

A PROBABILITY-BASED MODELLING APPROACH BEYOND A FEW SELECTED RETURN PERIODS FOR COMPREHENSIVE AND ROBUST HAZARD AND RISK ASSESSMENT

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ABSTRACT: We present an innovative modelling approach, which allows to derive probability-based hazard information at any location in avalanche-prone areas. Such an event-based modelling approach allows for comprehensive risk assessments as it provides continuous intensity-frequency-curves at any location and allows to calculate continuous loss-frequency-curves for individual objects as well as for groups of objects.

We simulate numerous possible avalanches, covering the entire range of release volumes, from small to very large. The probabilities of the different avalanche events are based on the exceedance probabilities of different snow accumulation heights, represented by the three-day snow accumulation, the key information currently used for the generation of hazard maps in Switzerland. The combined evaluation of avalanche intensities and probabilities in the area of impact allows to derive continuous intensity-frequency-curves at any given location. This approach contrasts with the current practice in Switzerland of assigning the return period of a single snow accumulation to all possible avalanche outcomes of this snow accumulation. In combination with exposed values and their vulnerability functions, this modelling approach allows to derive continuous loss-frequency-curves for comprehensive risk assessment and risk management.

We present the simulation results of this novel approach from a case study in the Bernese Highland in the Swiss Alps. The case study results highlight the advantages of this new modelling approach in hazard and risk assessment. We show that climate change can be included in this modelling approach and that uncertainties can be quantified.

KEYWORDS: Hazard modelling, risk modelling, probabilistic modelling, avalanche hazard, avalanche risk, loss-frequency-curves.

1. INTRODUCTION

We apply a modelling approach to avalanches, which is common in other natural hazards and in risk modelling applications. This modelling approach aims at providing information on intensity and return period at any given location in the affected area. The modelling approach is comparable to the one, which is commonly used for seismic hazard assessment (e.g. Silva et al., 2020 or Gerstenberger et al. 2020). The basic approach was already published much earlier by Cornell (1968). Since then, similar approaches have been applied 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), and for more localized hazards like hail (Schröer et al., 2022). It is also used in the global insurance and reinsurance industry for numerous hazards and for climate adaptation studies (Aznar-Siguan and Bresch, 2019).

The results of our modelling approach allow to conduct comprehensive risk assessments and provide a basis for decision makers and for risk management. The aim is to derive probabilities of hazard intensities, i.e. intensity-frequency-curves of avalanche pressure and height, for any location in space. This type of probabilistic modelling goes beyond sensitivity analyses.

This study is presenting the results of this first attempt of applying this approach to avalanches and providing indications for its applicability and further needs for research.

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2. PILOT STUDY REGION

The modelling approach is implemented and tested in a single couloir near Adelboden in the Canton of Berne. The release areas of this pilot study are located at about 2'500 meters of altitude, the runout is at about 1'400 meters.

3. MODELLING APPROACH

3.1 *Modelling Concept*

The modelling approach applied here consists of five parts, which are described in the following sections:

- the definition of avalanche fracture depths together with their probabilities or annual rates, for which avalanches are simulated,
- deriving potential release areas for each of the fracture depths,
- defining avalanche event rates,
- the modelling of each avalanche according to the above fracture depths and potential release areas, and
- the combination of all simulated avalanche events in a probabilistic manner for deriving hazard information.

Our modelling approach is principally independent of the model used for simulating each avalanche. It can be applied to simulations with any avalanche model which is able to store each simulated avalanche event for further analyses and allows to link the event rate to the simulation output.

3.2 *Definition of avalanche fracture depths*

The three-day snow accumulation is a key input to avalanche modelling. The probability distribution of the three-day snow accumulation is usually based on extreme value analyses of historic daily snow height data, commonly adjusted by local experts based on their expert judgement. For our study, we use a probability distribution of three-day snow accumulation which is based on the fit of a generalized extreme value distribution (GEV) to data of a station nearby and adjusted to the altitude of the potential release area (figure 1). This distribution is a reasonable fit to the values of snow accumulation and return period suggested by the experts from the Office for Forests and Natural Hazards of the Canton of Berne.

The probability distribution of three-day snow accumulation allows us to define snow accumulation bins with their respective probabilities (figure 2). The probabilities are taken from the difference of the exceedance probabilities of the bin borders taken from the exceedance probability distribu-

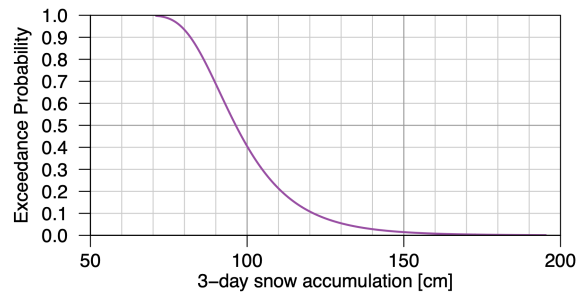


Figure 1: Probability distribution of 3-day snow accumulation used for this study depicted by exceedance probabilities (data: SLF).

tion. We use bins of 20 cm of three-day snow accumulation in this study. We assume the mean snow accumulation of each bin to be representative for this bin and use this snow accumulation for the consecutive avalanche simulations. A total of ten snow accumulations ranging from 90 cm to 270 cm were defined. The probabilities of the bins with 170 cm of snow accumulation and more are lower than 1 percent, with 210 cm of snow accumulation and more are lower than 1 permille.

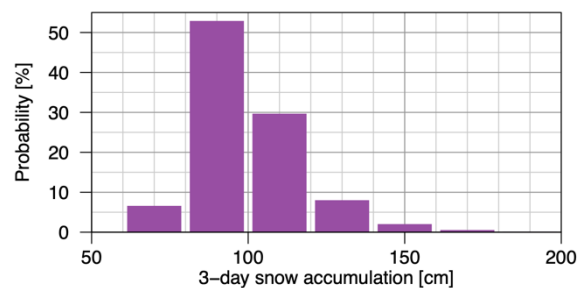


Figure 2: Bins of 3-day snow accumulation used for this study with their respective probabilities (data: SLF).

Snow drift is not included in the probabilistic definition of avalanche fracture depths in this study. This study aims at demonstrating the modelling approach in general. Further refinements can be included at a later stage.

3.3 *Potential release areas*

For each snow accumulation, multiple potential release areas were generated using the algorithm by Bühler et al. (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.

3.4 *Definition of avalanche event rates*

We assume the probabilities of snow accumulation to be interpreted as the probability that (at least) one of the potential release areas produces an avalanche. For defining avalanche event probabilities, we therefore divide the probability of

each snow accumulation bin with the number of potential release areas for this snow accumulation. We end up with avalanche event probabilities ranging from about 10^{-6} to 0.0027. We use these probabilities as yearly event rates in the analysis of the avalanches for deriving hazard information.

In this rate definition, the number of potential release areas has an impact on the event rates. Sensitivity analyses exploring this impact are presented in the discussion (section 5.3).

3.5 *Avalanche modelling*

653 Avalanches were simulated using RAMMS::EXTENDED (Glaus et al. 2024). Being able to access the output of each simulated avalanche event is required for the consecutive analyses of the simulations. Each event for the consecutive analyses needs to be a single event, which is in itself physically consistent, and which could happen this way. An output based on the combination of multiple events, as is frequently provided, is not usable for our modelling approach.

3.6 *Analyses of avalanche simulations*

We have 653 avalanche simulations with their respective rates available for the hazard analyses. The output of the simulations includes avalanche pressure and avalanche height. Using these intensity metrics, we can calculate continuous intensity-frequency-curves at any location in the runout zone. For calculating an intensity-frequency-curve, the events in the grid cell are first sorted by decreasing intensity. The event rates are then used to calculate the exceedance frequency of each event. We assume the events to be Poisson distributed and calculate the exceedance probability using the cumulative product of probabilities of no event.

Besides performing such analyses on grid cells, they can also be performed for potentially affected objects.

4. RESULTS

4.1 *Intensity maps for given return periods*

Using the approach described above, the avalanche pressure and the avalanche height can be calculated for any return period at any location in space. Figures 3 and 5 show the avalanche pressure and avalanche height for return periods of 30, 100, and 300 years. Maps of intensity for any other return period (e.g. 10, 50, or 1'000 years) can be generated.

As expected, the avalanche pressure and avalanche height are increasing with increasing return period. Both have their highest values in the center of the couloir with lower values at the edges.

Single avalanches can be extracted and mapped from the event set. This can help understand the type of events having led to specific impacts. The approach allows to extract all events leading to intensities of a certain range at a given location, e.g. those potentially causing severe damage.

4.2 *Intensity-frequency-curves*

In addition to a spatial representation of the results, continuous intensity-frequency-curves can be produced for any location in space. Such intensity-frequency-curves are shown in figures 4 and 6 for the three color-coded points in figures 3 and 5 for avalanche pressure (figure 4) and avalanche height (figure 6).

The intensity-frequency-curves reveal the different characteristics of the hazard at the different locations. The three points are affected at different return periods and the increase of intensity with increasing return period is very different. While the avalanche pressure is lower for the purple location compared to the blue location up to return periods of about 750 years, it is the inverse for higher return periods.

4.3 *Loss-frequency-curves*

For risk analyses of single objects, the intensity frequency curves can be combined with the values and vulnerabilities of the objects to derive loss frequency curves, which are an essential component for characterizing risk (Kleinn et al., 2022). Event based simulations are essential for risk analyses of a group of objects. The sum of the losses can be calculated for each of the events for deriving the loss frequency curve for the group of objects. For illustration, different values have been assigned to the three locations depicted in figures 3 and 5. The same vulnerability function has been applied to the three locations to derive loss frequency curves for each of the objects (figure 7). For the loss-frequency-curve of all objects together, the losses have to be summed up for each event before sorting the events by their total loss and deriving the loss-frequency-curve.

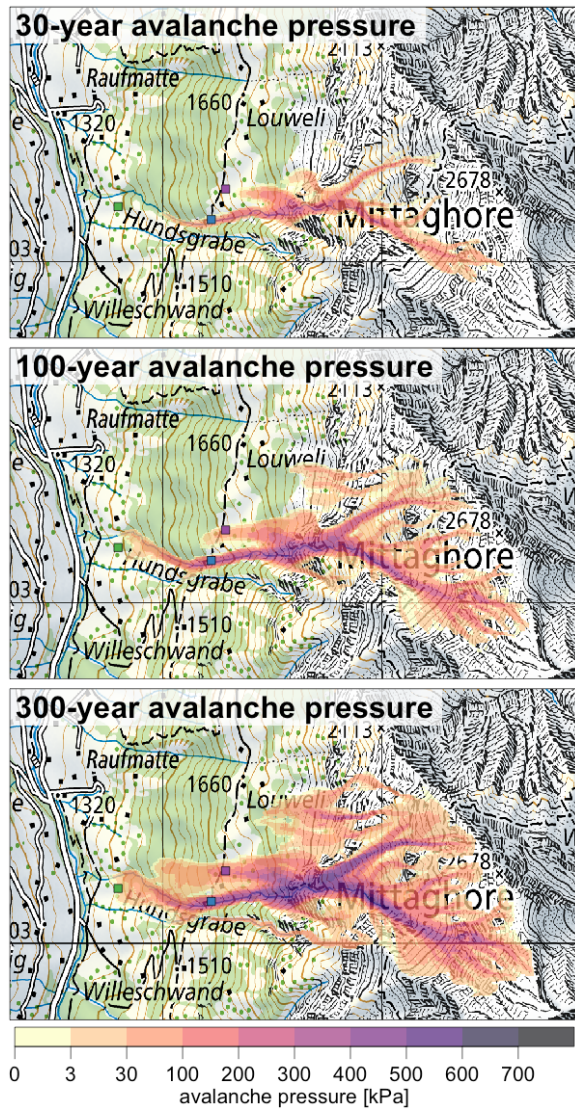


Figure 3: 30-, 100-, and 300-year avalanche pressure derived from 653 avalanche simulations and their respective event rates. Background map source: Swiss Federal Office of Topography.

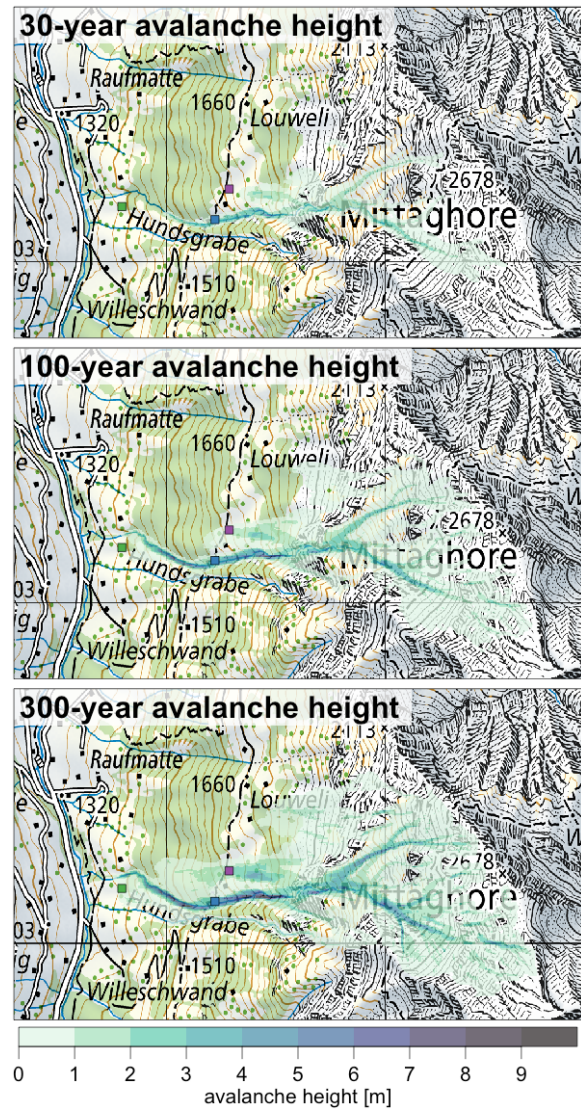


Figure 5: 30-, 100-, and 300-year avalanche height derived from 653 avalanche simulations and their respective event rates. Background map source: Swiss Federal Office of Topography.

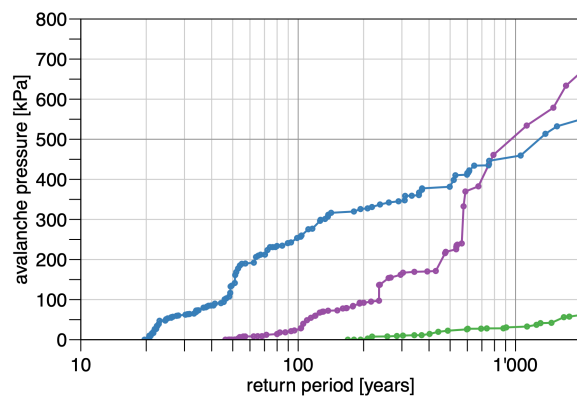


Figure 4: Intensity-frequency-curve for avalanche pressure for three different locations in the runout zone. The color-coding corresponds to the color-coded points in figure 3.

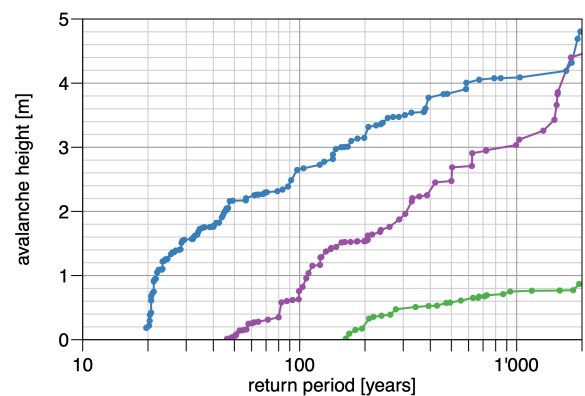


Figure 6: Intensity-frequency-curve for avalanche height for three different locations in the runout zone. The color-coding corresponds to the color-coded points in figure 4.

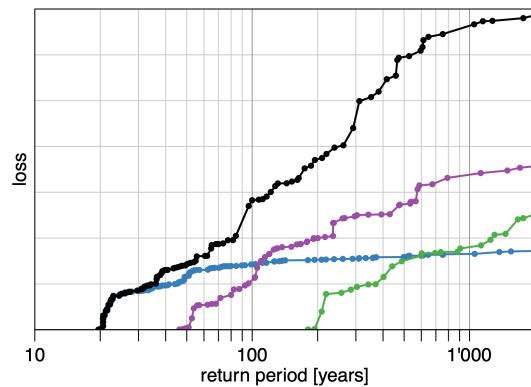


Figure 7: Loss frequency curves for objects at three locations and for their total (black). The color-coding corresponds to the color-coded points in figure 3.

5. DISCUSSION

5.1 Advantages and applications

The modelling approach presented in this study has the great advantage that it allows the creation of continuous intensity-frequency-curves at any given point. Furthermore, the modelling approach allows to calculate loss frequency curves for individual objects as well as for groups of objects.

This modelling approach can serve as a basis for hazard mapping at municipal or regional level, and for conducting comprehensive risk assessments. Furthermore, it can serve as a basis for compiling specific products for the planning of mitigation measures, such as spatial planning, building protection or structural avalanche protection.

5.2 Sensitivity analyses

Sensitivity analyses all the way to the impact on hazard and risk can be performed with this modelling approach. As long as the changes in input are limited to changes in the probabilities of avalanche release, the sensitivity analyses can be performed without having to perform additional avalanche simulations. This includes climate change analyses based on changes in the fracture depth distribution. Further sensitivity analyses, like the influence of changes in snow temperature, require additional avalanche simulations.

5.3 Event rates

The definition of event rates is an important part in the modelling approach. In our first attempt, we divide the rate attributed to a snow accumulation amount (and hence fracture depth) by the number of release polygons defined for this snow accumulation amount for defining event rates (bottom

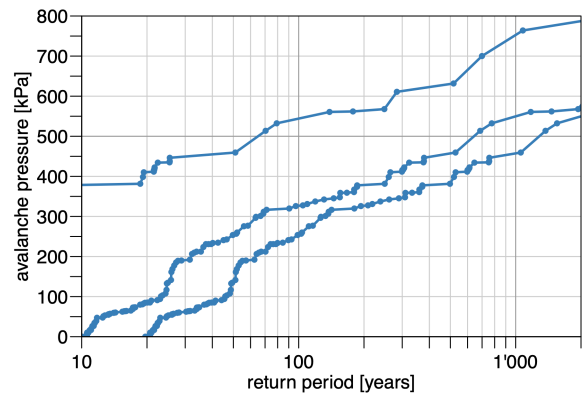


Figure 8: Intensity-frequency-curves using three different assumptions of event rates.

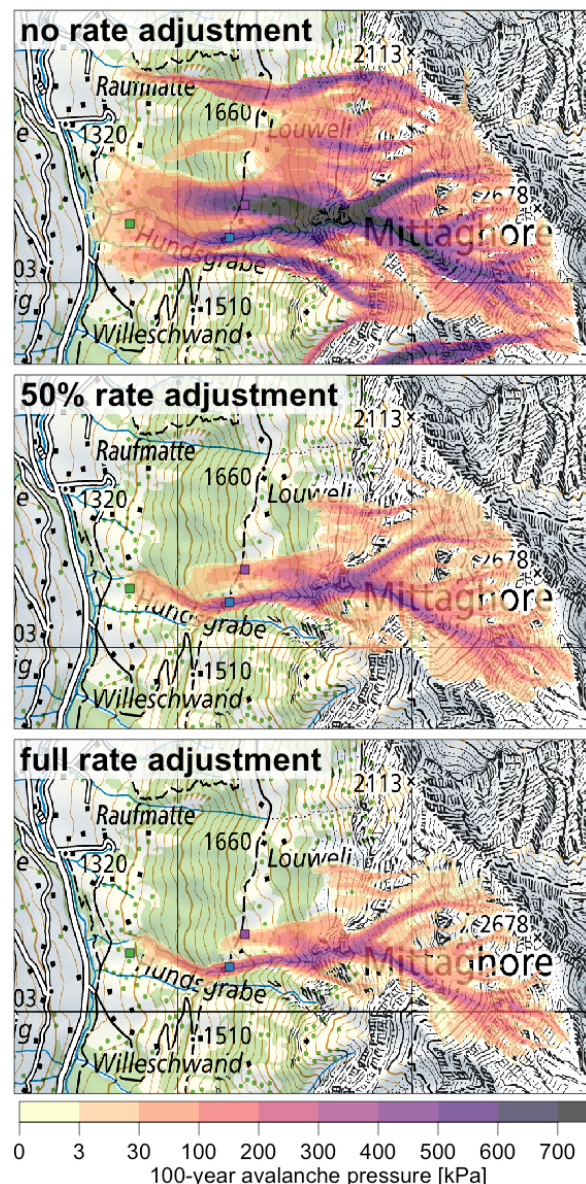


Figure 9: 100-year avalanche pressure for no rate adjustment (top), 50% rate adjustment (middle) and full rate adjustment (bottom) using the number of potential release polygons per snow accumulation for the rate adjustment.

line in figure 8 and as described in section 3.4). Using the snow accumulation probability for all release polygons of the respective snow accumulation instead of dividing the probability by the number of polygons results in a much higher intensity-frequency-curve (top line in figure 8). A partial adjustment of the event rates with half of the number of release polygons results in an intensity-frequency-curve much closer to the full adjustment than to no adjustment (figure 8). The event rates show a strong influence on the intensity-frequency-curves (figure 8) and on the intensities in space (figure 9).

The avalanche simulations and hence pressure values are the same for all three intensity-frequency-curves in figures 8 and 9. The different curves in figure 8 and the different 100-year intensities in figure 9 arise from the differences in the rate assumptions.

5.4 *Uncertainties*

The modelling approach also allows to quantify uncertainties. The uncertainty of the probabilities is the easiest to quantify as it only requires a resampling of the data and does not require additional avalanche simulations. Figure 10 shows an illustration of such a resampling for the intensity-frequency-curves of the three locations in the study area.

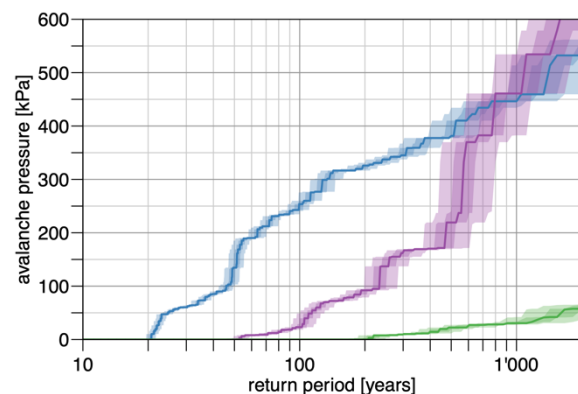


Figure 10: Sensitivity analysis of the intensity-frequency-curves at three different locations generated by resampling from the original intensity-frequency-curves.

6. CONCLUSIONS

This study has shown that it is possible to apply the modelling approach, which is common in other hazards and risk assessments, to avalanches. Although it requires more computational resources and more storage, this modelling approach makes it possible to generate products for a wide range of applications.

This modelling approach is not tied to a specific avalanche model. Other avalanche models can

be used for this modelling approach, as long as simulation results of individual events can be used for the analyses of this modelling approach (as described in section 3.6).

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 constructed using the event losses and event rates. Loss-frequency-curves are an essential component for characterizing risk (Kleinn et al., 2022) and for comprehensive risk management.

Comprehensive climate change analyses can be performed as long as avalanche models are used, which include the most relevant climate parameters (most likely snow accumulation distribution and temperature). This will allow to conduct differentiated climate change analyses of avalanche hazard and risks.

The definition of event rates (section 5.3) has a large impact on the hazard results. An improved definition of event rates is therefore desirable. Initial ideas for an inclusion of differentiated event rates within each snow accumulation height have already been discussed in the project team. The results show that a partial adjustment is much closer to the initial full adjustment than to no adjustment at all.

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