RiskCheck: A FRAMEWORK FOR AVALANCHE RISK ASSESSMENT, INTEGRATING MANUAL AND SEMI-AUTOMATED APPROACHES

Stephan Harvey[1]*, Benjamin Reuter[2], Josiah Rohrer[1], Martin Ruggli[3], Jürg Schweizer[1]

[1] *WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland*
[2] *Météo-France, Direction des opérations pour la prévision, Toulouse, France*
[3] *Head of Core Training Team for Avalanche Prevention KAT, Switzerland*

ABSTRACT: Those traveling in the winter backcountry expose themselves to avalanche danger, where the interplay of triggering probability and potential consequences of being caught determines the individual risk. To assess the risk, the focus is on the sections particularly exposed to avalanche danger, so-called cruxes. At a crux, the probability of triggering as well as the possible consequences of an avalanche are estimated by assessing the stability of the snowpack (failure initiation and crack propagation) and the characteristics of the terrain. In general, there are different approaches, ranging from pre-tour planning to on-site decision-making, which are applicable for beginners as well as experts. However, navigating the multitude of information, observations and assessment tools is a challenge. This requires a comprehensive view and a structured yet flexible approach. To address this issue, we introduce the RiskCheck framework, which systematically focuses on key issues related to avalanche triggering probability and the consequences of an avalanche, culminating in a graphical risk analysis. This modular framework allows flexibility and continuous refinement to adapt to further information and observations. On the one hand, we propose an automated to semi-automated application of the RiskCheck that uses digital avalanche terrain maps and up-to-date information from the avalanche bulletin as a starting point, with subsequent refinement and adaptation by the user following a Bayesian approach. On the other hand, we show how simple rules of thumb and process-oriented approaches can facilitate risk assessment in the field using the same framework. The integration of both automated and manual procedures provides an approach to backcountry risk assessment that considers the inherent uncertainty associated with the problem. The proposed framework ensures consistency across different information sources and application scenarios which also allows a smooth transition from automated to manual application. In summary, the RiskCheck provides a versatile tool to assess avalanche risk by promoting risk-based decisions with a universal approach (probability × consequences) based on the current state of knowledge on avalanche release.

KEYWORDS: avalanche risk assessment, avalanche terrain, avalanche hazard evaluation, Bayesian framework, decision-making

1. INTRODUCTION

Winter backcountry recreationist expose themselves to avalanche danger and take a risk. Avalanche risk is influenced by the interaction of avalanche release probability and potential consequences (Schweizer et al., 2023; Bründl et al., 2018). Key to understanding the release probability is assessing the stability of the snowpack (failure initiation and crack propagation) and its variability across the slope (Reuter and Schweizer, 2018). In the event of an avalanche, the consequences depend mainly on the size and type of avalanche, the terrain in the avalanche path and the number of people exposed.

Assessing avalanche risk in the backcountry requires repeated evaluation, from pre-tour planning to decision-making in front of a crux slope. It involves continuos adaptation to changing conditions and new information. This adaptive process reflects a Bayesian approach as suggested e.g. by Ebert (2019), McClung (2011), and Sykes et al. (2023). Digital technology now enables the automation of various steps in the assessment process, particularly in planning. The challenge ahead lies in seamlessly integrating automated and manual assessments.

To address the complexities of avalanche risk assessment, we introduce the RiskCheck tool. It builds on a graphical risk analysis approach (Harvey et al., 2018b) and the DCMR method presented by Reuter and Semmel (2018) and Reuter et al. (2021), and focuses on the elements of risk and the key questions to assess them.

Our aim is to demonstrate the versatility of applying this tool by integrating a semi-automated, Bayesian-informed approach for an initial rough assessment, which can then be refined manually.

* *Corresponding author address:*
Stephan Harvey, WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland;
phone: +41 81 417 01 29, fax: +41 81 417 01 10;
email: harvey@slf.ch

2. RISKCHECK

The risk of an avalanche accident is determined by the probability of triggering an avalanche (danger) and the potential consequences. Once the danger and the consequences are estimated for a particular crux, precautionary measures that can reduce the risk need to be considered. The RiskCheck serves as a guideline through this process by addressing the key questions and presenting the answers in a graphical risk analysis.

The key questions in Figure 1 guide the assessment of release probability (danger; blue) and the estimation of the consequences of an avalanche release (pink). Combining these assessments provides an initial risk evaluation (ochre), which is then refined by considering precautionary measures (purple). This approach outlines the following risk analysis process:

1. Identify and assess the danger
2. Assess the consequences

3./4. Consider precautionary measures, evaluate the risk

More details on the RiskCheck are given in Harvey et al. (2023b).

2.1 Assessing release probability (danger)

The assessment of the release probability ranges from “minor” to “major” and is to be understood as follows:

- *Minor*: Favorable avalanche situation with no pronounced avalanche problem. The snow stability is generally good.
- *Major*: Obvious avalanche problem, with clear indication for widespread poor snow stability, for instance, signs of instability are frequent.

An initial rough assessment is made using information from the current avalanche bulletin (danger level, avalanche-prone locations, avalanche problem type) and the terrain properties (slope angle). The graphic reduction method, GRM (e.g., Harvey et al., 2009) or similar approaches can serve as a quick and brief assessment aid. Further, simple observations, such as signs of instability or recent tracks, provide additional information on the probability of triggering an avalanche. In most cases, this initial evaluation, is sufficient to assess the danger (light blue shaded criteria in Tab. 1).

If the initial assessment is not conclusive, further local observations on snowpack stability are analyzed: detailed assessment. Here we focus on avalanche formation processes, particularly the slab-weak layer combination, and consider current avalanche problems. This approach helps us estimate whether a failure can be initiated and, if so, whether and how far a crack may propagate. Practical criteria for assessing the release probability are listed in Table 1.

Table 1: Criteria for assessing release probability. Light shading indicates initial assessment criteria (top), while criteria for in-depth analysis of the release probability are listed in dark shading (bottom).

Tendency towards «minor»	Tendency towards «major»
- Danger level 1	- Danger level 4
- No signs of instability, even though when breaking trail for a long period	- Signs of instability are frequent.
- ≤ 30° around track	- more than 35° around track
- Entire slope < 35°	- Parts of slope > 35°
- GRM «green»	- GRM «red»
- Many tracks present	
- Favorable avalanche situation	- Distinct avalanche problem
- Weak layer deeper than 1 m	- Weak layer in the upper meter
- Favorable layering ∘ No slab or no weak layer or weak layer above slab ∘ good stability results	- Unfavorable layering ∘ Large, faceted grains in the weak layer with well bonded slab above ∘ poor stability results
- High variability of snowpack, due to: ∘ Irregular or rough terrain ∘ Frequently travelled	- Low variability of snowpack, due to: ∘ Uniform terrain ∘ Seldom travelled

2.2 Assessing consequences of avalanche release

In the event of an avalanche, both its size (volume) and type as well as the terrain crucially determine the consequences, which can range from "mild" to "severe":

- *Mild*: Complete burial is unlikely, and no serious injury is expected.
- *Severe*: Serious or fatal injuries are likely, such as those resulting from a fall. Deep burial is probable due to large avalanche size and/or terrain trap, making a quick rescue impossible.

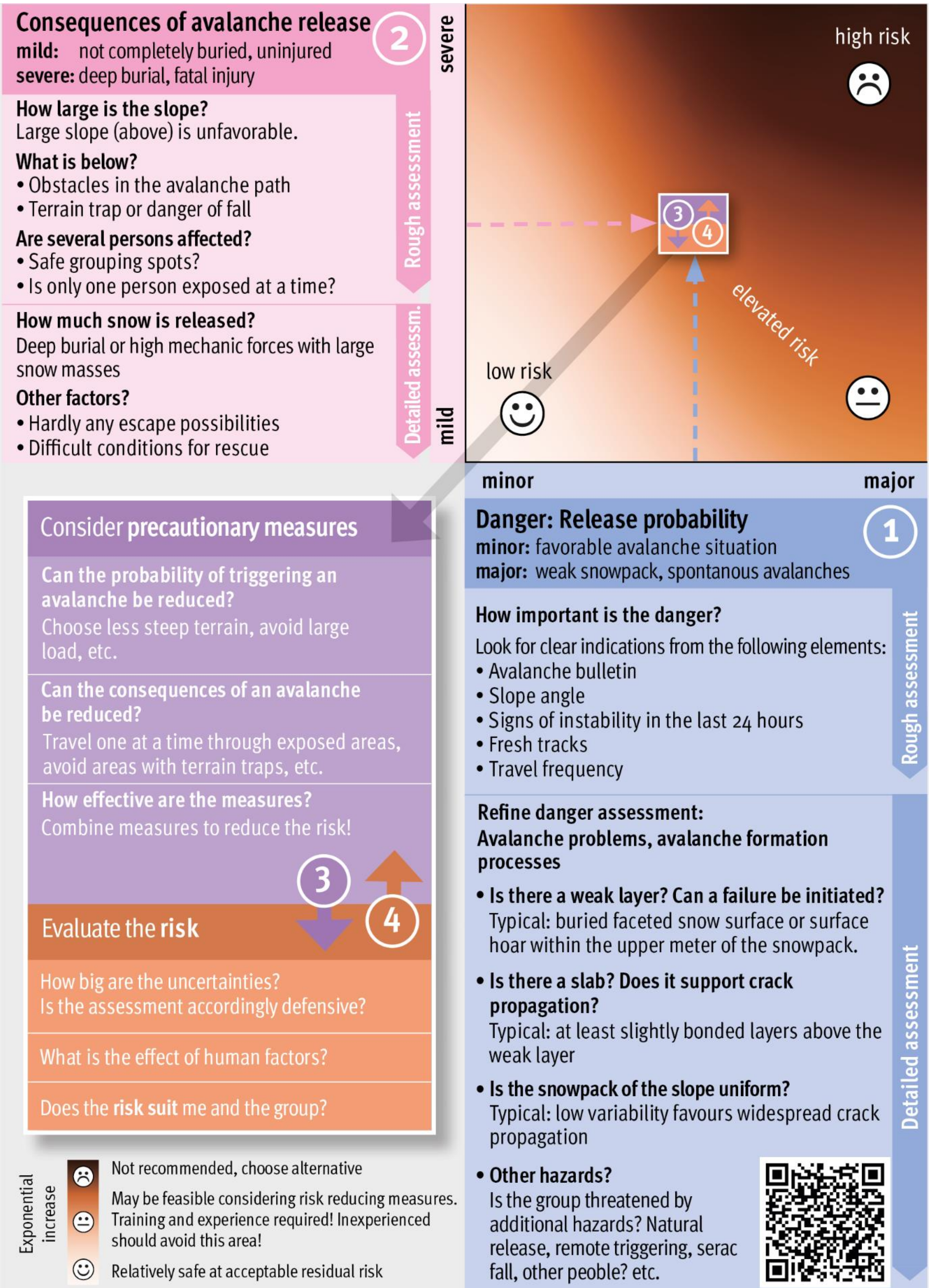

Figure 1: RiskCheck with assessment criteria and key questions 1.) avalanche release probability (danger), 2.) consequences of avalanche release, 3.) precautionary measures, and 4.) risk assessment. The QR code links to a web page where different worksheets can be downloaded.

The consequences of an avalanche primarily depend on the terrain, particularly the size of the slope, the amount of snow that will be moving and the terrain characteristics in the avalanche path. The consequences increase if several people are caught. A rough assessment involves estimating the slope size, identifying terrain traps, and making sure that only one person is on the critical slope at a time while the others wait in a safe spot – if possible.

A supplementary assessment considers the expected amount of snow to be released. Slab thickness is crucial in determining the size of the avalanche and its burial potential. Additionally, rescue options and escape possibilities must be taken into account. Poor visibility or remoteness may complicate the rescue. Criteria for assessing the consequences are listed in Table 2.

Table 2: Criteria for assessing consequences. Light shading indicates initial assessment criteria (top), while additional criteria for detailed evaluation of the consequences are listed in dark shading (bottom).

Tendency towards «mild»	Tendency towards «severe»
- Slope less than 20 m in elevation	- Slope more than 100 m in elevation
- Slope is below me.	- Slope is above me.
- Smooth runout / no terrain trap	- Terrain trap / boulders or trees in avalanche path
- There are safe spots to gather group between exposed sections.	- There are no safe spots to gather group or they are far away from the slope. Hence several people might be caught.
- Shallow fracture depth expected, approx. 20 cm	- Widespread and deep fracture expected
- Quick and effective rescue is possible.	- Poor visibility, remoteness, no effective rescue possible
- Good escape possibilities available (small slopes)	- Hardly any escape possibilities when caught by an avalanche

3. SEMI-AUTOMATIC APPLICATION

When assessing the probability of avalanche release and its potential consequences, key questions can be addressed automatically. Initially, the probability of an avalanche release can be estimated as a prior using the danger level from the avalanche bulletin, including critical aspects and elevations. Terrain information obtained from avalanche terrain maps derived from high-resolution digital elevation models allows for a brief estimation of the consequences. By applying a Bayesian approach, this initial assessment (prior) can be continuously refined with additional information and its likelihood. This methodology mirrors the assessment of crux slopes in practice. We utilized this approach to apply the Risk-Check semi-automatically for an initial rough assessment and thus to standardize the evaluation of the avalanche risk.

3.1 Data

The following data were used to determine likelihoods for refining and updating prior assessments using the methodology outlined below.

We used a dataset of 566 snow profiles from Davos, which includes detailed information on snow stratigraphy, avalanche activity, whumpf sounds, and shooting cracks in the vicinity. This dataset has been previously used by Schweizer et al. (2021b) and Mayer et al. (2022) and is accessible through Schweizer et al. (2021a). From these 566 profiles, we selected those with either a "good" or "poor" stability rating, based on the observation variables: Rutschblock (RB) score, RB release type, and stratigraphical threshold sum (Schweizer et al. 2008). This refined dataset comprised 381 snow profiles. We then assigned a binary release score variable corresponding to “good” or “poor” stability. The proportion of this score to recent avalanche activity and whumpfs or shooting cracks is illustrated in Table 3.

Table 3: Proportion of signs of instability in the vicinity and the release score variable from 381 profiles.

Release score	Recent avalanching	Whumpf or shooting cracks
0: good stability	29%	28%
1: poor stability	71%	72%

To estimate the consequences of an avalanche release, we used a dataset of human-triggered avalanches. The dataset included parameters such as outcome for people involved (dead, injured), elevation differences from highest to lowest point of avalanche, fracture depth, burial depth, and terrain type in the avalanche path. As above, we assigned a binary consequence score variable: accidents resulting in no or minor injuries were labeled as “0” (mild consequences), while those involving fatalities, severe injuries, or deep burial were labeled as “1” (severe consequences). The final dataset comprised 1505 human-triggered avalanches. Avalanche size and fracture depth increase the severity of an avalanche involvement (e.g., Schweizer and Lütschg, 2001). The relation between the consequence score and the two key variables elevation difference (indicating avalanche size) and fracture depth are illustrated in Figure 2. The distributions are significantly different ($p < 0.001$).

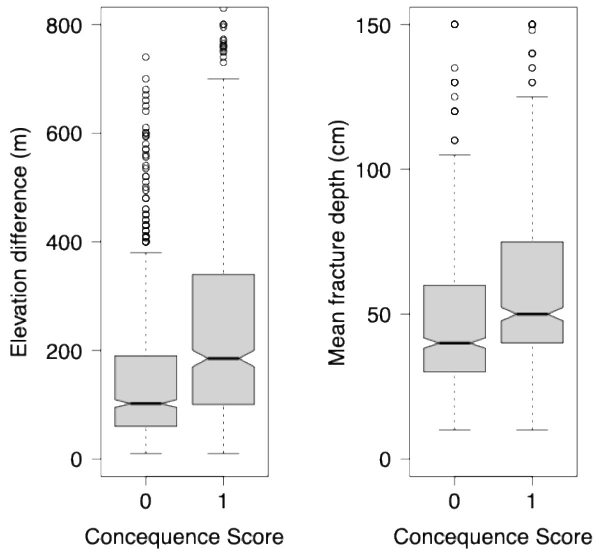

Figure 2: Distribution of elevation difference and mean fracture depth for the consequence scores 0 (mild consequences) and 1 (severe consequences).

3.2 <u>Method</u>

To apply the RiskCheck semi-automatically we used a Bayesian approach. Bayes' theorem (Eq. 1) is a fundamental principle in probability theory and statistics that provides a way to update the probability of a hypothesis as new information becomes available. It combines prior knowledge, in our case an initial assessment of either avalanche release probability (danger) or consequences, with new information (likelihood) to provide a revised probability (posterior). The theorem is expressed as:

$$P(A|O) = \frac{P(O|A)\,P(A)}{P(O)} = \frac{P(O|A)P(A)}{\sum_{i=1}^{n} P(O|A_i)P(A_i)} \qquad \text{(Eq. 1)}$$

where $P(A|O)$ is the posterior probability, $P(O|A)$ the likelihood, the probability of observing O given A, $P(A)$ the prior probability, the initial assessment before seeing new data, $P(O)$ the overall likelihood of observing O.

In our case, we applied this method using Beta distributions ($\mathrm{Beta}(\alpha, \beta)$), which yield continuous probabilities. The two parameters, α and β, were determined based on estimates of major or minor release probabilities, and severe or mild consequences. For all Beta distributions, the minimum of one of the two parameters was set to 2. The method was implemented as follows.

Release probability (danger)

The prior distribution $P(A)$ was derived from the avalanche danger levels. Here, the proportions of “poor or very poor” to “good” snowpack stability reported by Techel et al. (2020) were used as a reference to define the parameters of the Beta distribution for each danger level (Fig. 3).

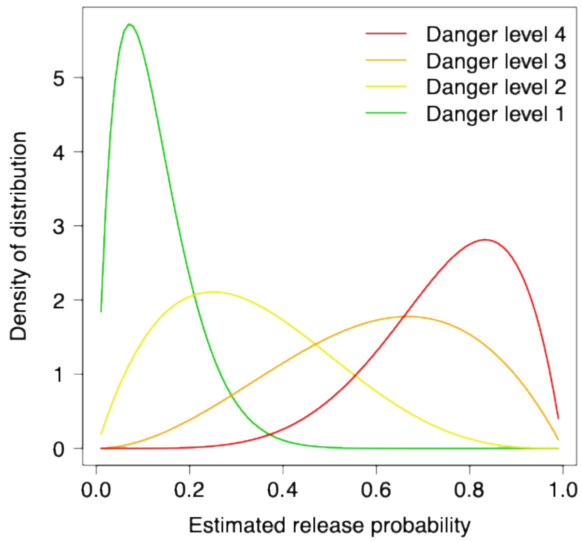

Figure 3: Prior Beta distributions for each avalanche danger level 1 (low) to 4 (high).

The likelihood distribution $P(O|A)$ was informed by local signs of instability, such as recent avalanches, whumpf sounds, and shooting cracks. The dataset of snow profiles (n=381) was filtered based on the selected observations (new information). From this subset, the proportion of release score classes was used to parameterize the Beta distribution. Figure 4 shows the semi-automatic procedure for estimating the release probability (danger) including the possible observation class to generate a likelihood distribution from the data.

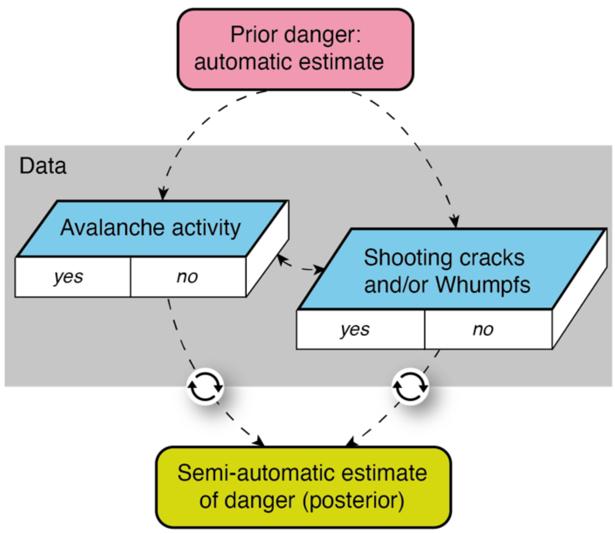

Figure 4: Procedure for estimating the release probability (danger) by updating a prior belief with new data. The white blocks show possible observations to select.

The posterior distribution expressing the semi-automatic estimate of release probability (danger) was calculated from the prior and likelihood distribution using Eq. 1 (Fig. 5)

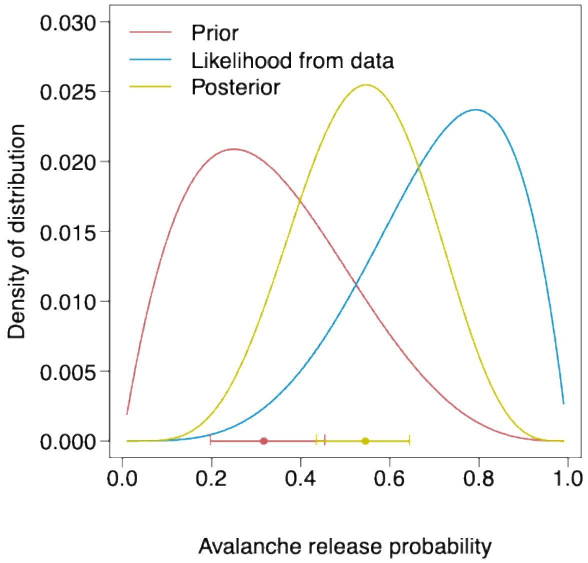

Figure 5: Example of calculating the release probability at a given danger level 2 (moderate) as prior (red curve) and the likelihood from the new information of observed avalanche activity (blue curve) resulting in a posterior estimate (yellow curve). The error bars represent the 25th and 75th percentiles, with the point indicating the median, of the prior and posterior release probability.

Consequences of an avalanche release

The prior probability of the consequences was derived from a raster map layer representing the consequences, as part of the avalanche terrain maps calculated by Harvey et al. (2018a) and Harvey et al. 2024). The parameters for the Beta distributions were obtained from the distribution of pixel values from this consequence raster intersecting the automatically detected crux area of the route according to Harvey et al. (2023a).

To derive the likelihood distribution for the consequences we used the dataset of human-triggered avalanche accidents (n=1505). The dataset was filtered according to the selected observation, such as elevation difference, mean fracture depth and terrain characteristics in the avalanche path summarized in a variable indicating a terrain trap (Fig. 6). The proportion of the consequence score classes from the filtered data was used to determine the parameters of the Beta distribution.

The posterior distribution was calculated in a manner analogous to the release probability.

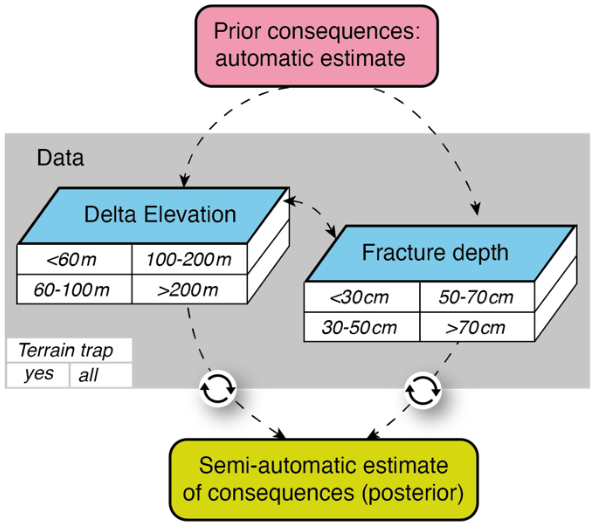

Figure 6: Procedure to estimate the consequences by updating a prior belief with new data. The white blocks show possible observations to select.

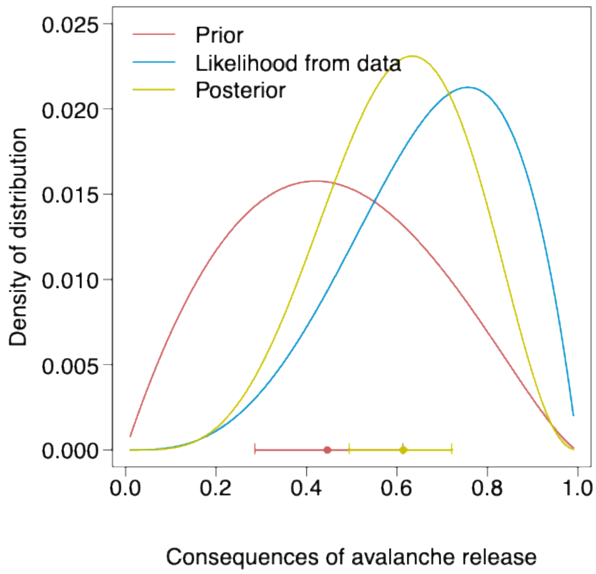

Figure 7: Example of calculating the consequence probability for a crux using the White Risk platform. Red: prior density. Blue: likelihood from the data assuming an elevation difference of >200 m. Yellow: resulting posterior estimate. The error bars represent the 25th and 75th percentiles, with the point indicating the median, of the prior and posterior consequence probability.

3.3 Example

The automatic initial analysis of release probability and consequences can be refined with additional information using the procedure described above. The RiskCheck scheme illustrates how these two components and their adjustments (Fig. 5 and 7) contribute to the overall risk. Figure 8 illustrates the automatic initial assessment (prior) in red and the adjusted assessment (posterior) in yellow after incorporating additional information manually.

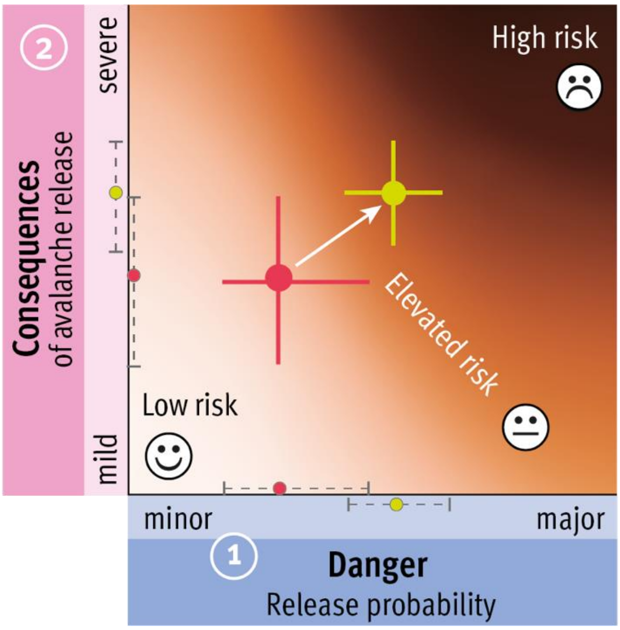

Figure 8: Example of a semi-automatic crux assessment using the RiskCheck. The initial assessment (red) is based on moderate avalanche danger (level 2) and the calculated consequences at a specific crux. Incorporating observed avalanche activity and an elevation difference of more than 200 m, the assessment was updated (yellow).

This preliminary semi-automatic assessment should now be manually refined using on-site observations and personal judgment. Additionally, appropriate precautionary measures that reduce both the release probability and potential consequences must be incorporated into the risk assessment to make a well-judged decision.

4. DISCUSSION

Our objective was to present the RiskCheck tool and to demonstrate the potential for a semi-automatic risk calculation.

The semi-automatic approach employs a Bayesian framework for an initial assessment of danger and consequences. This approach mirrors the real-world decision-making process in backcountry avalanche terrain, where prior beliefs are continuously updated with new information. Applying practical scenarios showed that the semi-automatic method provides reasonable rough estimates. One of its key advantages is, that it provides users with an automatically generated initial "guess", which can then be refined using simple, yet decisive factors related to release probability and consequences. This is particularly valuable during trip planning, as it allows users to interact with an automated system before moving on to a detailed manual assessment – if needed at all. Furthermore, the suggested approach effectively manages uncertainties, offering a probabilistic range for the rough assessment.

This semi-automatic procedure integrates seamlessly into the RiskCheck. The initial rough assessment can be refined manually by addressing the same key questions and issues. The RiskCheck enables beginners to grasp essential principles of risk assessment and apply the tool using simple rules of thumb.

In addition to the graphical analysis (Fig. 1), the RiskCheck can be visualized through a simple hand gesture with our thumbs. This simplified visualization clearly demonstrates that both elements of risk—danger and consequences—must be considered and combined (Fig. 9). The right thumb represents the assessed release probability (danger): a thumbs-up indicates a "favorable" avalanche situation with a low probability of release, while a thumbs-down signals an "unfavorable" situation with a high probability of release. The left thumb represents the potential consequences: a thumbs-up suggests that, in the event of an avalanche, no injuries or burial are expected, while a thumbs-down indicates severe consequences, such as deep burial or fatal injuries. The overall risk is determined by the combined positions of both thumbs. If the average position points downward, the risk is high, indicating that an alternative route might be a safer choice. This intuitive gesture, much like using emojis, makes the assessment easy to teach and effective for communication during a tour.

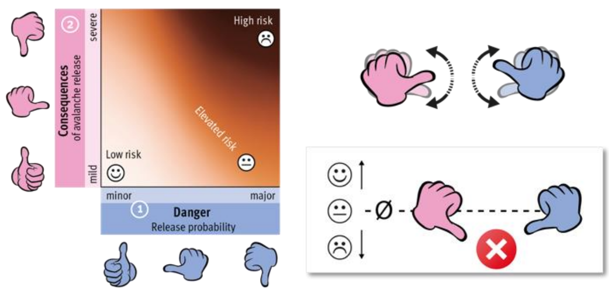

Figure 9: Simplified RiskCheck visualization through hand gesture with thumbs.

The RiskCheck tool provides a versatile guide for risk assessment, suitable for both beginners and professionals, whether for planning or assessing individual crux slopes during tours. The combination of semi-automatic and manual refinements enhances accuracy and reduces errors. The process remains transparent and consistent across different scenarios, ensuring a smooth transition between automated and manual applications.

However, the semi-automatic application has its limitations. The estimated prior distribution for avalanche release probability relies on avalanche danger levels from regional forecasts, which do not account for slope-specific conditions. Nevertheless, the danger level can be considered as a prior estimate (Schweizer et al., 2023). Additionally, the accuracy of the underlying map layers used to derive the prior distribution of consequences is limited due to limitations of the simulation output. Therefore, updating the system with new information from the user enhances its accuracy.

Finally, manual interpretation is subject to human biases, which can impact the risk assessment.

5. CONCLUSION AND OUTLOOK

The RiskCheck provides a consistent framework for risk assessment that structures the decision-making process and focuses on key issues. The tool also supports automated assistance in trip planning, providing real-time estimates of avalanche risk. Refining the suggested Bayesian framework and improving data selection could further enhance this semi-automatic approach.

The next step is to integrate this method into the White Risk tour planning portal (whiterisk.ch), enabling real-time avalanche risk assessment at automatically detected cruxes.

ACKNOWLEDGEMENT

We would like to thank Hansueli Rhyner, Hansmartin Henny and Chris Semmel for their support on developing the RiskCheck.

Many thanks to all members of the Swiss core training team for avalanche prevention for their helpful comments and discussions.

Finally, we would like to thank Jan Klein for giving insights from the risk analysis perspective as well as Cyrill Hänni and Dominik Müller for their technical expertise in implementing a prototype.

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