EUROPEAN AVALANCHE WARNING SERVICES

Determination of the avalanche danger level in regional avalanche forecasting

EAWS-Working Group Matrix and Scale

The working group Matrix & Scale recommends using the definitions and related terms and classes to describe avalanche danger presented in this document. The following sections define the avalanche danger level and the contributing factors: snowpack stability, frequency distribution of snowpack stability and avalanche size. An avalanche danger level can only be issued for an area of a certain size. The chapter setting the spatial and temporal frame provides terms and guidelines for this process. We conclude with the workflow and the EAWS Matrix that should be applied to determine the avalanche danger level. The appendix provides further details and examples on our considerations and work process.

Our working group included the following members: Müller, Karsten (NO, group leader); (in alphabetical order): Bellido, Guillem (AD); Bertranda, Lorenzo (IT); Feistl, Thomas (DE); Mitterer, Christoph (AT); Palmgren, Petter (SE); Sofia, Stefano (IT); Techel, Frank (CH); since September 2021: Dufour, Anne and Roux, Nicolas (FR)

Avalanche Danger

Avalanche danger is the potential for an avalanche, or avalanches, to cause damage to something of value (Statham et al., 2018).

Avalanche danger level

Definition:

> Avalanche danger level is a function of snowpack stability, the frequency distribution of snowpack stability and avalanche size for a given unit (area and time). There are five avalanche danger levels: *5-very high, 4-high, 3-considerable, 2-moderate, 1-low*.

Setting the spatial and temporal frame

The following spatial scales must be considered when determining the avalanche danger level for a region.

Forecasting domain

Forecasting domain is the area of responsibility of an avalanche warning service issuing public avalanche forecasts. The forecasting domain is generally static for a service/operation.

Micro-region

Micro-regions are the smallest, geographically clearly specified areas used for avalanche danger assessment. They are static. Furthermore, they permit the forecast user to know exactly which region is described. They may be delineated by administrative boundaries (e.g., between countries, federal states, or regions and provinces); describe climatologically, hydrologically, or meteorologically homogeneous regions; or may be based on orographic divisions, or a combination of these (Techel et al., 2018).

Reference unit

A reference unit is the smallest spatial-temporal entity at which an avalanche danger level can be assessed. A reference unit can be delineated by different elevations and/or aspects within a micro-region (Figure 1). It must still be large enough to include a variety of avalanche terrain thus that issuing an avalanche danger level makes sense. The reference unit needs to be defined and remain consistent within a forecasting service (and ideally across forecasting services).

Warning region

A warning region is an aggregation of micro-regions, where avalanche conditions are considered similar and are assessed with the same danger level, critical aspects, and elevations where the danger and the avalanche problems prevail, and danger description. The way they are aggregated can vary from day to day. A warning region is smaller or equal to the forecasting domain and larger or equal to a micro-region.

Resolution

The spatial-temporal resolution used to assess avalanche danger depends primarily on the availability of relevant and reliable data in a sufficient spatial density and temporal frequency. Therefore, the resolution of avalanche danger assessment will vary between warning services. Typically, the following elements characterize the spatial-temporal resolution used to determine the avalanche danger level:

– the size of the micro-regions within a forecasting domain (Figure 1a),
– the resolution of elevation and/or aspect (Figure 1b and c), and
– the temporal subdivision within the valid period of a forecast (e.g., in the morning/evening, Figure 1d).

The resolution of these elements defines the lowest spatial and temporal units at which a forecaster can issue an avalanche danger level, which we refer to as reference unit.

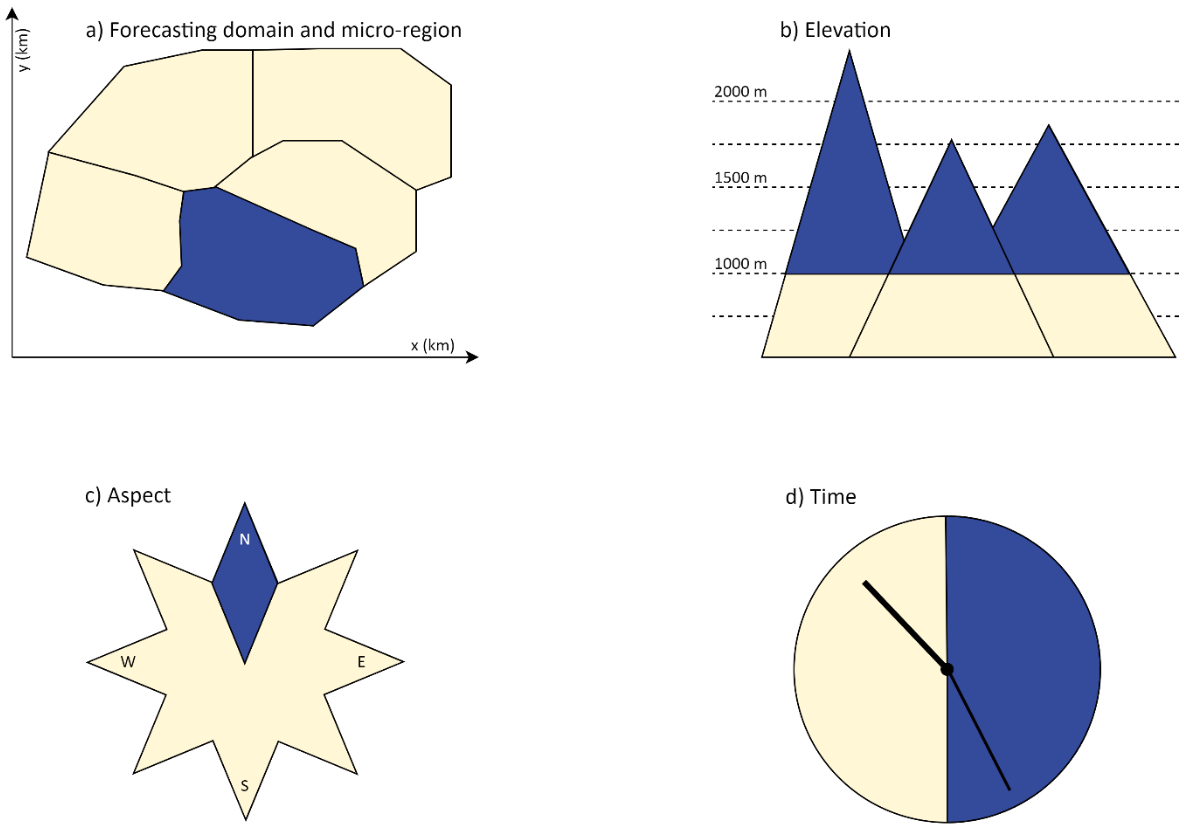

Figure 1: Typically, a reference unit can be characterized by the combination of the smallest sub-divisions for the elements: (a) the smallest geographical entity (the micro-region) within a forecasting domain, (b) the resolution of elevation and (c) aspect, and (d) a temporal subdivision. In the figure, exemplary sub-divisions are highlighted. Here, the size of a single micro region defines the spatial extent, elevation is resolved in 200 m increments but is assessed as above (and below) an elevation threshold, the aspect is split into eight parts, while the temporal subdivision allows a distinction between morning and afternoon. The combination of the elements highlighted red, would be the reference unit, the smallest spatial-temporal entity at which the avalanche danger level can be assessed.

Snowpack stability

Definition:

Snowpack stability is a local property of the snowpack describing the propensity of a snow-covered slope to avalanche (Reuter and Schweizer, 2018). Snowpack stability is described using four classes: *very poor*, *poor*, *fair,* and *good*.

Remarks

1. Depending on the avalanche type, snowpack stability is described by:
    a. Failure initiation, crack propagation and slab tensile support (slab avalanche) (Reuter and Schweizer, 2018)
    b. Loss of strength/bonding (loose-snow avalanche) (e.g., McClung and Schaerer, 2006)
    c. Loss of basal friction and slab tensile and/or compressive support (glide-snow avalanche) (e.g., Bartelt et al., 2012).
2. Snowpack stability is inversely related to the probability of avalanche release. Snowpack stability describes the snowpack to fail given a specific trigger (Statham et al., 2018), as for instance a person skiing a slope. Table A-1 in Appendix A provides an overview of synonymous terms from the literature.
3. The term *local* refers to a point which ranges in size from a potential trigger location or stability test to a starting zone.
4. All snowpack stability assessments may refer to either future (forecast) or present (nowcast) based on observations or models. E.g., if the snowpack in a release area is considered *fair* today, and until tomorrow a layer of new snow is expected, the stability of tomorrows snowpack including the new snow layer needs to be assessed. Likely, it has changed to *poor* or even *very poor* by that time.

Table 1: Stability classes, and the type of triggering typically associated with these classes. For more examples relating to these classes refer to Figures A1 – A3 in Appendix A.

Stability class	How easy is it to trigger an avalanche?
very poor	Natural / very easy to trigger
poor	Easy to trigger (e.g., a single skier)
fair	Difficult to trigger (e.g., explosives)
good	Stable conditions

Frequency distribution of snowpack stability

Definition:

The frequency distribution of snowpack stability describes the percentages of points for each stability class relative to all points in avalanche terrain. Thus, the frequency f for all points with stability class i (n_i) compared to all points (n) is $f(i) = n_i/n$. The frequency distribution of snowpack stability is described using four classes: *many*, *some*, *a few*, and *none or nearly none* (Table 2).

Remarks

1. The frequency distribution of snowpack stability refers to (many) points (i.e., stability tests, snowpack models or potential triggering locations) or avalanche starting zones.

2. The frequency must be assessed for a warning region which must be equal to or larger than the reference unit.
3. The definition asks, in theory, for a percentage. However, this is often impossible to assess since the frequency distribution must often be inferred from sparse data in a real situation. Percentages or thresholds for *many*, *some*, *a few,* or *none or nearly none* differ depending on the measurement/evidence used or available (see Appendix B). E.g., the percentages for slopes that produce spontaneous avalanches might be lower than the percentage of points with stability tests that indicate *very poor* stability.
4. See Appendix B for a brief overview of research related to frequency distributions of snowpack stability.

Table 2: Classes of frequency distribution of snowpack stability.

Frequency class	Description	Evidence (e.g., observations)
Many	Points with this stability class are abundant.	Evidence for instability is often easy to find.
Some	Points with this stability class are neither *many* nor *a few*, but these points typically exist in terrain features with common characteristics (i.e., close to ridgelines, in gullies).	
a few	Points with this stability class are rare. While rare, their number is considered relevant for stability assessment.	Evidence for instability is hard to find.
none or nearly none	Points with this stability class do not exist, or they are so rare that they are not considered relevant for stability assessment.	

Figure B-1 illustrates the concept of frequency distribution for an idealized case.

Avalanche size

Definition:

Avalanche size describes the destructive potential of avalanches.

The question "How large can avalanches likely become?" must be answered based on Table 3.

Table 3: Description of classes of avalanche size. For a more detailed description see EAWS (2022).

Size	Name	Destructive potential
1	**Small**	Unlikely to bury a person, except in run out zones with unfavorable terrain features (e.g., terrain traps).
2	**Medium**	May bury, injure, or kill a person.
3	**Large**	May bury and destroy cars, damage trucks, destroy small buildings and break a few trees.
4	**Very large**	May bury and destroy trucks and trains. May destroy fairly large buildings and small areas of forest.
5	**Extreme**	May devastate the landscape and has catastrophic destructive potential.

Workflow to determine the avalanche danger level

The workflow describes the path from assessing the avalanche problems to setting the avalanche danger level for a warning region. All relevant avalanche problems must be considered, and their snowpack stability, frequency and avalanche size evaluated. The highest resulting danger level will be communicated for the given warning region.

Table 4: Workflow to determine the avalanche danger level. See also chart in Appendix E.

Task		Explanation and remarks
1	**Assess which avalanche problems are present.**	Choose from the avalanche problems defined by EAWS (EAWS 2022)
	If no avalanche problems exist, the avalanche danger level is 1-low.	
2	**For each of these problems, assess the locations (elevation, aspect) where and time of the day when the problem is present.**	
3	**For these locations/times assess the classes of snowpack stability**.	Snowpack stability is related to the question: "What does it take to trigger an avalanche?" Often, the locations with the lowest snowpack stability are decisive.
4	**For these stability classes, assess the frequency.**	The frequency is related to the question "How frequent are points where avalanches can release by the trigger specified in step 3?"
5	**Assess the avalanche sizes.**	Avalanche size is related to the question: "How large can avalanches become?" Often, the largest avalanche size you consider likely is decisive.
	In case the snowpack stability, frequency and/or avalanche size vary considerably between aspects and/or elevations and/or during the forecast period, repeat steps 3 to 5 to identify the locations/times with the most severe combination of these three factors.	
6	**Refer to the EAWS Matrix and obtain the danger level for the combination of snowpack stability, frequency and avalanche size selected in steps 3-5.**	
	Repeat steps 2 to 6 for other avalanche problems that are present.	
7	**Choose the highest danger level obtained in step 6.**	

EAWS Matrix

The matrix is used to determine the avalanche danger level based on the snowpack stability, frequency of snowpack stability and avalanche size.

The user assesses the three factors snowpack stability, frequency of snowpack stability, and avalanche size according to the workflow described above and then selects the corresponding cell within the Matrix.

The matrix is obtained by a survey of numerous forecasters (approach described in Appendix D). Some fields contain two danger levels. The median danger level is indicated showing the integer value for each danger level (e.g., *1* for *1 (low)*). If the distribution of responses was rather heterogeneous, a second value is shown in brackets, representing the interquartile range, if this value was different from the median danger level.

When applying the matrix in Figure 2 you should use the first danger level given in the cell. An optional danger level in parenthesis indicates that forecasters might disagree and a tendency towards a second danger level. These cells should be considered carefully and collected feedback on for future evaluation.

For example, if you assessed that the dominant avalanche problem is best described by the factors *poor* stability on *many* slopes and avalanches up to *size 3* are likely, the result would be danger level 4-high.

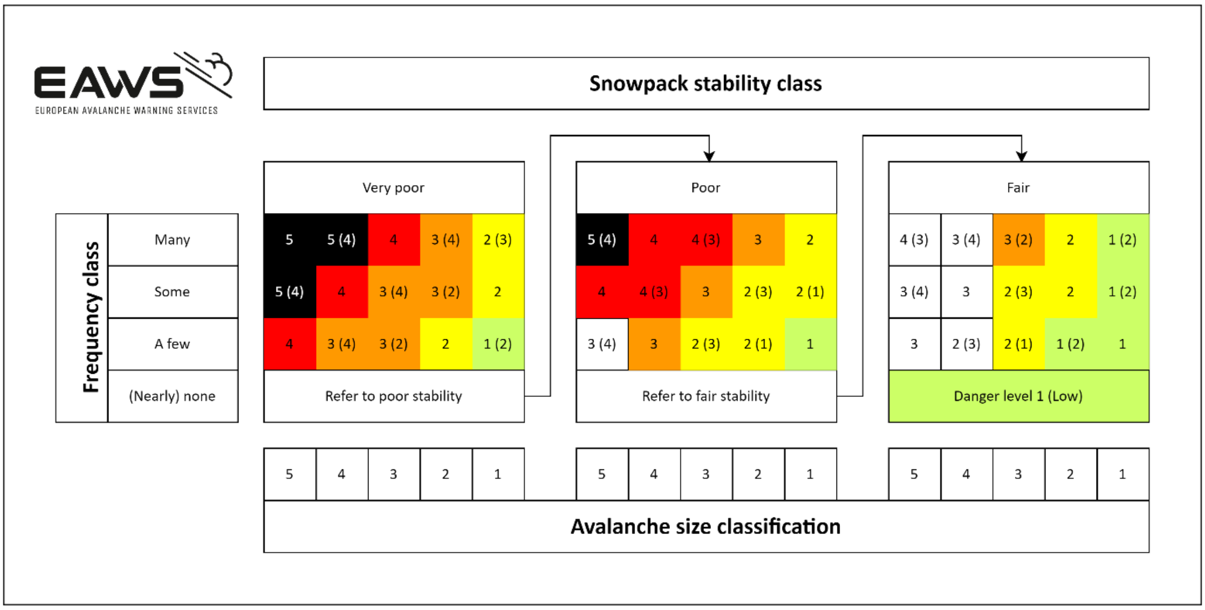

Figure 2: Updated EAWS Matrix based on the approach described in Appendix D. The layout is preliminary and was chosen to accommodate all possible combinations of snowpack stability, frequency, and avalanche size.

Appendix A: Snowpack stability

Figures A-1 to A-3 provide an overview of the relation between the snowpack stability classes and typical phenomena or observations.

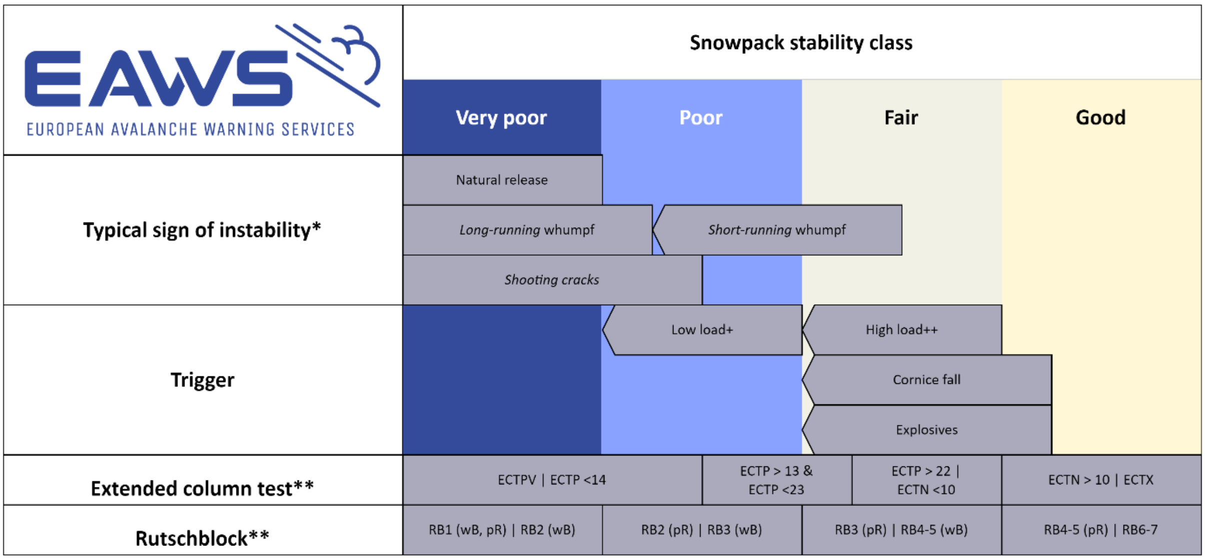

*Figure A-1: Common evidence or indications for snowpack stability classes focusing on dry-snow slab avalanches. Arrows indicate that existence towards lower stability classes is imperative. Natural avalanches are a clear indication for the class very poor, while a low and a high additional load are considered approximately equivalent to poor and fair stability. Observations and stability test results should be regarded as indicative only. Abbreviations: Extended Column Test (ECT), Rutschblock (RB), whole block (wB), partial release (pR). *Schweizer et al. (2021), **Techel et al. (2020)a, +single skier not falling, ski-cut, ++single skier falling, group of skiers, person on foot.*

For wet snow stability and glide-snow stability, the separation between fair and poor is often difficult. Wet snow avalanches most often release naturally and are therefore connected to the class *very poor*. Observations will often only provide a tendency towards either *good* or *very poor* stability (Figures A-2 and A-3). Stability tests generally work poorly in wet snow. If they indicate *very poor* stability, they should still be considered but not otherwise.

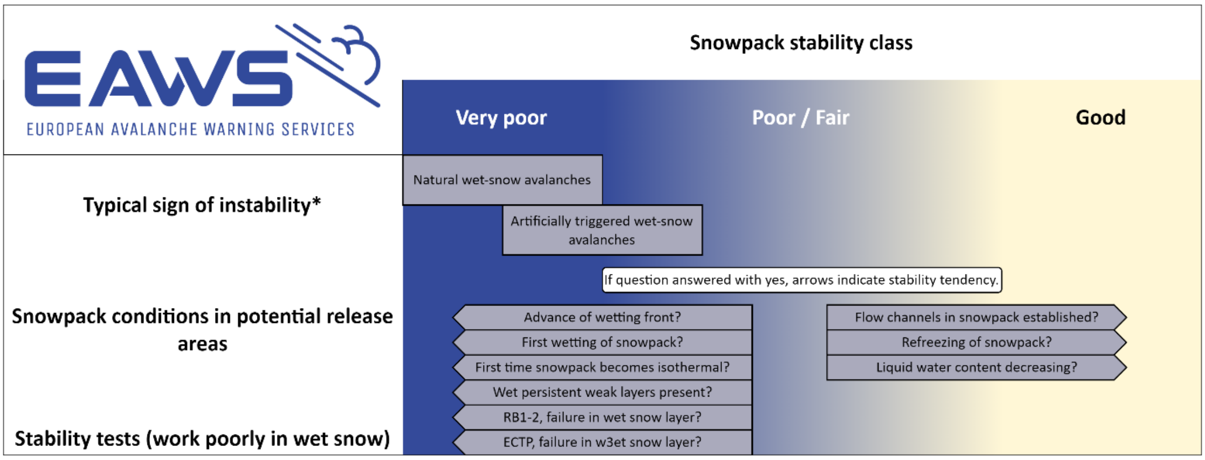

Figure A-2: Common evidence or indications related to wet-snow stability. If no liquid water is present in the snowpack, wet-snow avalanches are not possible.

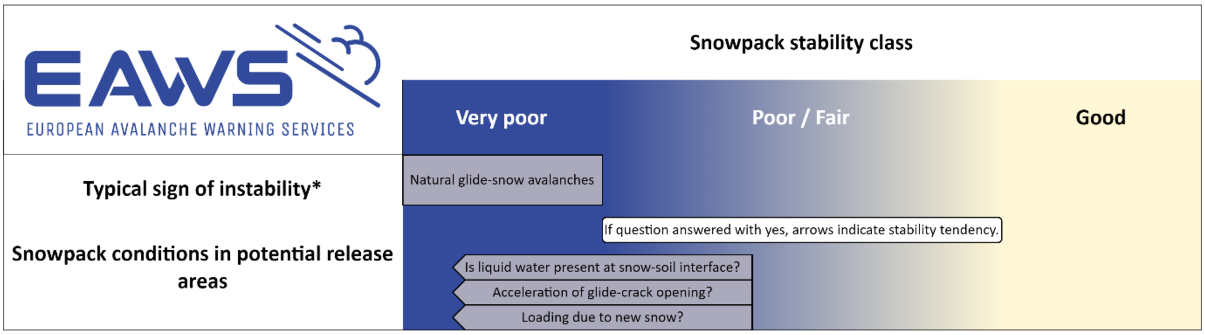

Figure A-3: Common evidence or indications related to glide-snow stability. Glide-snow avalanches are not possible if there is no liquid water present at the snow-spoil interface.

We compare the classes for snowpack stability as defined in this document to other stability classifications in the literature. See Table A-1.

Table A-1: Overview of class labels describing snowpack stability and a comparison to terms describing sensitivity to trigger from the Conceptual Model of Avalanche Hazard (CMAH). We neglected columns from the CMAH that included a spatial component, because we think stability and its corresponding frequency should be decoupled.

Snowpack stability (EAWS)	**Snow stability (CAA, 2014; Greene et al., 2014)**	**Sensitivity to triggers (Statham et al., 2018, Table 5)**			
		Sensitivity	**Human triggers**	**Explosive triggers**	**Cornice triggers**
Very poor	Very poor	Touchy	Triggering almost certain	Any size	Any size
Poor	Poor	Reactive	Easy to trigger with ski cuts	Single hand charge	Medium
Fair	Fair	Stubborn	Difficult to trigger	Large explosives and air blasts	Large
Good	Good – very good	Unreactive	No avalanches		No slab from very large cornice fall

Appendix B: Considerations when assigning classes of frequency distributions of snowpack stability

Figure B-1 illustrates the concept of frequency distribution. It shows an idealized case.

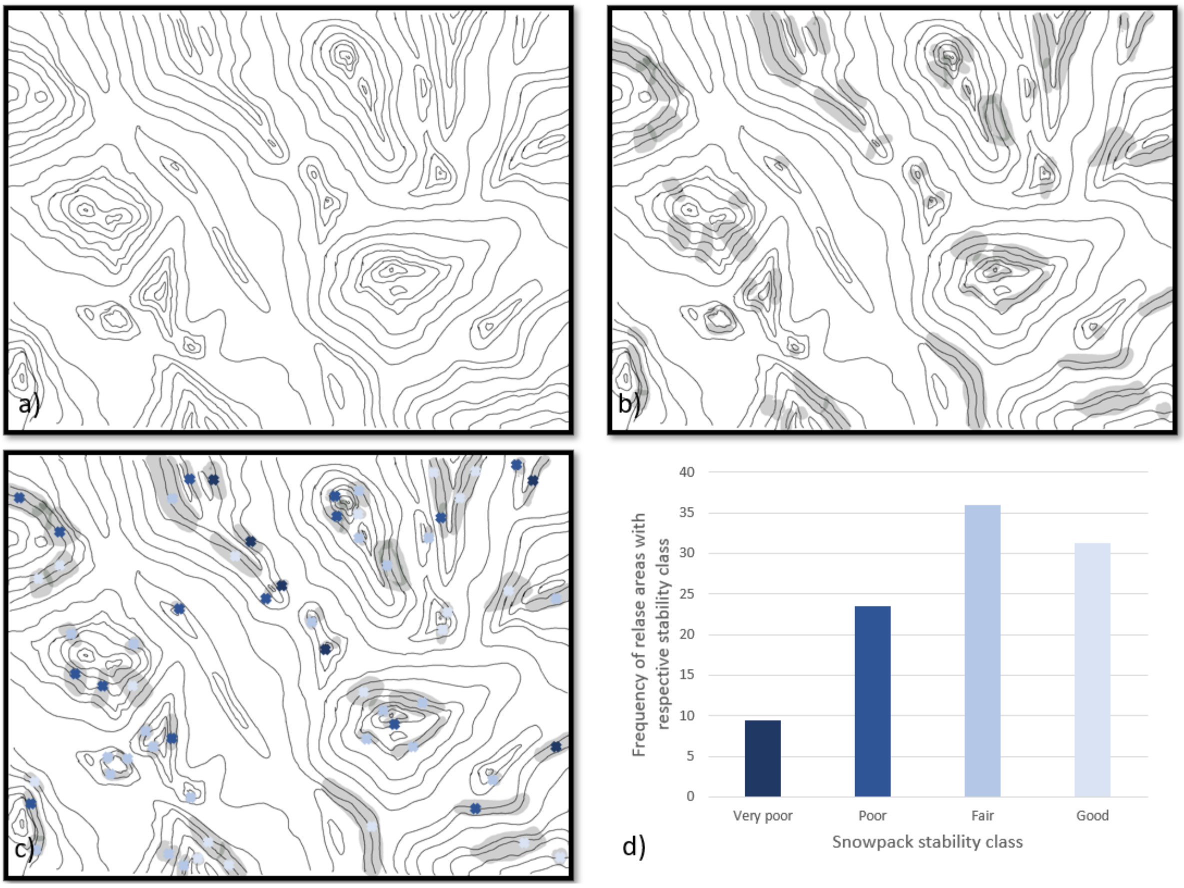

Figure B-1: Illustration of frequency distribution. We consider a hypothetical and idealized scenario where a stability assessment for points within starting zones is available. Here, our micro-region is defined by the contour map in panel a). For sake of simplicity, we choose the reference unit to be equal to the micro-region. Thus, considering all points in the starting zones within the region independent of elevation, aspect or other possible subdivisions (Panel b). Panel c) shows the stability class assessed in each point. Panel d) shows the resulting frequency distribution of these stability classes. Generally, the frequency of the weakest stability class, in this case very poor, needs to be considered to determine the danger level.

The challenge of assigning percentages, or deciding on thresholds between classes, has been debated a lot and we have no clear answer, yet.

Few forecasters or avalanche workers have enough data available that is conclusive and evenly distributed over relevant release areas in the region they are assessing. Therefore, assigning a frequency distribution class remains an expert opinion and experience for the time to come. We believe that much more data in combination with verification campaigns need to be assessed before we can provide good answers. In the following paragraphs, we list some studies that tried to quantify the frequency distribution of snowpack stability in one way or another. The presented numbers are currently the best estimates we have describing the frequency distribution of snowpack stability. They have different bases and cannot be compared directly or combined to describe classes uniformly. More studies of this type need to be conducted in the future to provide reliable percentages for the frequency of snowpack stability.

Stability tests (Rutschblock):

Frequency classes derived by Techel et al. (2020)b for the frequency of the Rutschblock stability class *very poor*:

- ***None or nearly none: 0%***
- ***a few*: >0% - <4%**
- ***some or several*: 4% - 20%**
- ***many*: >20%**

Avalanche activity (1):

Avalanche activity, as observed from satellite images over Switzerland in two extreme avalanche situations in January 2018 and January 2019 (Hafner, 2019): The proportion of potential release areas which was active (which avalanched) varied for a subset of 13 micro-regions between 4% and 23% with a mean of 13%. These micro-regions cover a surface area between 56 and 506 km^2, while the potential release area within these micro-regions covers between 21 and 159 km^2 of the surface area of these regions. When only considering the two most active neighboring 45°-aspects within these regions (e.g., from NW – N – NE), the observed maximum was 41% of the total release area being active. These values can be considered representing high values for the term *many*.

Avalanche activity (2):

Based on a 15-year data set of manually mapped natural avalanches in the region of Davos, Switzerland (Völk, 2020), the following frequency classes were obtained using the approach described by Techel et al. (2020)b for the proportion of potential release areas which were active (which avalanched):

- ***a few*: <0.02%**
- ***some*: 0.02-2.2%**
- ***many*: >2.2%**

Note, this mapping approach has a comparably low detection rate (Hafner et al. 2021). As an estimate, these class thresholds may be too low by a factor of ~2.

Appendix C: Avalanche size

The avalanche size used in the matrix to determine the avalanche danger level should be the largest size class that is likely to occur in case that an avalanche releases under the given or expected conditions. For example, for a situation that could be described as: "If avalanches are released, up to *size 3* avalanches are likely". In this case, we would expect *none or nearly none* of size 4 and 5 avalanches. However, in this scenario, we consider it likely that avalanches of size classes 1, 2 and 3 can occur. Thus, we choose the largest of these – in this case *size 3* (see following table).

Avalanche size	If avalanches release or are released, this size class is...	
	Likely	Unlikely
5		x
4		x
3	**x**	
2	x	
1	x	

Appendix D: Methodology to revise the EAWS Matrix

The EAWS assigned the working group (WG) Matrix & Scale with the task to revise the definitions for the contributing factors of avalanche hazard, as described in the previous sections of this document. Consequently, a revision of the existing EAWS matrix (version 2017) was required to be in line with these definitions.

Previous versions of the look-up tables assisting avalanche forecasters to assign a danger level, the so-called "Bavarian matrix" (EAWS, 2005) and its successor, the "EAWS-Matrix" (EAWS, 2017), were developed relying on the joint knowledge of EAWS avalanche forecasters. However, the process of how individual opinions about the danger levels in the cells, was not documented.

In the following, we describe the methodology used to obtain the revised EAWS Matrix.

Methodology

Due to the general lack of data allowing a quantitative description of the danger levels, the WG followed an approach combining many expert opinions. Expert elicitation is particularly suitable in cases when appropriate data is lacking (e.g., Rowe and Wright, 2001). In other words, for this task, we relied on the wisdom of the avalanche forecasters as for previous matrix versions. However, instead of having the members of a small work group decide in group discussions on danger levels, we relied on a heterogeneous, larger group of experts. We considered experienced EAWS forecasters as having the appropriate domain knowledge, and, thus, to be equally competent for this task. This approach was motivated by the fact that the combined judgment of a group of experts is generally more accurate than that of an individual, if non-interacting individuals make judgments (e.g., Stewart, 2001). Finally, by offering the chance to participate, we expected a greater acceptance of the proposed matrix.

Therefore, we invited EAWS forecasters to provide their version of the matrix considering the new terminology and definitions.

Survey

The matrix was distributed as a survey with the following instructions:

Forecasters should assign a danger level to the combination of the terms describing snowpack stability, the frequency distribution of snowpack stability, and avalanche size. As an example, a danger level should be assigned to a scenario that could be described like "*Many* locations with *poor* stability exist. In case that avalanches release, avalanches up to *size 3* are likely." Starting with the most unfavorable combinations, forecasters had to first assign a danger level to all frequency – avalanche size – combinations relating to *very poor* stability, which is typically associated with natural avalanches. In a second step, forecasters had to consider *poor* snow stability as the decisive stability class. This meant that forecasters had to assume the frequency of locations with stability class *very poor* to be *none or nearly none* (or at most *a few*). Last, forecasters did the same for *fair* stability. If forecasters considered a class as not plausible, or if they did not know what danger level to assign, they were advised to leave this cell empty. If forecasters were uncertain between two danger levels, they could indicate a first and a second danger level.

Following best practice for expert elicitation, we instructed forecasters to do this task independent from other forecasters. Most importantly, danger levels assigned to specific combinations of stability, frequency, and avalanche size, should not be discussed between forecasters prior to forecasters submitting their response to the specified member of the working group.

The deadline for submitting responses was set to May 5th to allow the preparation of the documents for the EAWS General Assembly in Davos 2022. We will continue to collect answers for future considerations after the GA.

Matrix responses

1. The WG members filled in a matrix at a meeting in 2019, and again in 2022 (N = 5 and 9, respectively). Both these versions were considered following the methodology of test-retest (e.g., Ashton, 2000) to obtain more reliable estimates when judging. The second round was also used to test the sheet distributed to other forecasters.
2. Avalanche forecasters were invited by contacting forecasters on the EAWS mailing list and/or the heads of the warning services to provide their matrix version (N = 60).
3. Quantitative studies were included where available (N = 2; Swiss data: Techel et al., 2020b, Hutter et al., 2021).

Table D-1: Distribution of matrix responses received.

Country	**N**
Andorra	3
Austria	4
Czech Republic	0
Finland	0
France	7
Germany	5
Great Britain	7
Iceland	0
Italy	18
Norway	15
Poland	0
Romania	1
Slovenia	1
Slovakia	0
Spain	5
Switzerland	8
Sweden	2
Total	**76**

Analysis

The working group decided on the approach to combine the different matrix versions before EAWS forecasters had sent their responses. Not favoring any one opinion, the WG opted to calculate the median danger level for each combination of stability, frequency, and avalanche size. In addition, we checked that this was also the majority opinion. This is in line with best practice approaches when combining judgments from experts (e.g., Dietrich and Spiekerman, 2022).

We weighted responses as follows:

- If forecasters indicated one danger level, this danger level was weighted with 100.
- If forecasters indicated two danger levels, the first danger level was weighted with 67 and the second with 33.

Revised EAWS Matrix as of 2022 – content and reliability of content

Figure D-1 shows the matrix based on the 76 responses. The same matrix, although in a different lay-out, is shown in Figure 2 in the [main document](). For each combination of snowpack stability, frequency, and avalanche size, the following values are shown:

- The median danger level is indicated showing the integer value for each danger level (e.g., *1* for *1 (low)*). If the distribution of responses was heterogeneous, a second danger level is shown in brackets, representing the interquartile range, if this danger level was different from the median danger level.
- The color coding of a cell corresponds to the median danger level.
- Combinations, which had a danger level assigned in ≤70% of the cases (Fig. D-1), have a white background, although the median danger level is shown. These cells represent combinations many forecasters did not feel comfortable with assigning a danger level. These cells have rather low support (Fig. D-1).

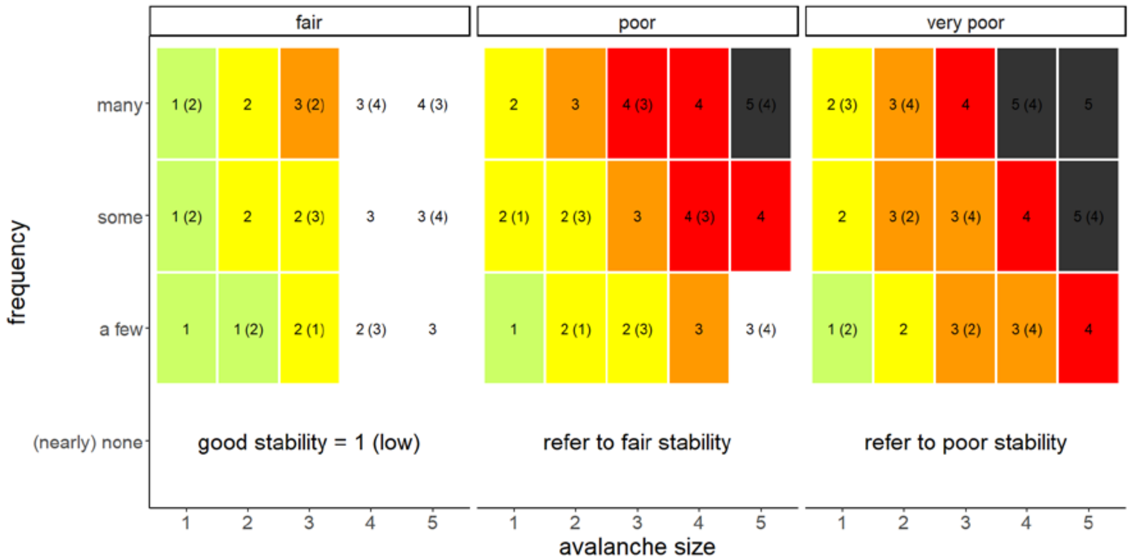

Figure D-1: EAWS matrix (v2022). Table and caption to be updated. For details refer to the text.

It is in the nature of expert judgments, that there will be variations between them. Such variations may be caused by different perceptions regarding the meaning of the terms or mental images of danger levels. Therefore, in the following, we briefly show some findings that highlight uncertainties regarding the danger levels assigned by respondents, and in the aggregated final matrix.

Forecasters were advised to fill in all cells for which they felt comfortable assigning a danger level. Moreover, fair stability was optional with the goal to increase the participation rate. On average, respondents provided a danger level value for 85% of the possible 45 combinations. Figure D-2 shows the proportion of the 76 responses, for which a danger level was provided. A danger level was indicated by 72 of the 76 respondents (≥95%) for 17 of the 30 combinations with *very poor* and *poor* stability. *Fair* stability, in combination with avalanche *size 5* (≤50%) or *size 4* (≤66%) had the lowest response rate, and consequently, a higher uncertainty related to the median danger level.

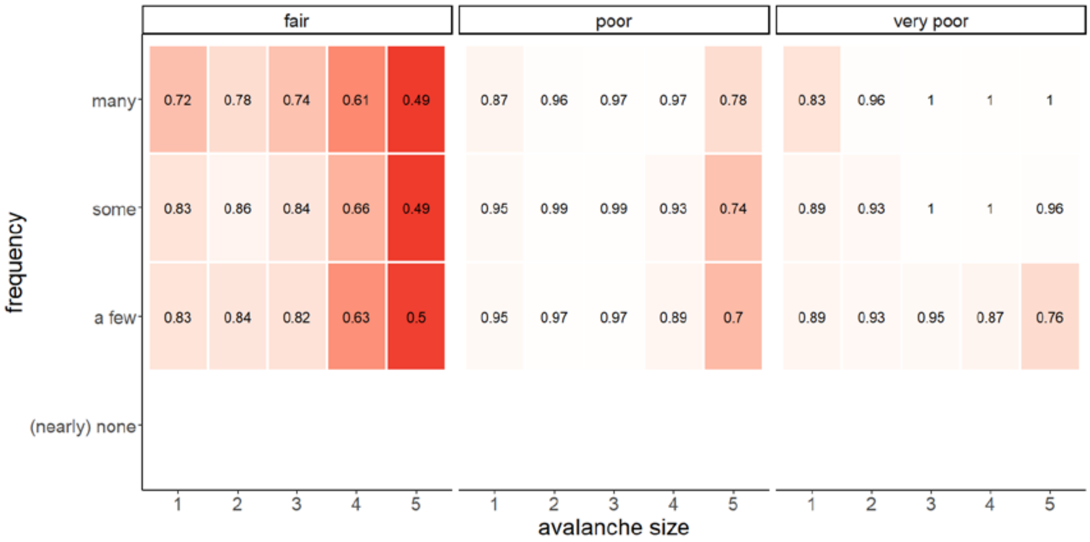

Figure D-2: Proportion of responses indicating a danger level for each of the combinations of stability – frequency – avalanche size. The respective proportion is shown (number). Light colors correspond to combinations with a high proportion (i.e., a danger level was always indicated for very poor – many – size 5), dark colors to comparably low proportions (i.e., about 50% of the responses indicated no danger level for fair stability and avalanche size 5).

Respondents had the option to indicate one danger level or two danger levels if uncertain. 64% of the time one danger level and 36% of the time two consecutive danger levels were indicated. This highlights that it is sometimes difficult to assign a specific danger level to a combination of stability, frequency, and avalanche size.

Figure D-3 shows the proportion of the weights assigned to the median danger level (see matrix in Figure D-1). In 12 of the 45 (27%) combinations, the most frequent danger level received ≥75% of the weights, indicating a low number of cases with two danger levels and/or a high agreement between forecasters. Only two cells had values of >95%. In contrast, there were also six cells (13%) with rather low support for the most frequent danger level (proportion <55%).

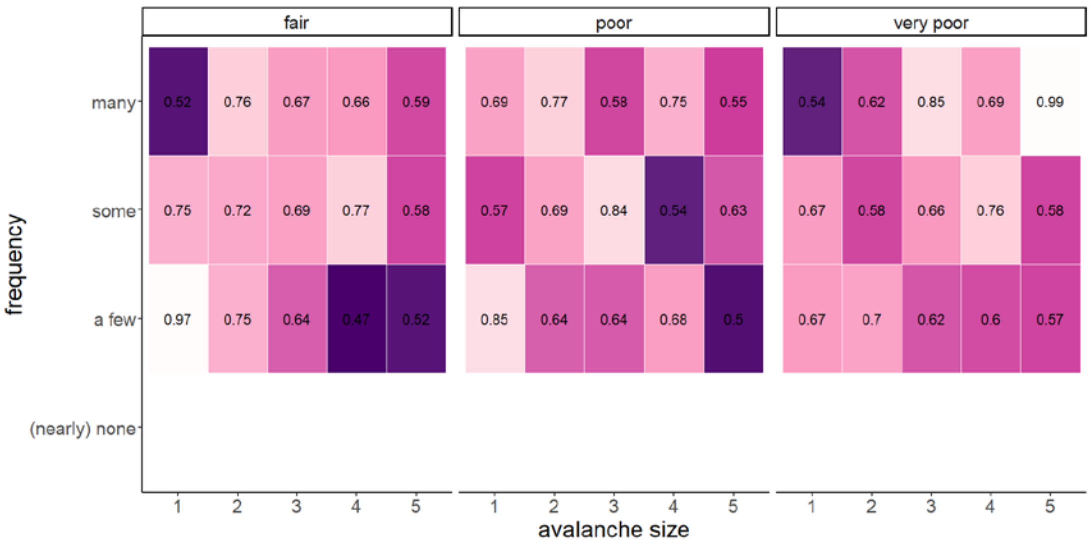

Figure D-3: Proportion of responses indicating the most frequent danger level (equal to the median in Figure D-1) for each of the combinations of stability – frequency – avalanche size. The respective proportion is shown (number), light colors correspond to a high proportion (i.e., close to full agreement for very poor – many – size 5*), dark colors to a comparably low agreement (i.e., 54% of the responses indicated 2 (moderate) for* very poor – many – size 1*).*

Appendix E: Workflow chart

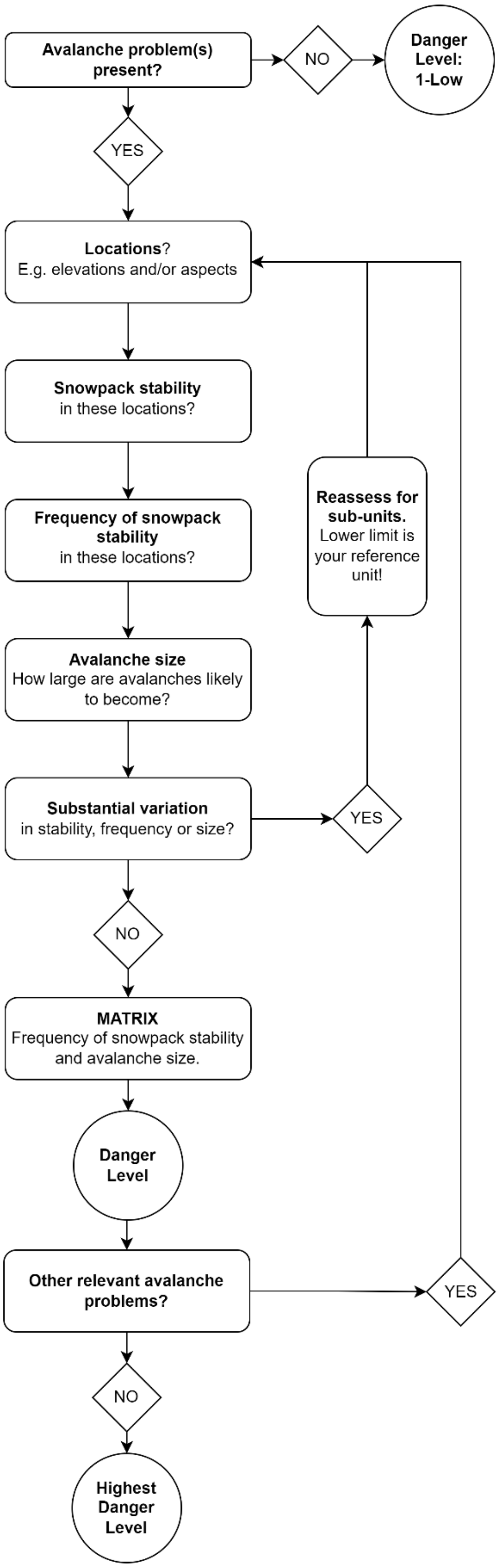

Figure E-1: Workflow to determine the avalanche danger level.

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