THE FOUR KEY COMPONENTS OF THE PHYSICAL HAZARD POSED BY SNOW AVALANCHES ACROSS TERRAIN

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ABSTRACT: Forecasting the physical hazard posed by snow avalanches is the prediction of the magnitude, likelihood, timing, and location of potential avalanches within defined mountain terrain over a specific period. The process of hazard assessment and communication is fundamental for avalanche professionals. Avalanche hazard is typically and has been historically described as the combination of the likelihood and the expected size of avalanches assessed for specific characteristics of expected avalanches (e.g. avalanche problems). Clearly defining the type of avalanche (or avalanche problem) expected is essential for accurate forecasting because it contextualizes their location in the terrain and allows the forecaster to assess how the snowpack will respond to weather influences and other dynamic loads (e.g. humans, explosives). While leveraging avalanche problems for hazard assessment yields valuable insights, there is a lack of guidance on how to integrate these assessments into an overarching hazard rating. Current avalanche hazard scales often fall short in capturing the nuanced expertise of professional forecasters perhaps because they have been designed as public communication tools with the intention of mitigating the avalanche risk for public backcountry recreationalists. This limits their utility for professional risk management. To address this gap, this paper aims to lay the groundwork for a more formalized professional avalanche hazard rating scale by describing the four core components comprising the physical avalanche hazard when assessed spatially across mountain terrain: 1) Likelihood of Avalanches, 2) Size, 3) Spatial Distribution, and 4) Snowpack Complexity. These components directly contribute to avalanche hazard and must be integrated into a comprehensive hazard assessment, where significant increases in any component increase the overall avalanche hazard. This paper discusses the current systems and processes for describing these four components, offers insights for improvement, and suggests a path forward for the development of a professional avalanche hazard rating system.

KEYWORDS: Avalanche hazard assessment, Forecasting, Physical hazard, Hazard rating systems.

1. INTRODUCTION

Assessing, rating, and forecasting the physical hazard posed by snow avalanches is fundamental to daily work for Avalanche Professionals. Avalanche risk mitigation strategies – e.g. avalanche explosive control, communicating danger level and terrain advice to public, closing terrain at a resort, selecting terrain when guiding – are implemented largely based on the assessment of the physical avalanche hazard. That is, the physical hazard posed by avalanches is assessed first and mitigation strategies typically follow.

Avalanche Professionals assess avalanche hazard for terrain over varying spatial scales: mountain range or region (e.g. public forecast regions, > 10,000 km^2), mountain or drainage (e.g. ski resort, group of paths affecting transportation corridor, guiding tenure, > 100 km^2), path or terrain feature (e.g. specific avalanche start zone, < 1 km^2). The variability of the snowpack across larger spatial scales means that the physical hazard on terrain features also varies, meaning that there may be areas of low or no hazard and areas of elevated hazard within the hazard assessment extent. Avalanche hazard assessment across the terrain in the forecast area must account for this variation.

Modern avalanche hazard assessment systems (e.g. Statham et al., 2018; McClung and Schaerer, 2022) incorporate the concept of Avalanche Problem Types (e.g. Dry Loose, Wet Slab, Persistent Slab) based on Atkins (2004) descriptions of the character of expected avalanches. Incorporating the type of avalanche expected provides valuable information about the behavior of these avalanches, location of the avalanches in the terrain, and the time this type of avalanche can be expected to exist for. Snowpacks can be assessed with a varying number of avalanche problems, and in general, early season snowpacks have fewer expected problems due to the lack of buried persistent weak layers. As the season progresses, snowpacks generally get more complex with multiple buried weak layers, cornice growth, and surface snow instabilities. An effective assessment of avalanche hazard across terrain must include an

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analysis of how multiple avalanche problem types contribute to the overall hazard assessment. More complex combinations of avalanche problem types typically equate to higher hazard.

Most traditional and recent avalanche hazard assessment literature (e.g. Meister, 1994; Canadian Avalanche Association, 2016; Statham et al., 2018; McClung and Schaerer, 2022) describe avalanche hazard across terrain as a function of the expected size and likelihood of triggering of avalanches. Figure 1 shows an example of avalanche hazard with uncertainty illustrated by the extent of the ellipses for two avalanche problems. Avalanche size is well described with the Canadian destructive potential scale (McClung and Schaerer, 2022), and in general larger expected avalanche sizes equates to increased avalanche hazard. Assessing the likelihood of avalanches is complex and involves subjective probability assessments (process described well by Vick, 2002) derived from many data sources like recent avalanche activity, snowpack structure, and weather inputs. Subjective probability assessments are now widely communicated with an ordinal scale of verbal probability descriptors: Unlikely, Possible, Likely, Very Likely, Almost Certain (Statham et al., 2018). Higher likelihood assessments should mean more avalanches are expected across terrain or that higher potential of avalanche release is expected. In general, increasing expected avalanche size or likelihood equates to higher avalanche hazard. However, assessing avalanche hazard across terrain as only a function of likelihood and size is simplistic and does not: 1) include the spatial variation of hazard across the forecast region, nor does it 2) allow for the assessment of the complexity of the snowpack.

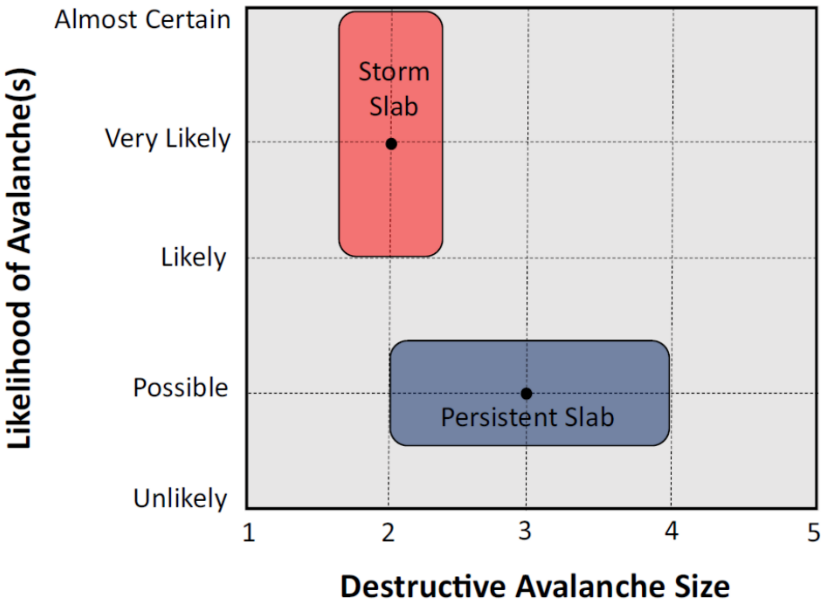

Figure 1 – An example of qualitative avalanche hazard chart from the CMAH showing two avalanche problems. In this example, Persistent Slab avalanches are Possible from Size 2 to 4, while Storm Slabs near to Size 2 are Likely to Almost Certain.

The objective of this paper is to describe how these two key components contribute to the overall avalanche hazard, and to lay the groundwork for the development of a robust professional avalanche hazard rating system.

2. PHYSICAL AVALANCHE HAZARD

What components effectively describe the physical hazard due to snow avalanches across terrain? First it is important to define the physical hazard across terrain – a source of potential harm, damage, or loss. Physical hazard can be described as the potential hazard posed by the current or expected state of the snowpack. While our knowledge about the state of the snowpack always involves a degree of uncertainty - and more uncertainty can increase risk - the snowpack and the resulting physical hazard does not change based on our knowledge of it. That is to say, we can - and in many cases it is valuable to - separate the description of the potential hazard due to the current snowpack before considering elements at risk.

Using the concepts presented above we propose that the following four components describe physical avalanche hazard across terrain: Likelihood of Avalanches, Magnitude, Amount of Terrain, and Complexity of the Snowpack.

1) Likelihood of Avalanches – also sometimes referred to as release probability and has historically been called snow stability. Likelihood of avalanches is basically the chance of avalanche activity in the forecast area with the forecast time period, or the chance that a specific path or start zone will release during the time period, regardless of avalanche size. Higher likelihood assessments should indicate increased avalanche activity is expected, or increased potential of avalanches. An effective system used to communicate forecaster's likelihood assessment should use clear definitions to promote effective communication (Fischer and Jungermann, 1996), increase forecasting accuracy (e.g. Rapoport et al., 1990), and improve decision-making (Friedman et al., 2018). The likelihood definition and system should also be largely independent of the spatial scale being assessed. That is, the system should work equally well when assessing single paths to larger regional scales. The following definition is proposed: Likelihood of avalanches is the chance of the start zones or avalanche paths being assessed releasing within the forecast time period, regardless of avalanche size.

2) Magnitude – the estimated size (i.e. destructive potential) of the expected avalanches as defined by the Canadian avalanche size definitions shown in Table 2 (OGRS, 2024). Magnitude is a core component of avalanche hazard. The size definitions are widely used and accepted across the industry, and there is currently work being done to potentially improve the scale (Jamieson et al., 2023).

Table 2: Canadian Avalanche Size definitions (OGRS, 2024).

Size	Destructive potential	Typical Mass (t)	Typical length (m)	Typical deposit volume (m^3)	Typical impact pressure (kPa)
1	Relatively harmless to people.	< 10	10	50	1
2	Could bury, injure, or kill a person.	10^2	100	500	10
3	Could bury and destroy a car, damage a truck, destroy a wood-frame house or break a few mature trees.	10^3	1,000	3,000	100
4	Could destroy a railway car, large truck, several buildings or a forest area of approximately 4 hectares.	10^4	2,000	25,000	500
5	Could destroy a village or a forest area of approximately 40 hectares.	10^5	3,000	200,000	1,000

3) Amount of Terrain – the proportion or amount of terrain across the forecast area where avalanche problems are expected to exist. More terrain in the forecast region containing avalanche problems equates to higher hazard. For example, a day where the assessed avalanche problem and corresponding hazard is expected to exist only on southerly aspects in the forecast region (e.g. Persistent Slabs Likely to Size 2.5) presents less overall physical hazard than another day where the assessed avalanche problem exists on all aspects. Put in another way, if the assessment of avalanche problems results in more terrain features or start zones across the forecast region then it follows that there will be more physical avalanche hazard across the forecast region.

4) Complexity of the Snowpack – this component of avalanche hazard relates to the number and type of avalanche problems expected to exist for a given snowpack structure and how forecasters assemble them into an overall hazard rating. Simpler snowpacks that are less deep, contain less weaknesses, and are more homogeneous across terrain are less hazardous than deeper snowpacks with multiple weak layers that vary in the terrain. For example, a snowpack assessed as only having a Storm Slab problem (e.g. Likely to Size 2) will behave more predictably (less complexity) – and thus is less hazardous - compared to a similar snowpack with additional deeper weaknesses assessed with a Deep Slab problem (e.g. Fair Chance to Size 3.5). It is important to note that this type of uncertainty with the snowpack structure is different than the uncertainty that a forecaster may have due to the lack of data or observations, which may result in lower confidence in hazard ratings.

A complete and thorough assessment of avalanche hazard across mountain terrain requires all these four elements be included. Rating and communicating the hazard assessment is natural next step that Avalanche Professionals must complete.

3. OPERATIONAL AVALANCHE HAZARD RATING SYSTEM

Avalanche hazard rating systems have proven an effective method for describing the output of a forecaster's hazard assessment (e.g. Statham et al., 2010a; SLF, 2015; EAWS 2016a; Avalanche Canada, 2024). Ordinal five-level systems complete with descriptions of each level are common, although many industrial applications employ simpler three-level systems. For valid reasons, different operations tailor their hazard rating systems specific to their operational needs, and consequently rating systems often incorporate risk management strategies. For example, the widely adopted North American Public Avalanche Danger Scale (NAPADS) shown in Figure 3 includes Travel Advice and "*the purpose of the avalanche danger scale is public risk communication*" (Statham et al., 2010). The NAPADS was designed specifically for the element at risk (i.e. public backcountry recreationalists) and includes risk management mitigations (i.e. Travel Advice), thus its description of the physical avalanche hazard is specifically tailored for communicating with public recreationalists. For example, there is no indication of the complexity of the snowpack and how it is incorporated into the hazard rating.

North American Public Avalanche Danger Scale

Avalanche danger is determined by the likelihood, size, and distribution of avalanches.
Safe backcountry travel requires training and experience. You control your risk by choosing when, where, and how you travel.

Danger Level	Travel Advice	Likelihood	Size and Distribution
5 - Extreme	**Extraordinarily dangerous avalanche conditions.** Avoid all avalanche terrain.	Natural and human-triggered avalanches certain.	Very large avalanches in many areas.
4 - High	**Very dangerous avalanche conditions.** Travel in avalanche terrain not recommended.	Natural avalanches likely; human-triggered avalanches very likely.	Large avalanches in many areas; or very large avalanches in specific areas.
3 - Considerable	**Dangerous avalanche conditions.** Careful snowpack evaluation, cautious route-finding, and conservative decision-making essential.	Natural avalanches possible; human-triggered avalanches likely.	Small avalanches in many areas; or large avalanches in specific areas; or very large avalanches in isolated areas.
2 - Moderate	**Heightened avalanche conditions on specific terrain features.** Evaluate snow and terrain carefully; identify features of concern.	Natural avalanches unlikely; human-triggered avalanches possible.	Small avalanches in specific areas; or large avalanches in isolated areas.
1 - Low	**Generally safe avalanche conditions.** Watch for unstable snow on isolated terrain features.	Natural and human-triggered avalanches unlikely.	Small avalanches in isolated areas or extreme terrain.

Figure 3: The North American Public Avalanche Hazard Rating Scale (Avalanche Canada, 2024).

A rating system effective for use by all Avalanche Professionals would be designed specifically to describe physical avalanche hazard across terrain and would be independent of any element at risk. Definitions for each hazard level would enable clear and effective communication of an Avalanche Professional's assessment of avalanche hazard and would support risk mitigation strategies. The definitions and the process employed to assign the ratings should be applied independent of the spatial scale, include analysis of the four components of avalanche hazard described above, and would be built from clear meaningful language. These hazard definitions and associated guidance will likely reduce variation between practitioner's evaluations, provide a learning resource for new professionals, and improve consistency in communication across the profession.

4. REQUIRED SOLUTION

There are currently no established hazard rating systems complete with guidelines for how ratings are to be applied that effectively describe physical avalanche hazard independent of elements at risk. The conceptual model proposed by Statham et al., (2018) does not yet include a hazard rating system, nor does it offer guidance on how forecasters should combine multiple avalanche problems. That is, the final step in assembling avalanche problem assessments into an avalanche hazard rating remains to be completed. The recent hazard analysis proposed by McClung and Schaerer (2022) also does not include a rating scale, nor does it offer advice for multiple avalanche problems, and uses the simplistic description of hazard as a function of only chance and consequence analysis (i.e. it does not specify how the variation of hazard across terrain be included). As discussed, the established NAPADS was developed as a “public risk communication” tool with the inclusion of risk management strategies, therefore its utility for rating avalanche hazard independent of the element at risk is limited.

The required solution is an avalanche hazard rating system that includes well-defined hazard levels and guidance on the process forecasters should use to assign the ratings. The solution can ultimately be considered the final remaining step in the conceptual model proposed by Statham et al. (2018). The rating system would be used widely to describe the raw physical avalanche hazard prior to consideration of operation or element at risk; and therefore, would be useful for the InfoEx community, taught in the industry training programs, and be integral to daily workflows for the majority of Avalanche Professionals.

ACKNOWLEDGEMENT

Thank you to Mike Conlan for reviewing and providing valuable feedback on this article. Grant Statham and Bruce Jamieson have provided fascinating opportunities to discuss avalanche hazard and likelihood assessment.

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