THE EAWS MATRIX, A LOOK-UP TABLE FOR REGIONAL AVALANCHE DANGER LEVEL ASSESSMENT, AND ITS UNDERLYING CONCEPT

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ABSTRACT: With the motivation to increase consistency between forecasters and warning services when assessing regional avalanche danger, a working group of the European Avalanche Warning Services (EAWS) was assigned to define the factors determining regional avalanche danger, and to develop a workflow and a look-up table – referred to as EAWS Matrix - assisting forecasters with the consistent assignment of a danger level. The workflow starts by an evaluation of avalanche problems relevant for the given region. Each avalanche problem is assessed according to three factors determining regional avalanche danger: i) snowpack stability, ii) the frequency of snowpack stability, and iii) avalanche size. Combining the three factors, each avalanche problem is assigned a danger level using the EAWS Matrix. The highest resulting level is issued for the region. Workflow, definitions, and the look-up table were accepted at the EAWS general assembly in 2022. We present workflow, definitions, the corresponding EAWS Matrix, and the process and considerations that led to this proposal.

KEYWORDS: avalanche, forecasting, danger level, matrix, workflow, consistency

1. INTRODUCTION

In most regional avalanche forecasts, a danger level is indicated, which is the central piece of information summarizing the severity of avalanche conditions. In Europe, the European Avalanche Danger Scale (EADS) was accepted as a definition of five danger levels (DL) in 1993: 1-low, 2-moderate, 3-considerable, 4-high, and 5-very high. The EADS describes each DL by the expected snowpack stability and the likelihood of triggering an avalanche (EAWS, 2023a). Dissecting the textual description of each column in the EADS leads to three factors describing the DLs: i) snowpack stability, ii) the frequency of snowpack stability, and iii) avalanche size. In general, locations where the snowpack is unstable are more frequent and avalanches are larger with higher DL. The classes used to describe snowpack stability, which relates to a triggering level, and the frequency of locations with a specific snowpack stability were not defined and, thus, led to various interpretations among different forecasters and forecasting services. The same is true for the likelihood terms used in the Conceptual Model of Avalanche Hazard (Statham et al., 2018, Thumlert et al., 2020). For instance, the description of DL-3 “The snowpack is moderately to poorly bonded on many steep slopes.” permits widely differing interpretation since neither “moderately to poorly bonded” nor “many steep slopes” are defined. Another drawback of the EADS is that sometimes more than one factor increases from the definition of one DL to the next, thus, again leaving room for subjective choices when only one factor increases or decreases. Due to the lack of clear definitions, many services in Europe developed their own guidelines over the years. Aligning these guidelines is further complicated by the multitude of languages and cultures in the European countries.

In 2005, the Bavarian Matrix (BM) was introduced in addition to the EADS. The BM included two matrices. One plotting the likelihood of triggering avalanches by additional load against the spatial distribution and a second one plotting the likelihood of spontaneous avalanches of various sizes against spatial distribution. The advantage over the EADS was that now each change of the factors was assigned a DL. However, the terms in the BM were still the same as in the EADS and largely undefined.

Several other attempts over recent years were made to improve the BM such as Avalanche Danger Assessment Matrix (Müller et al. 2016), the first version of the EAWS Matrix (EAWS, 2017), and a data-driven matrix (Techel et al., 2020a).

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Recent studies have shown inconsistencies when assigning DL between individual forecasters and forecasting services. While forecasters seem to agree well at the margins of the scale at DL-1 and DL-5 when assessing the same situation, substantial differences in judgment exist when the danger rating was in the middle of the scale (i.e., DL-2 and DL-3) (Lazar, 2016). According to Techel (2018), who analyzed the spatial agreement of forecast DLs across the European Alps for five consecutive winter seasons, sources for variations were not only related to variations in snow climate but also to the size of the micro-regions, the smallest spatial units used in the forecasts. Moreover, variations were particularly large when comparing immediately neighboring regions across the boundaries of avalanche warning services, in some cases suggesting a different use of the DLs.

The EAWS assigned a workgroup with the task to define the terms characterizing the DLs as used by European avalanche warning services (EAWS). The definitions presented in sections 2 and 3 were presented together with the workflow (Sect. 4) and the EAWS Matrix (Sect. 5) at the general assembly of the EAWS in 2022. The definitions, workflow and Matrix were accepted as standards with a three-year qualifying period. Until 2025 feedback on the operational use of the definitions, the workflow and the matrix will be collected and used to their improvement.

2. SETTING THE SPATIAL AND TEMPORAL FRAME

An avalanche danger level is always assigned to a region and period. The working group proposed the following terminology to communicate the scale a forecasting service is operating at.

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-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).

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

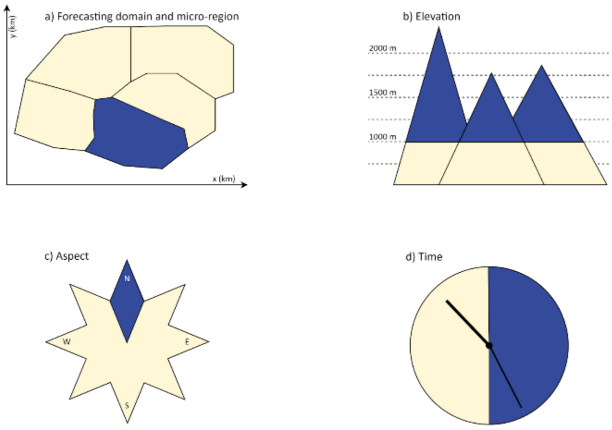

Figure 1: Typically, a reference unit can be characterized by the combination of the smallest sub-divisions for the elements: (a) the smallest geographical entity (the micro-region) within a forecasting domain, (b) the resolution of elevation and (c) aspect, and (d) a temporal subdivision. In the figure, exemplary subdivisions are highlighted. Here, the size of a single micro region defines the spatial x-y-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 in blue, would be the reference unit, the smallest spatial-temporal entity at which the avalanche danger level can be assessed.

forecasting service (and ideally across forecasting services).

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.

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 a **reference unit**.

3. DEFINITIONS

The following definitions were presented at the General Assembly of the EAWS in June 2022, where they were accepted as standards for regional avalanche forecasting services in Europe.

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

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.

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 (Table 1).

Table 1: Stability classes, and the type of triggering typically associated with these classes.

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

Depending on the avalanche type, snowpack stability is described by:

- Failure initiation, crack propagation and slab tensile support (slab avalanche) (Reuter and Schweizer, 2018)
- Loss of strength/bonding (loose-snow avalanche) (e.g., McClung and Schaerer, 2006)
- Loss of basal friction and slab tensile and/or compressive support (glide-snow avalanche) (e.g., Bartelt et al., 2012).

Snowpack stability is further described by three charts connecting typical observations to the four stability classes (EAWS, 2023b). 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. The term local refers to a point which ranges in size from a potential trigger location or stability test to a starting zone. All snowpack stability assessments may refer to either future (forecast) or present (nowcast) based on observations or models. E.g., if the snowpack stability in a release area is considered fair today, and 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 decreased to poor or even very poor by that time.

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).

Table 2: Classes of frequency distribution of snowpack stability.

Frequency class	*Description*
Many	Points with this stability class are abundant.
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.
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.

The frequency distribution of snowpack stability refers to (many) points (i.e., stability tests, snowpack models or potential triggering locations) or avalanche starting zones. The frequency must be assessed for a warning region which must be equal to or larger than the reference unit. 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 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.

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.

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.

4. WORKFLOW TO DETERMINE THE AVALANCHE DANGER LEVEL

The workflow in Table 4 describes the path from assessing the avalanche problems to setting the avalanche danger level for a micro-region. All relevant avalanche problems must be considered, and their snowpack stability, frequency and avalanche size evaluated within the reference unit. The highest resulting danger level will be communicated for the given micro-region. Micro-regions with the same avalanche problems, factors and therefore DL can be aggregated into a larger warning region.

5. EAWS MATRIX

The EAWS Matrix is used to determine the avalanche danger level (DL) based on the snowpack stability, frequency of snowpack stability and avalanche size of the relevant avalanche problems.

5.1 Derivation of the matrix

Due to the general lack of data allowing a quantitative description of DLs, we 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 DLs, 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

Table 4: Workflow to determine the avalanche danger level in a micro-region.

	Task	***Explanation and remarks***
1	**Assess which avalanche problems are present.**	Choose from the avalanche problems defined by EAWS (EAWS 2022)
	If no avalanche problem exists, 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.**	

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

Forecasters should assign a DL 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 as "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 DL to all frequency – avalanche size – combinations relating to very poor stability (Figure 2), 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). Finally, 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 DLs, they could indicate a first and a second DL.

Following best practice for expert elicitation, we instructed forecasters to do this task independent from other forecasters. Most importantly, DLs 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.

We received 60 responses from 17 different forecasting services in Europe. In addition, we included responses from the work-group members from a similar exercise in 2019 and 2022 and from two quantitative studies (Techel et al., 2020b, Hutter et al., 2021). Resulting in a total of 76 individual matrices. We combined these matrices into one (Figure 2). The median DL is indicated showing the integer value for each DL (e.g., 1 for 1-low). If the distribution of responses was rather heterogeneous, and a second value was suggested in more than 30% of the responses, this DL is shown in brackets, representing the interquartile range.

5.2 *Matrix usage*

The forecaster assesses the three factors snowpack stability, frequency of snowpack stability, and avalanche size according to the workflow described in section 4 and then selects the corresponding cell within the Matrix.

When applying the matrix in Figure 2 you should use the first DL given in the cell. An optional DL in parenthesis indicates that forecasters might disagree with a tendency towards this DL. 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*

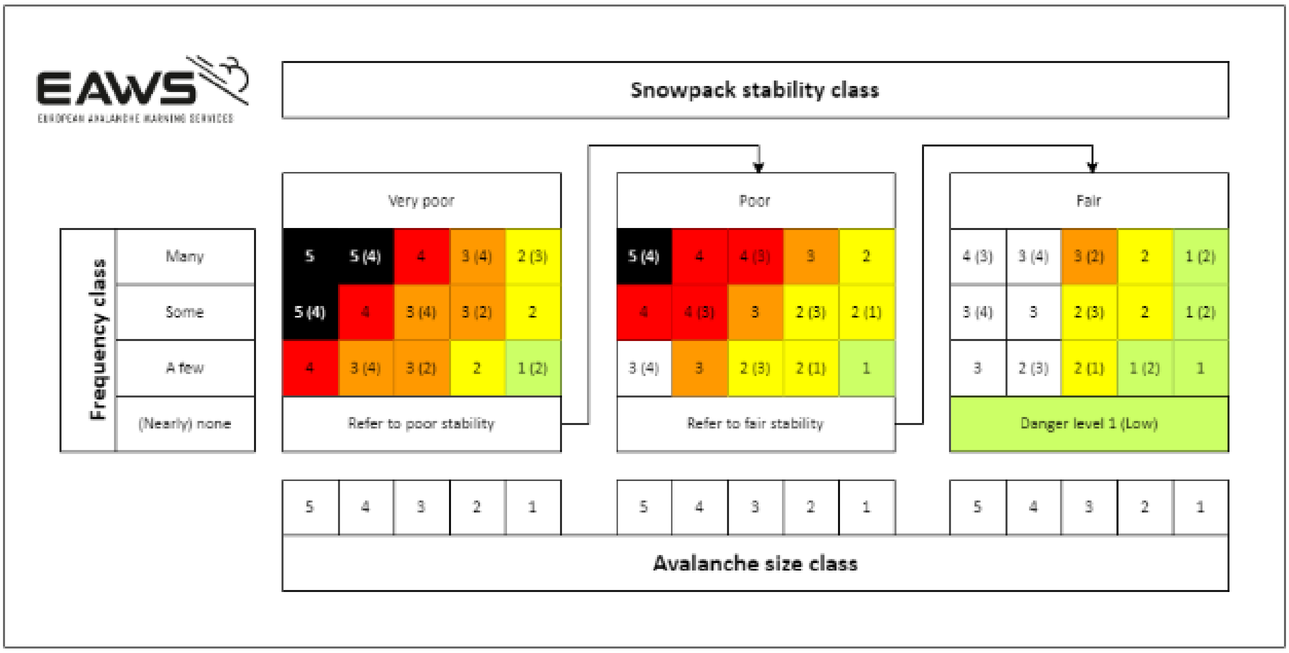

Figure 2: Updated EAWS Matrix based on European avalanche forecaster's expert opinion. The layout is preliminary and was chosen to accommodate all possible combinations of snowpack stability, frequency, and avalanche size.

stability on *many* slopes and avalanches up to *size 3* are likely, the result would be danger level 4-high.

6. DISCUSSION

Compared to previous versions of the matrix that had been developed by only a hand-full of avalanche experts, we tried to involve many forecasters from various services. We used the median and an arbitrary threshold of >30% to set DL and potential second choice for each combination of snowpack stability, frequency, and avalanche size.

The terms defined to describe the spatial scale of a forecasting operation were designed to allow a flexible and dynamic aggregation of warning regions. However, many forecasting services operate with static warning regions, meaning boundaries for areas that get assessed and assigned a DL do not change. In such cases the micro-region and warning-region are congruent and static.

The EAWS decided on a test phase until 2025 for the current matrix. Services have thus, three years to implement the standards in their operational routines and provide feedback and suggest adjustments. During this period, we will collect feedback from operational use to further improve the definitions, workflow, and matrix. We will gather data on how often forecasters choose individual cells in their day-to-day work and how often they agree or disagree with the DL suggested by the matrix.

An important task during this test period will be to check if the use of the matrix leads to higher consistency between forecasters when assigning a DL. Cells that include a second choice need to be evaluated carefully. Usage data might provide either a clear allocation of a single DL or will need clear guidelines on when to use the DL in the parenthesis. It might also indicate that the terms are not yet defined well enough or decisive factors are lacking in the matrix.

The final goal is to provide a decision matrix that provides the basis for assigning an avalanche danger level to a region. Once the matrix is set, we will update the avalanche danger scale to ensure tight integration of the two tools. While the matrix is intended to serve as a base defining all possible combinations, the danger scale will only contain the typical combinations for a given DL and serve as a communication tool for the public.

7. CONCLUSION

We presented the definitions of terms used to describe and assess regional avalanche danger. Common definitions are the basis for consistent usage and understanding of terms in a field. We provide a look-up table, called the EAWS Matrix, together with a corresponding workflow to assess regional avalanche danger. The motivation is to provide tools that increase consistency among avalanche forecasters and forecasting services when assigning a danger level.

The matrix and workflow are currently in a test phase and will be evaluated operationally until 2025. The European avalanche danger scale will be updated during this period to align with the matrix and the definitions of snowpack stability, frequency, and avalanche size.

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