Probabilistic modelling for avalanche hazard and risk assessment

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Overview

This manuscript describes a case study application of probabilistic modelling to snow avalanche hazard for a test site in Switzerland. The modelling approach is established in other natural hazard fields and in the realm of insurance. It introduces a useful way to estimate avalanche hazard and risk by producing a large number of simulations and combining them into continuous map output. The main emphasis is on describing the methods for determining relevant probabilities, with intensity frequency and loss frequency curves and maps as the main output. A conceptual comparison to traditional avalanche hazard mapping is described, and a more detailed comparison to large scale automated avalanche hazard mapping is presented. The analysis uses weather station data paired with existing potential avalanche release area mapping and RAMMS simulations to characterize the hazard across many simulated conditions.

Overall the paper makes a novel contribution to avalanche hazard mapping and risk assessment. The methods are well established in adjacent fields, and the manuscript shows that they can be assembled for avalanches with tools already used in Switzerland. I found the intensity frequency curves, probability maps (Fig. 11), and the comparison in Fig. 15 especially helpful for seeing what the approach can add.

The manuscript currently reads as a mix of a feasibility study and a sales pitch for probabilistic modelling. The writing is quite repetitive, and the claims about the value of the method are stated often and too generally. The case study is interesting on its own. I would tone down the general claims about the value of the method, shorten the manuscript, and focus more on what this specific application shows, including where the results are still limited.

The claims about how this method relates to manual avalanche hazard mapping are not well supported by the present study. I would emphasize this as a novel way to synthesize and interpret large scale automated mapping. In this initial exploratory example, presenting the method as a means to replace or offset expert based hazard mapping goes beyond the results.

The authors already note that expert judgement is not included and that the approach is not meant to replace legally binding hazard maps. That more careful framing should also guide the abstract and the discussion. Future refinements of the method, and actual validation of the output against automated and manual hazard maps, would be needed before making larger claims about the method's value.

I recommend another review after a major revision to the writing and a narrowing of the main results to focus on claims that are well founded in the present study.

Detailed Comments

1. Intro

* Line 28 - It might be worth adding a little more detail about the guidelines for differentiating runout area probabilities versus release area probabilities. These two probabilities are directly tied, and to a reader unfamiliar with FOEN, 2025, calculating them separately seems confusing.
* Line 32 - This reads as if the extreme case of a 1000 yr return period is recommended by the Swiss Federal Office of the Environment but is not part of the standard practice.
* Line 36 - What does "most relevant possible avalanches" mean in this context? Does expert judgement decide how to interpret the statistical estimate of 3-day snow accumulation, or is it focused on release area size and location, friction, snow characteristics, etc.? A little more detail on the current standard practice would be useful beyond "expert judgement."
* Lines 41-42 - "neglecting the different probabilities in space." Can you clarify what this statement means? I think you are making the case that a probabilistic approach adds value beyond existing methods. The current method is not trying to produce a probabilistic output though. My understanding is that the goal of the existing method is to estimate destructive potential for given return periods so that infrastructure can be regulated in hazard areas. It is a design criterion for construction and planning more than a probability of being hit. The probabilistic products are still useful, but the contrast with current practice would be clearer if this distinction is stated more carefully.
* Line 45 - This is a good pivot from "the method works well" to "here is how it can be improved." This lands much more intuitively than the last sentence of the prior paragraph.
* Line 46 - Is there data about buildings or roadways being hit or damaged that you could also reference? Fatalities have a small sample size in recent decades, so some additional impact data could help paint a bigger picture of how common avalanche incidents with infrastructure still are.
* Figure 1 - Do you have any explanation for why the number of fatalities dropped dramatically after ~2000? There are still quite a few fatalities from the 50s/60s to the 90s, after hazard maps became standard practice.
* Lines 50-52 - This short paragraph seems out of place. It would be more intuitive to put the

paragraph defining integrated risk management first, then make the point that it allows integration of stakeholder concerns.
* Line 90 - The term “more differentiated” is used several times within a few paragraphs and it is not clear exactly what that means. “Wide range of advantages” and “additional products” are also fairly general. A more specific and concise summary of the advantages of probabilistic event based modelling would strengthen the argument here.
* Lines 96-97 - This feels tacked on and could be better integrated into the study setup and problem statement.

2. Study Region

* Line 104 - 20 km is quite far given the variability of mountain snowpack and local orographic effects on snowfall. Is this uncertainty in snowfall estimates accounted for in the probabilistic modelling approach?
* Line 108 - The statement that the exact station is of “minor relevance” downplays an important source of uncertainty. Part of showing feasibility is showing that available data can still give a meaningful representation of the hazard. A long period of record makes sense, but if the snowfall climate at the station is not representative of the test site, that should be treated as a limitation of this first application rather than as a minor detail.
* Figure 2 - It would be useful to more clearly outline and label the panels. Including the location of the weather station would also help.

3. Modelling approach

* Line 131 - “avalanche takes a certain course.” I’m not sure exactly what this means. Are you saying that if an avalanche releases, what is the probability of flowing in different tracks? Since avalanches typically follow the same track for a given start zone, it might be more accurate to say something like “probability of an avalanche reaching a certain distance along the track.”
* Figure 4 - I am not very familiar with extreme value statistics. In panel a you extend the 3 day accumulation from a ~50 year record out to a 500 year return period. That seems well beyond the data. If this is common practice, it would be useful to comment on the general practices and limitations of extreme value statistics based on records of this length.
* The captions for Figures 4 and 5 give a general description, but don’t go into much detail on how to interpret the three panels.
* Line 167-170 - This makes it sound like accounting for wind and weak layers is a straightforward addition for a later stage. I think that understates how much those processes matter both spatially and for event probability. Fine to leave them out of this first study, but I would frame them as a real gap rather than a simple next step.
* Line 180-184 - My understanding is that the PRA algorithm varies the size and connectedness of start zones based on return frequency (2, 10, 30, 100 yr) but the extent of release areas remains constant. This approach uses an object based image analysis method to segment

PRA. Can you clarify how the size of release areas was adjusted based on the 13 values of snow accumulation?
* Figure 7 - This would be more informative at a higher zoom, so slopes at the scale of a single avalanche release area would be visible.
* Line 195-197 - Does scaling the Pspatial value based on the average CAT of all release areas for that fracture depth make this approach dependent on the study area? For example, if all release areas in the sample had relatively low CAT values, this would inflate Pspatial based on the start zones in that sample.
* Figure 6, lines 173-174 - A little more context about how the return period and number of avalanches per path are calculated in Evin et al. 2021 would be useful, since you are relying heavily on these values to estimate the probability of release given fracture depth.
* Lines 217-220 - In the last section you already listed several avalanche models. It would be clearer to refer back to those instead of relying mainly on Wirbel et al. 2026.
* Figure 8 - Is this the sum of avalanche paths from all 13 fracture depths, so the same start zones are modelled multiple times? Or is this output for a single set of start zones and fracture depths?

4. Results

* Lines 269-272 - This ties back to the earlier comment about extending the weather station data from ~50 to 500 years and how that affects the extreme value statistics.
* Line 281 - Does the dataset really support return periods of 1000-5000 years? I would just be more cautious about presenting those return periods with much confidence.
* Figure 10 - How are these maps different from showing RAMMS output using a more traditional approach? As you stated in the introduction, the standard approach is to estimate 30, 100, and 300 year avalanches using RAMMS, with expert judgement to parameterize the simulations.
* Line 282-284 - The current practice in automated avalanche terrain mapping is to calculate runout simulations for different return periods or magnitudes that are calibrated by release depth or runout distance. I’m not seeing yet how that is much different from the results shown here. How are you demonstrating the probability of a location being affected in a different way from that approach?
* Lines 291-295 - This section is answering my last comment. It might help to hold the comments about the method’s ability to determine the probability of an avalanche at a given location until you explain this in section 4.3. Figure 11 does a good job of showing the difference.
* Figure 11 - This is an effective illustration of the value of the method. It differentiates the probabilistic output from a single RAMMS simulation much more clearly than the intensity maps in Fig. 10.
* Lines 320-325 - You are explaining the methods for this analysis in the results section. Moving the methods for the RAMMS friction parameter sensitivity analysis to the methods section would match the structure of the rest of the paper better.

* Figure 13 - It appears that most of the impact of the RAMMS parameter variations shows up at return periods beyond 100 years. Is that an artifact of the snow depth time series?

5. Discussion

* Lines 346-348 - Saying the approach is applicable to other gravitational hazards is reasonable as a brief outlook, but it is beyond what this manuscript shows. I would keep this to one sentence. Without specifics on how probabilities would be defined or how the method compares to standard practice in those fields, it is hard to evaluate.
* Lines 358-361 - I agree with much of the critique of current practice. The way it is written comes off a bit as “this is the way it should be done,” which may not be the best way to introduce a new method in an established field. Framing it more as “here is a unique contribution probabilistic modelling could make” would be more approachable.
* Lines 360 - Is it the large number of simulations that identifies the source region of the most damaging avalanches? The loss frequency output seems to identify runout areas with the greatest impact on potential damage. It is still the PRA and RAMMS modelling that let you trace those high risk runout zones back to source areas.
* Line 365-369 - This is an important point and I think it should be more central to how the paper is positioned. Expert judgement, historic avalanche records, and field evidence such as tree rings are still a key part of creating hazard maps. This method is a novel and useful way to combine automated avalanche terrain mapping into probability maps. At the same time, the present application is limited to dry storm snow avalanches (no wind deposition, weak layers, powder, or wet runout) and snowfall data from a single weather station some distance from the site. Characterizing this as a new way to describe hazard and risk from model output is appropriate. It is not yet a replacement for expert driven hazard maps.
* Figure 15 - This is a good comparison figure. Better labelling of the map rows and a clearer statement of how the difference is calculated (traditional minus probabilistic, or the reverse) would help.
* Lines 381-383 - I’m a little confused why the probabilistic maps are not shown for the 30, 100, and 300 year return periods. That would be a more direct comparison than 20, 75, and 220, even if those values fall at the bin centres you used.
* Lines 385-389 - A more detailed description of the differences would be useful. In Figure 15 there are a few large gullies where the difference is positive and most of the map where the difference is negative. Can you offer a possible explanation for why those few paths behave differently?
* Line 418-419 - The point that probability during the lifetime of a building can be derived is made several times. It might be worth showing this explicitly for one of the example sites, rather than leaving it as a general statement.
* Line 471-484 - Introducing EconoMe this late in the paper is unusual. If this tool is important to the discussion, it should be introduced earlier (intro or methods) and then picked up again here. Otherwise it feels like a lot of detail on a peripheral method in a paper that is already heavy on modelling description.

* Line 527-530 - This is an interesting idea and could be a good way to explore the sensitivity of runout results to release depth and the spatial structure of snowfall events.

Minor / technical comments

* Line 23 - “avalanches” should be “avalanche.”
* Line 60 - remove “The” and start with “Integrated risk management…”
* Line 61 - define the PLANAT acronym.
* Several maps (Figures 2, 8, 11, and 15) would benefit from a scale bar and north arrow.
* Figure 11 - a clearer legend would help.
* Figure 15 - label the rows more clearly so it is obvious which is the current approach, which is the probabilistic result, and which is the difference.