ADAPTING AVALANCHE HAZARD MAPPING TO A CHANGING CLIMATE – EMERGING PRACTICAL APPROACHES AND UNCERTAINTIES

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ABSTRACT: Avalanche hazard mapping in Switzerland is based on long-established regulations and methods and provides a valuable basis for avalanche risk management in settlement and infrastructure areas. The designation of avalanche hazard zones relies, amongst others, upon data from the past, like weather records and historic avalanche events. The avalanche hazard maps are based on scenarios with a return period of up to 300 years and are used for long-term land-use and infrastructure planning, which is why it is crucial that the hazard map provides robust information on the expected avalanche risk in the next decades.

In today's changing climate, the established methods may not be fully adequate to prepare for the avalanche risk of the future. The Swiss Federal Government therefore requires that climate change be systematically taken into account in hazard assessments. To support this requirement, the Swiss Network of Natural Hazards Experts (FAN) is developing a new methodology that combines historical avalanche activity with projections of future snow-climate conditions. To demonstrate the practical implications of this new methodology, we provide selected case studies of avalanche paths across different elevation ranges and discuss the anticipated changes in local avalanche risk. We provide an insight into how climate change considerations could be included into avalanche hazard assessment. Furthermore, we qualitatively discuss the associated uncertainties and identify open questions and challenges for hazard mapping in a changing climate.

KEYWORDS: climate change, hazard mapping, case study, avalanche path, wet snow avalanche

1. INTRODUCTION

1.1 Avalanche hazard mapping in Switzerland

Avalanche hazard maps have been an integral part of Switzerland's strategy to mitigate the risk of avalanches to settlements and infrastructure for many years, starting with the first avalanche hazard map drawn in 1954. Nowadays, avalanche hazard maps exist for every municipality in the Swiss Alps. Hazard zones are designated based on the intensity of avalanche events with a return period of 30, 100 and 300 years (BFF/SLF, 1984).

Modern avalanche hazard mapping relies on a comprehensive and detailed combination of field observations, historical records, numerical simulations, and expert judgement. First and foremost, the avalanche history of a location is studied. Historic records of avalanches provide a baseline for possible avalanche paths and sizes, as well as an estimate of the frequency and intensity of events. The fracture depth (d_0), which is a key input parameter for avalanche simulations, is estimated using extreme value statistics applied to records of the observed three-day snow depth increase, ΔHS(3), for return periods of 30, 100, and 300 years. Furthermore, avalanches with different return periods are simulated, using models like RAMMS::Avalanche (RAMMS AG, 2024) for flowing avalanches and RAMMS::Extended (RAMMS AG, 2025) for mixed/powder snow avalanches. The final expert assessment of the results obtained is very important for ensuring a robust and reliable hazard assessment.

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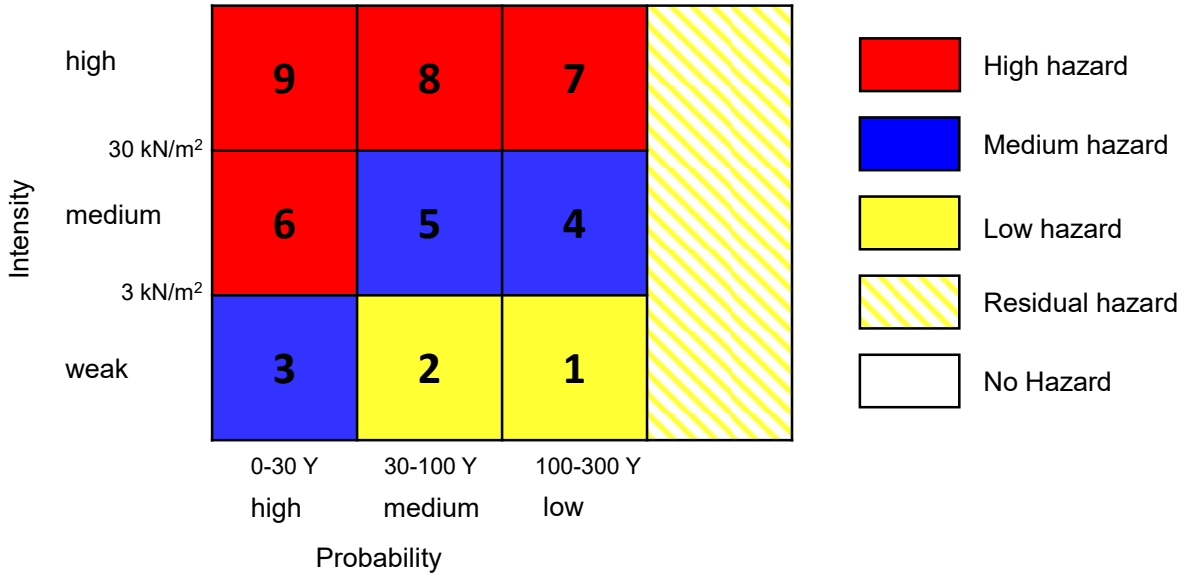


Figure 1: Definition of avalanche hazard zones for dense flow avalanches (DFA) and powder snow avalanches (PSA) in Switzerland (BFF/SLF, 1984).

The resulting avalanche hazard maps are a valuable tool for long-term infrastructure and land-use planning, regional development, and risk mitigation. Avalanche hazard maps have generally proven to be reliable, as only a small number of avalanches during the extreme winters of 1999 and 2018 extended beyond the boundaries of the previously designated avalanche hazard zones.

However, current approaches to avalanche hazard mapping rely heavily on historical records and observational data, thereby assuming stationarity in regional avalanche conditions. This assumption may no longer hold under a changing climate. Avalanches are a result of the topography and the snow climate of a region. While the topography can be assumed to me mostly stable (with the exception of glaciated areas), it has become abundantly clear that the climate in the alps is changing rapidly. Recent studies show that the alps are warming up significantly faster than the global average. In Switzerland, federal guidelines (BAFU, 2023) require climate change to be considered in hazard assessments for gravitational natural hazards (e.g., avalanches, debris flows or rockfall) to proactively account for potential future changes in hazards and associated risks. We are currently exploring practical approaches for implementing this requirement for avalanches.

1.2 Short summary of the known impact of climate change on avalanches

Climate change affects avalanche activity in the Swiss Alps in several well-established ways. The most important effects are briefly summarized below. For a more detailed discussion, see Bast et al. (2025), Mayer et al. (2024), Ortner et al. (2025), Le Roux et al. (2021, 2023), Farvacque et al. (2026) and MeteoSwiss (2025). At elevations below 2500 m a.s.l., warmer temperatures are expected to cause a significant decrease in overall avalanche activity. This is driven by a rising snowline, a reduction of both snow height and snow cover duration, and a lower probability of persistent weak layers in the snowpack. These factors not only cause a reduction in the overall avalanche activity, but also shorter runout distances. However, above 3000 m a.s.l., an increase in snowfall, especially during storms, is possible.

Overall, dry snow avalanches become less frequent, while the probability for wet snow avalanches increases, driven by higher temperatures and precipitation falling as rain more frequently even in the coldest months of December, January and February.

In some cases, climate change can alter the disposition for avalanches by reshaping the topography. This effect can be mostly observed in glaciated areas, where glacier melt can both create and remove release zones, but also in thawing permafrost areas, where mass movements alter the topography.

There are, however, large uncertainties concerning extreme events. Predictive models don't show clear results regarding the future frequency and magnitude of extreme precipitation in the winter months. Especially at higher elevations, an increase of extreme snowfall events is possible, while at low elevations below 1500 m a.s.l., even extreme precipitation is very likely to fall as rain rather than snow in the future.

2. A NEW APPROACH

To bridge the gap between science and practice in the integration of climate change considerations into avalanche hazard mapping, we apply a new methodology currently being developed by the Swiss Network of Natural Hazards Experts (FAN, 2026). The methodology builds on historical observations from individual avalanche paths and seeks to extrapolate these records under projected future climate conditions. Because the impacts of climate change on snow cover and avalanche activity vary strongly with elevation, the core element of the methodology is an elevation-dependent matrix that interprets historical avalanche activity and the disposition for avalanches in the context of future snow-climate scenarios. The FAN methodology is currently under discussion and is being further refined through ongoing expert review and practical application.

Table 1: The matrix for addressing climate change in avalanche hazard assessments.

Release elevation	***No recorded avalanche event in the last 100 years. Disposition for avalanches uncertain.***	***Largest known avalanche event occurred before 1990. Disposition for avalanches possible/proven.***	***Largest known avalanche event occurred after 1990. Disposition for avalanches proven.***	***Significant changes of the disposition for avalanches possible.***
< 1500 m a.s.l.	**A**	**A**	**B**	**D**
1500 – 2500 m a.s.l.	**A**	**B**	**C**	**D**
> 2500 m a.s.l.	**B**	**C**	**C**	**D**

- Category A: Decrease in avalanche size and frequency.
  Given the low elevation of the avalanche-prone area and the absence of avalanche activity - or the fact that any such activity occurred a long time ago - it can be assumed that the risk has decreased significantly or no longer exists. The missing physical conditions for avalanches are decisive. With the snow line expected to rise by several hundred metres by the end of the century, an increasing proportion of precipitation will fall as rain rather than snow. As a result, even extreme precipitation events may no longer generate large dry-snow avalanches. Two cases are possible:
    - Case 1: Future avalanches are nearly impossible. If all indicators point towards a very low probability for avalanches (especially release area below 1500 m a.s.l.), the risk of future avalanches can be regarded as negligible.
    - Case 2: Avalanches are still possible but are expected to be significantly smaller and less frequent. In hazard assessments, the release area and fracture depth may be reduced, and the friction along the avalanche path increased.

  The following requirements need to be considered (not conclusive):
    - Complete and critical analysis of the avalanche history.
    - Check for distortions: Make sure that the observed avalanche activity hasn't been influenced by avalanche control measures, such as snow supporting structures, reforestation or artificial release.
    - Search for geomorphological evidence of historic avalanches, like damaged or fallen trees, forest gaps, historic damage to buildings or infrastructure.
    - Check the change of local snow and weather data: Three-day snow depth increase ΔHS(3), snow cover period, number of snowfall days, number of days below 0°C. A decreasing trend must be visible.
    - Check factors influencing the avalanche probability: exposition and slope angle of release area, roughness of the terrain.

- Category B: Avalanche size and probability remain largely unchanged.
  If the largest known avalanche is regarded as representative of the design scenario, it may be used as the upper limit of the future avalanche hazard potential. When defining the fracture depth of the design event from snowfall statistics, check whether the data since 1990 shows a decrease in the three-day snow depth increase *ΔHS(3)* compared to older data. If this is the case, the fracture depth may be reduced accordingly.
    - As for Category A, several criteria must be evaluated. Special emphasis should be placed on geomorphological evidence to verify the absence of signs of larger historical avalanche events.

- Category C: Avalanches larger than previously known are possible.

With increasing elevation, an increase in avalanche size and frequency is possible. Climate projections for changes in extreme snowfall events at high elevations are inconclusive so far. Above 3000 m a.s.l., an increase in snowfall is expected (Le Roux et al., 2021, 2023).
Three cases are possible:

- Case 1: The design scenario is to be defined using the established methodology. Applicable if there are no indications for an increase in snowfall, like a release area above 3000 m a.s.l. or a trend towards increased snowfall observed by local weather stations.
- Case 2: If the release area is above 3000 m a.s.l., a higher fracture depth may be applied.
- Case 3: For avalanche paths with run-out zones at low elevations, shorter run-out distances may be expected as a result of the increased friction caused by a thinner and wetter snowpack.

- Category D: Changes in the disposition for avalanches.
  Changes in the topography can cause both increases or decreases in avalanche activity. This applies especially to glaciated areas, where the topography is changing rapidly. Avalanche release zones can both disappear or emerge due to melting. This is a large source of uncertainty, since glacier bed topography is often either unknown or rather unprecise. Release areas can also appear temporarily on steepening ice, only to disappear with progressing melt.
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Particularly for Categories B and C, the potential shift from dry-snow to wet-snow avalanche activity should be carefully considered. Wet-snow avalanches generally have shorter runout distances but greater lateral spreading than dry-snow avalanches.

3. EXAMPLES OF PRACTICAL APPLICATION

3.1 Avalanche hazard zones in Plaffeien, Fribourg

The small settlement Rohrmatta in the municipality Plaffeien in the canton of Fribourg lies at the bottom of the valley Seeschlund at an elevation of 1030 m a.s.l. The adjacent slopes are mostly forested and reach up to 1300 m a.s.l. No avalanches reaching the village perimeter have been observed in the past; however, there are several small forest clearings with a slope angle >30°, in which avalanches could release.

In accordance with the established method for avalanche hazard mapping, avalanches with a return period of 300 years from one of these forest clearings at 1150 m a.s.l. can reach the village perimeter in a small area, resulting in a blue hazard zone.

Applying the matrix from chapter 2, this avalanche path can be classified as class A, since there are no recorded avalanche events, and the release elevation is below 1500 m a.s.l. All indicators point towards the application of case 1: The risk of avalanches reaching the village perimeter in the future is negligible. The blue hazard zone could be removed under these assumptions.

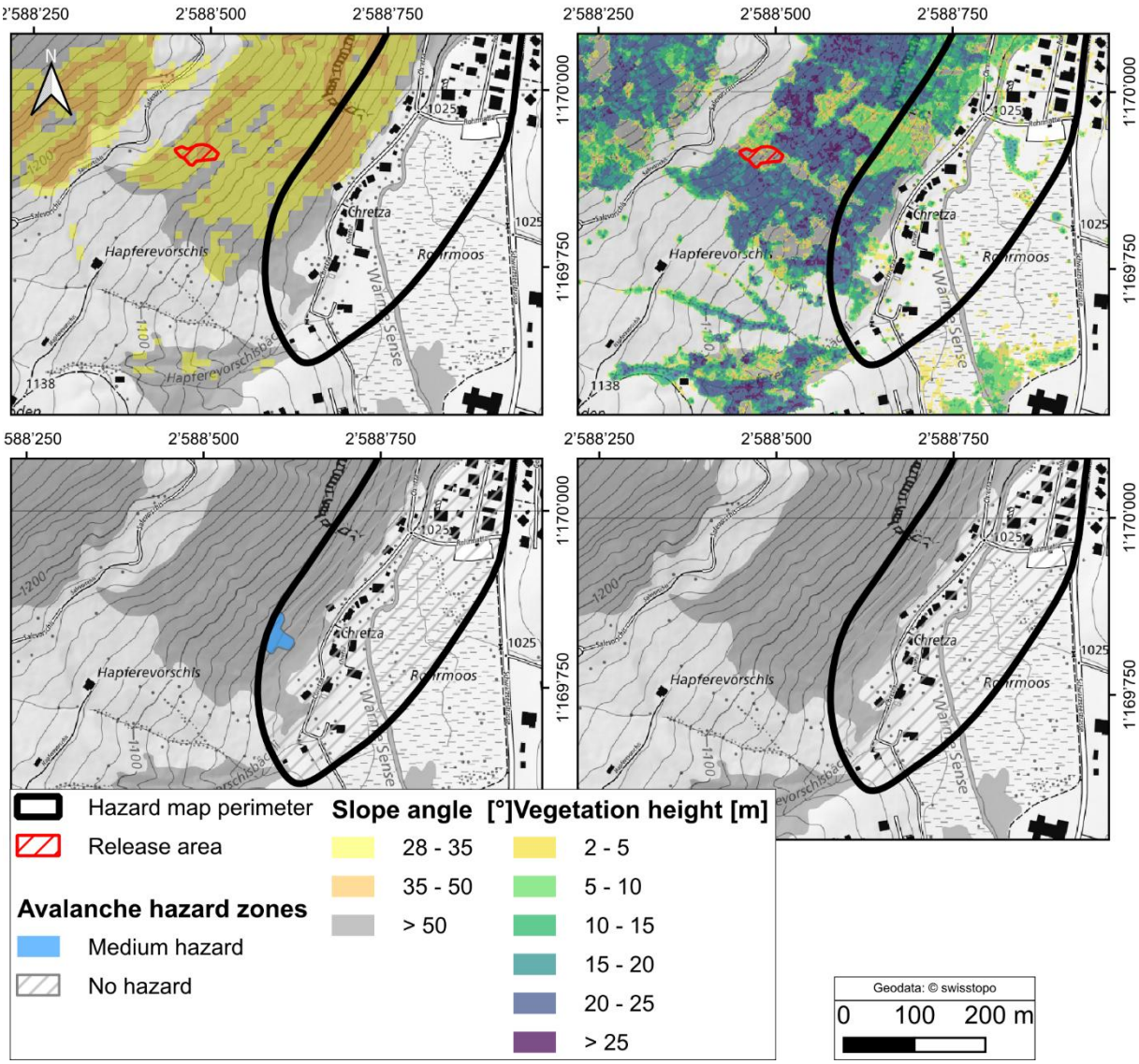


Figure 2: Slope angle (top left), vegetation height (top right), current avalanche hazard map (bottom left) and avalanche hazard map after application of the FAN matrix (bottom right).

3.2 Wiler, Lötschental

The village of Wiler in the canton of Valais lies at 1400 m a.s.l. The slopes surrounding the valley are steep and reach up to 3300 m a.s.l. There are multiple avalanche paths threatening the village, and many events reaching the village have been recorded in the past. To showcase the potential use of the matrix, we selected two examples.

First, we look at avalanches releasing in the area called Turand. The south-facing release zone is at an elevation of 2000 m a.s.l. There are two recorded avalanche events, which occurred in 1999 and 2018. These avalanches both reached all the way down to the road in the valley floor. According to the matrix, the avalanche path needs to be classified as Category C: Avalanches larger than the observed events are possible. However, due to the elevation and the southerly exposition of the release zone, we expect that the established method to define the 300-year design event is sufficient; an increase in the fracture depth due to climate change seems unlikely in accordance with the climate model results. Although climate change is taken into account, the avalanche hazard is assessed to remain unchanged.

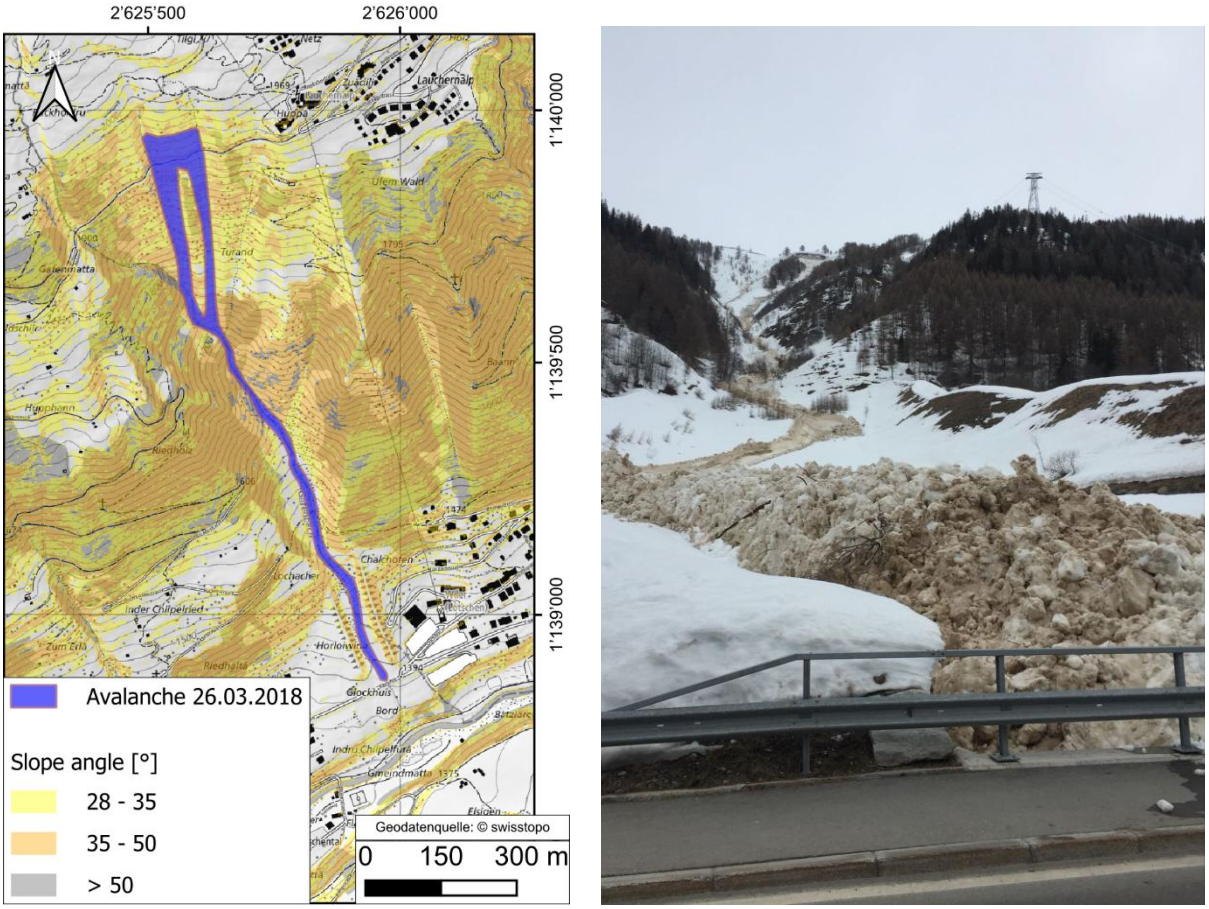


Figure 3: Avalanche on the 26th of March 2018 in the avalanche path Turand. Photo(right): B. Rieder.

Finally, we present an example of a substantially larger avalanche path. The valley floor around Wiler has in the past been struck by catastrophic avalanches originating from the very top of the slopes north of the summit of Hockenhorn. In the avalanche path of Gafenbach, 10 avalanches reaching the valley floor have been documented between 1806 and 1996. The release areas of the past events are not exactly known, but they can be assumed to be somewhere near the ridgeline above 3000 m a.s.l. These areas used to be largely covered by glaciers; nowadays, only small remnants of the glacier exist. Usually, release areas at this high elevation and with such a large track record of massive avalanches would need to be categorized as Category C, with an increase in avalanche activity due to climate change possible. However, avalanche simulations have shown a surprising result: It is virtually impossible to simulate an avalanche that reaches the valley floor in this avalanche path. This, together with the fact that no avalanche to the valley floor has been observed since 1996, leads to the conclusion that the retreating glaciers in the release zones have resulted in such significant changes in the topography that nowadays, avalanches like the past events have become practically impossible. Unfortunately, there are no digital elevation models of the past extent of the glaciers to check this hypothesis with avalanche simulations. Nevertheless, a classification in Category D is considered justified, as the potential release zones are believed to have been significantly steeper and larger in the past than they are today. Additionally, the aspect of the formerly glaciated area may have been more southerly than the southwest-facing slopes visible today, causing avalanches from the Hockenhorn release areas to flow into the adjacent Milibach ravine instead of following the Gafenbach ravine. It should be noted that avalanches from release areas at lower elevation still pose a threat to the valley floor, as the topography below the formerly glaciated area remains largely unchanged.

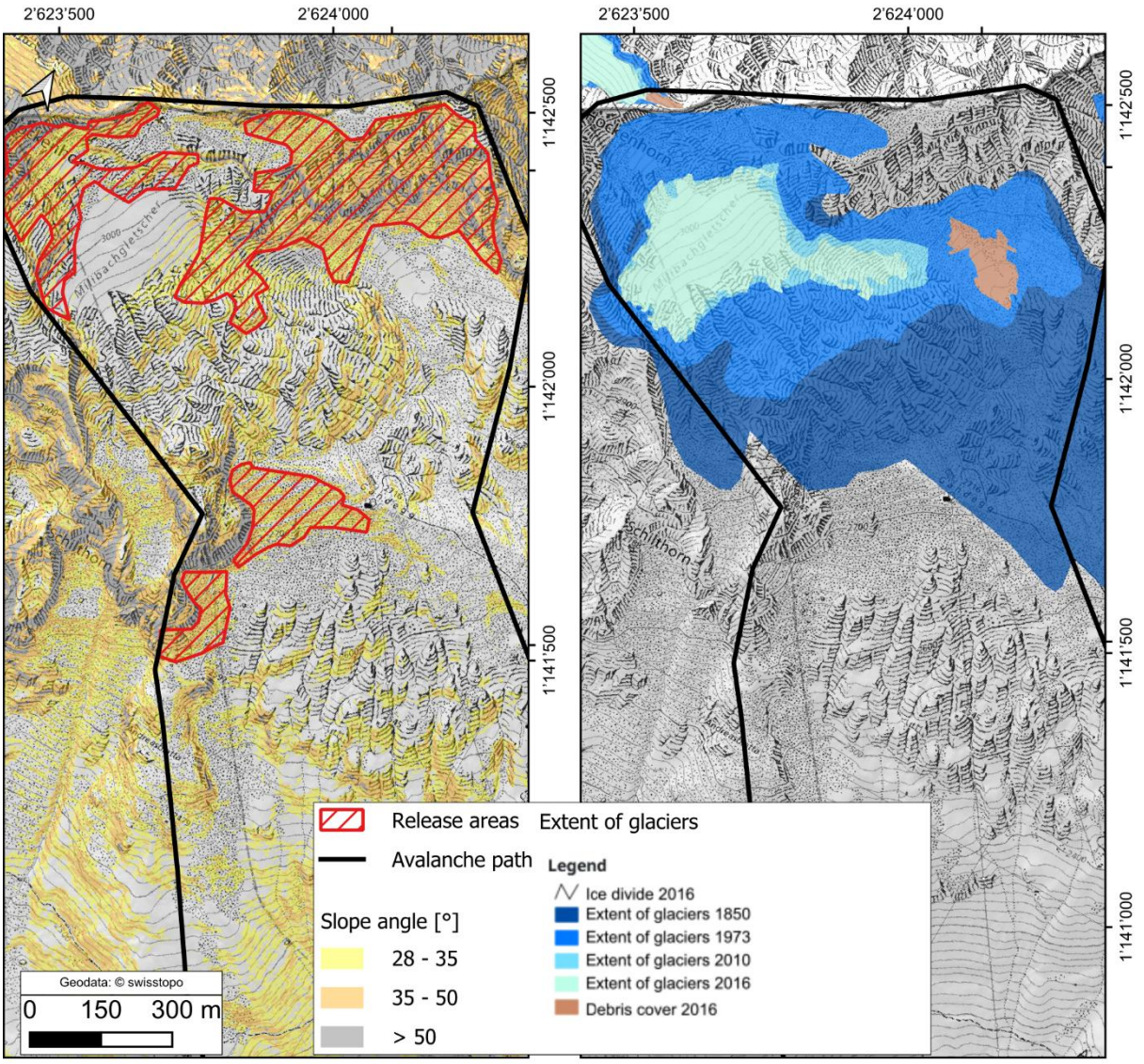


Figure 4: Current topography and release zones of the Gafenbach avalanche path (left) and historic glacier extend (right).

4. DISCUSSION AND UNCERTAINTIES

The presented examples illustrate the application of the developmental FAN-methodology and provide insight into a promising new methodology for incorporating climate change considerations into avalanche hazard mapping.

In practice, the application of the FAN-methodology faces numerous challenges: In many cases, the avalanche history is incomplete or unprecise. Confounding factors like reforestation, artificial avalanche release or other protective measures might have changed the avalanche activity, especially in more recent years, which increases the uncertainty in the attribution of changes in the avalanche regime to climate change. Potential increases in snowfall associated with extreme cold snowfall events at high elevations remain highly uncertain. Consequently, it is currently difficult to quantify an appropriate increase in fracture depth for future scenarios. A further challenge arises from the temporal scale of climate projections, which are generally provided for specific future periods or reference years, such as 2100. Avalanche hazard maps, however, must remain sufficiently reliable over extended time horizons to support long-term land-use planning decisions. In addition, the timing of potential shifts in avalanche activity cannot be determined precisely. Consequently, it is difficult to identify the point at which avalanches of a certain magnitude may no longer occur and to incorporate such changes into quantitative risk assessments. The question remains whether and to which extent it is justified to include the climate of 2100 into new avalanche hazard maps today.

The incorporation of climate change into hazard mapping requires careful consideration. Currently, reductions in hazard zones can be justified only in few cases, predominantly at low elevations.

5. OUTLOOK

There are several opportunities to improve the integration of climate change considerations into avalanche hazard assessments. However, important information remains missing or highly uncertain, highlighting the need for further research.

Future climate models are expected to provide a better understanding of changes in extreme short-duration winter precipitation events. In particular, estimates of future snowfall amounts and snowfall elevations would substantially enhance the assessment of climate change impacts on avalanche activity.

Although previous studies have demonstrated an overall decline in dry-snow avalanche activity and runout distance, it remains unclear whether similar trends apply to rare and extreme avalanche events. To date, the available evidence is not conclusive. In addition, there is still a lack of validated models for the simulation of wet-snow avalanches, which represents an important limitation in the assessment of future avalanche hazards.

The FAN-methodology will be discussed with practitioners and tested using case studies through the end of 2026. Furthermore, the avalanche-specific methodology will be coordinated with methodologies developed for the other gravitational natural hazards. The ultimate objective is to establish a scientifically robust and practically applicable framework for integrating climate change considerations into avalanche hazard assessments.

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