Regions Science and Technology, 46, 192–203. doi:10.1016/j.coldregions.2006.08.024, 2006.

Rickenmann, D., and Zimmermann, M. The 1987 debris flows in Switzerland: Documentation and analysis. Geomorphology, 8(2–3), 175–189. https://doi.org/10.1016/0169-555X(93)90036-2, 1993.

Swiss Federal Act on Forests, Bundesgesetz über den Wald, https://www.fedlex.admin.ch/eli/oc/2025/403/de, 2025.

Swiss Federal Act on Hydraulic Engineering, Bundesgesetz über den Wasserbau, https://www.fedlex.admin.ch/eli/oc/2025/430/de, 2025.

Tonnel, M., Wirbel, A., Oesterle, F., and Fischer, J.-T.: AvaFrame com1DFA (v1.3): a thickness-integrated computational avalanche module – theory, numerics, and testing, Geoscientific Model Development, 16, 7013–7035, https://doi.org/10.5194/gmd-16-7013-2023, 2023.

Wiemer S., P. Bazzurro, P. Bergamo, C. Cauzzi, I. Dallo, L. Danciu, B. Duvernay, E. Fagà, D. Fäh, C. Hammer, F. Haslinger, P. Kästli, A. Khodaverdian, P. Lestuzzi, M. Marti, Ö. Odabaşı, F. Panzera, A. Papadopoulos, V. Perron, P. Roth, N. Schmid, N. Valenzuela, and S. Zaugg, Earthquake Risk Model of Switzerland, ERM-CH23. https://doi.org/10.12686/a20, 2023

Wirbel, A., Oesterle, F., Chambon, G., Faug, T., Gaume, J., Glaus, J., Hergarten, S., Issler, D., Ito, Y., Martini, M., Mergili, M., Rauter, M., Robl, J., Rosatti, G., Tsunematsu, K., Tollinger, C., Vicari, H., Zugliani, D., and Fischer, J.-T.: ISeeSnow v1.0 – a pilot study for snow avalanche model intercomparison of thickness-integrated shallow flow approaches and beyond, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-6053, 2026.

WSL Institute for Snow and Avalanche Research SLF, Fatal avalanche accidents in Switzerland since 1936/37. EnviDat. https://www.doi.org/10.16904/envidat.412, 2023.