Nat Hazards
DOI 10.1007/s11069-017-3070-5

ORIGINAL PAPER

A conceptual model of avalanche hazard

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Received: 21 March 2016 / Accepted: 9 October 2017

Abstract This conceptual model of avalanche hazard identifies the key components of avalanche hazard and structures them into a systematic, consistent workflow for hazard and risk assessments. The method is applicable to all types of avalanche forecasting operations, and the underlying principles can be applied at any scale in space or time. The concept of an *avalanche problem* is introduced, describing how different types of avalanche problems directly influence the assessment and management of the risk. Four sequential questions are shown to structure the assessment of avalanche hazard, namely: (1) *What* type of avalanche problem(s) exists? (2) *Where* are these problems located in the terrain? (3) *How likely* is it that an avalanche will occur? and (4) *How* big will the avalanche be? Our objective was to develop an underpinning for qualitative hazard and risk assessments and address this knowledge gap in the avalanche forecasting literature. We used judgmental decomposition to elicit the avalanche forecasting process from forecasters and then described it within a risk-based framework that is consistent with other natural hazards disciplines.

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Published online: 02 November 2017

Keywords Avalanche hazard · Avalanche danger · Avalanche risk · Avalanche forecasting · Avalanche problem

1 Introduction

Snow avalanche hazard affects recreation, transportation, property and resource industries in snow-covered, mountainous areas worldwide (Stethem et al. 2003). It is estimated that about 250 people die in avalanches every year (Schweizer et al. 2015). About sixty percent of these fatalities occur in North America and Europe, where national avalanche warning services maintain detailed records of fatal avalanche accidents. In Canada, an average of 14 people per year died in avalanches from 1996 to 2016 (Jamieson et al. 2010a; Avalanche Canada 2016), while in the USA during the same period, avalanches claimed an average of 28 people per year (CAIC 2016). In the European Alps, an average of 103 people per year died in avalanches from 1970 to 2015 (Techel et al. 2016). A lack of detailed records on avalanche accidents in other parts of the world (e.g., Asia, South America) prevents a more accurate estimation of the annual number of avalanche fatalities worldwide.

Exposure to avalanche hazard may be voluntary, as is the case with skiing or snowmobiling, or involuntary, such as on public transportation corridors or in settlements. The techniques used to mitigate the risk from avalanches are different depending on the particular circumstances (CAA 2016). The long-term risk from avalanches to permanent settlements and critical infrastructure is typically managed by conducting hazard mapping during the planning process and/or the installation of defense structures, such as snow fences, diversion dikes and avalanche sheds. Safety services for ski resorts, temporary worksites and transportation corridors use closures and explosives to manage short-term avalanche risk, backcountry guides use professional route selection to control the exposure of their clientele, and public avalanche forecasters communicate regional avalanche danger to an audience who manages their own risk.

Despite these differences in risk mitigation techniques, the process of avalanche forecasting is common to all operations that manage short-term avalanche risk. Avalanche forecasters assess avalanche hazard, which is the potential for an avalanche, or avalanches, to cause damage to something of value. Avalanche hazard is a function of the likelihood of avalanche(s) and the destructive size of the avalanche(s). It implies the potential to affect people, facilities or things of value, but does not incorporate vulnerability or exposure to avalanches (Statham 2008; CAA 2016).

Avalanche forecasting has been the focus of numerous papers that describe the objective of avalanche forecasting (McClung 2002a), the nature of the reasoning process (LaChapelle 1966, 1980; McClung 2002a), the types of observations used for forecasting (Perla and Martinelli 1975; LaChapelle 1980; McClung 2002b) and the human influences on the hazard assessment process (McClung 2002a). These publications, however, fall short of describing the actual avalanche forecasting process, the pathway between field observations and hazard assessment that precedes risk assessment and mitigation.

Meister (1994) provides one of the first descriptions of avalanche hazard, which highlights that it is a combination of the probability of avalanche release and expected avalanche size. In 2005, the European Avalanche Warning Services introduced the Bavarian Matrix (EAWS 2016b), which combines the probability of avalanche release with the distribution of hazard sites to guide forecasters toward assigning an avalanche danger rating. While these papers offer deeper insight into the forecasting process, their descriptions are closely tied to assigning a rating on a public avalanche hazard scale.

Depending on the objective of the assessment, however, assigning a hazard rating is not necessarily required to make risk mitigation decisions. Atkins (2004), for example, illustrates that the character of expected avalanches is more important for making terrain choices when guiding groups of heli-skiers than a stability or hazard rating.

Although the existing literature provides a good overview of the general nature of the avalanche hazard assessment process and its inputs, tangible guidance on how to undertake and assemble an avalanche hazard assessment that informs risk mitigation decisions is lacking. The objective of this paper is to address this shortcoming by introducing a conceptual model of avalanche hazard (CMAH) that is universally applicable in all types of avalanche safety operations, is directly informative for risk mitigation decisions and aligns with best practices for risk management in other natural hazards disciplines. While this proposed model has direct advantages for operational avalanche forecasting, the overall framework also offers benefits for education, communication and research.

Our paper starts with a background section that provides an extended literature review on avalanche forecasting and describes additional concepts that contributed to the development of the CMAH. We then briefly discuss our approach to building the CMAH in the development Section before describing the structure and components of the CMAH in detail in Sect. 4. We follow with a discussion of operational experiences with the CMAH in Canada and the USA before concluding the paper with a summary of the benefits of the model.

2 Background

2.1 Overarching risk framework

Risk-based systems that use an explicit combination of hazard, exposure and vulnerability to determine and compare risks are widely used in the field of natural hazards. From 1980 onward and especially toward the end of the millennium, the risk concept has been increasingly adapted and introduced as a systematic approach for dealing with natural hazards (Bründl and Margreth 2015). Formal methods for avalanche risk evolved from landslide risk assessment techniques (Varnes 1984; Fell 1994; Barbolini et al. 2004; McClung 2005) and are today's best practice for determining risk to fixed infrastructure such as buildings, utilities and transportation corridors (e.g., Bründl and Margreth 2015; CAA 2016). Even though the use of risk-based systems was becoming well established for land-use planning in avalanche terrain, the risk concept had not been formally applied to backcountry recreation and operational avalanche forecasting until Statham (2008) described how hazard, exposure and vulnerability interact with mobile elements-at-risk. This formalized an assessment process that had developed naturally over years in the Canadian helicopter skiing industry. CAA (2016) then separated avalanche risk management into two streams: *planning* and *operations*, and described methods for risk assessments in each stream based on the common risk framework of ISO Guide 73: Risk management—Vocabulary (ISO 2009). Using the same risk-based framework for all types of avalanche risk situations helps to highlight the similarities between different applications (Statham and Gould 2016). Since avalanche hazard is independent of the element-at-risk, methods for avalanche hazard assessment are similar across different applications.

2.2 Nature of the avalanche hazard assessment process

LaChapelle (1980) described conventional avalanche forecasting methods as an iterative, ongoing process that uses deductive methods to analyze some data but is dominated by inductive logic. Avalanche forecasters produce forecasts by making subjective judgments based on their synthesis of the available data and evidence. These judgments occur in an environment of uncertainty, are based upon data of limited validity and are processed using experience-based heuristics (Tversky and Kahneman 1974; Gigerenzer et al. 1999). The use of heuristics allows experienced avalanche forecasters to break down the complex task of assessing avalanche hazard into simpler, judgmental operations (Adams 2005). These judgments are beliefs concerning the likelihood of uncertain events based on a few pieces of key evidence (Tversky and Kahneman 1974). Though heuristic methods work well most of the time, they are prone to bias and can sometimes trap people into making severe errors (McCammon 2002). Forecasting systems should mitigate these ‘heuristics traps’ by employing debiasing strategies (Vick 2002) and using methods for reducing uncertainty (Jamieson et al. 2015). The key is to have a tool box of heuristics and know when to apply which heuristic (Todd et al. 2012).

The CMAH aims to articulate the current, state-of-the-art judgmental assessment process used by avalanche forecasters and to describe the concepts and terminology commonly applied in practice. The CMAH describes key questions that avalanche forecasters ask themselves and provides a framework for how to combine disparate pieces of evidence into an overall assessment. Having an explicit framework that guides the assessment process can help to avoid heuristic traps, strengthen communication and provide a platform for studying forecasters’ heuristics with the long-term objective of capturing the existing expertise and developing evidence-based decision aids.

2.3 Data and evidence used in avalanche forecasting

Avalanche hazard assessments rely on observations of avalanches, snowpack, weather and terrain and require integrating a complex array of data and evidence to produce a forecast, often with considerable uncertainty. Avalanche forecasters strive to minimize this uncertainty by assimilating data and evidence accumulated incrementally over time (LaChapelle 1980), and extrapolating this across the landscape using their knowledge of local geography.

LaChapelle (1980) proposed three classes of data to prioritize data interpretation, organized according to its entropy, or predictive power. The higher the class number, the more uncertain the interpretation and the less direct the evidence. An observed avalanche is considered Class 1 data because it is direct evidence of current avalanche activity, whereas a measurement of air temperature is considered Class 3 data because of its indirect relation to avalanche activity.

However, all data and evidence are potentially relevant, including observations of *none*, such as when no avalanche activity (Class 1 data) implies low hazard. In other situations, a sudden rise or fall in air temperature (Class 3 data) might be the most important observation. This is clearly highlighted by Jamieson et al. (2010b), who show that relevant observations differ depending on the type of avalanches to be assessed. Close attention must be given to evidence that can be indicative of both low hazard and high hazard situations, as each condition has important implications that influence risk mitigation strategies and operational outcomes. The CMAH is designed to be flexible enough to accommodate these context-specific differences.

3 Development

The CMAH presented in this paper emerged from a project to revise and update the North American public avalanche danger scale (Statham et al. 2010a). During the initial work on the danger scale, it quickly became apparent that the danger scale was missing a foundation. Forecasters were using the descriptions included in the scale to determine the danger level, even though these descriptions were primarily intended to explain the danger levels to end users. This issue was not unique to the public danger scale. As pointed out in the introduction, the existing literature on avalanche forecasting falls short of describing the pathway between observations and the hazard assessment in a way that offers tangible guidance to avalanche forecasters.

Even though avalanche forecasters have high levels of skill developed through empirical experience, they are often unable to communicate their methods, or their personal connection between experience and skill (LaChapelle 1980). To overcome this challenge, we used judgmental decomposition (MacGregor 2001; Vick 2002) to systematically break down avalanche hazard into a progressive series of subset components. Decomposition is often regarded as a useful technique for reducing the complexity of difficult judgmental problems: a large, messy problem is divided into a set of smaller and presumably easier judgments (Ravinder et al. 1988). For each of the identified components, we derived ordinal scales to articulate the range of possible states and guide their assessment by requiring forecasters to make discrete choices based on observable data and evidence. These components were then assembled into a logical sequence that represents the authors' consensus of the avalanche hazard assessment process. The expertise of the team—more than 250 years of combined forecasting experience in ski area and highway avalanche forecasting, backcountry avalanche forecasting, mountain and ski guiding, residential and worksite avalanche mitigation, and avalanche research—would ensure the resulting framework captured the essence of avalanche forecasting and was applicable in all types of applications.

Following the initial development of the CMAH in 2008, we continued to develop the model through an ongoing, iterative process of consultation and feedback to determine its efficacy. We presented the CMAH at avalanche forecasting workshops, meetings and conferences in Europe and North America (e.g., Statham 2008, 2010b). Haegeli (2008) developed software to test the practicality of the workflow and begin a statistical examination of the model (Haegeli et al. 2012). Additional avalanche forecasting software (Aval*X* and InfoEx™) was developed and implemented nationally in Canada (Statham et al. 2012; Haegeli et al. 2014). Throughout this process, we used critical feedback to make incremental changes to the model. This paper describes the current, field-tested version of the CMAH.

4 The conceptual model of avalanche hazard

The CMAH provides a general framework for qualitative avalanche hazard assessments and is applicable to all types of avalanche forecasting applications. In this section, we describe the conditions for applying the approach, explain the various components of the model and how to combine them, describe the link to risk assessment and mitigation and elaborate on the advantages of this approach.

4.1 Conditions for applying the CMAH

At the beginning of an avalanche hazard assessment, it is crucial that forecasters establish situational awareness and context by considering the operational objectives (Table 1) and spatiotemporal scales (Tables 2 and 3) of the forecasting task. While the CMAH can be applied in a wide variety of settings and scales, these factors must be established at the start.

4.1.1 Operational objectives

Avalanche safety operations vary, each with specific objectives and desired outcomes beyond solely the prediction of avalanches (Table 1). Some operations may publish an avalanche hazard forecast as an end product, while others will introduce elements-at-risk and plan risk mitigation (CAA 2016). Operational objectives provide forecasters with important context that determines available data sources, data gathering tactics, decision methods (e.g., individuals vs. teams), available tools (e.g., software vs. paper checklists) and end-products (e.g., terrain travel decision vs. communication of hazard ratings).

Table 1 Types of operational avalanche forecasting applications

Operational application	Objective
Commercial backcountry operations	To keep clients safe, while providing a high-quality guided backcountry experience
Public backcountry recreation	To provide accurate avalanche information that enables the public to safely enjoy backcountry recreation
Ski areas	To provide safe access to as much in-bounds ski/snowboard terrain as early as possible each day
Transportation corridors	To keep roads/rails and travelers safe and to minimize the frequency and duration of closures
Worksites	To keep workers safe, and enable work objectives by minimizing the frequency and duration of closures
Mobile workers	To provide accurate avalanche information that enables workers to safety accomplish backcountry work objectives
Utilities	To minimize the frequency and duration of service interruptions
Occupied structures	To keep occupants safe and prevent or minimize damage to infrastructure

Table 2 Spatial scale for avalanche hazard assessments

Spatial extent	Description	Examples	Scale
Terrain feature	Individual geographic features contained within a larger slope	Convex roll, gully or terrain trap	Micro $< 1\ km^2$
Slope	Large, open, inclined areas with homogenous characteristics bounded by natural features such as ridges, gullies or trees	Typical avalanche starting zone or wide open area on a ski run	
Path or run	Multiple interconnected slopes and terrain features running from near ridge crest to valley bottom	Full length avalanche paths with a start zone, track and runout zone or typical long backcountry ski run	
Mountain	An area rising considerably above the surrounding country with numerous aspects and vertical relief running from summit to valley bottom	Ski resort area or typical single operating zone in a snow cat skiing area	Meso $> 10^2\ km^2$
Drainage	An area with a perimeter defined by the divide of a watershed	Typical single operating zone in a helicopter skiing area	
Region	A large area of multiple watersheds defined by mapped boundaries	Typical public forecasting area or public land jurisdiction	Synoptic $> 10^4\ km^2$
Range	A geographic area containing a chain of geologically related mountains	Mountain ranges or sub-ranges	

Table 3 Common temporal scales for avalanche forecasting

Time span	Description	Example
Now	Assessments with immediate consequence	Final, on-the-ground decision to enter or avoid a terrain feature
Hours	Assessments that are valid for a matter of hours, or portion of a day up to 24 h	Daily, or twice daily assessments of avalanche hazard that are common in most operational forecasting programs
Days	Assessments that are valid for more than 24 h but less than a week	Two to three day outlooks common with public avalanche forecasts
Weeks	Assessments of seasonal trends and patterns that emerge in the course of a single winter season	Avalanche problems that remain a concern for weeks to months, sometimes for an entire winter season
Years	Assessments that are valid beyond a single winter, often for many years	Land-use planning based on a long-term analysis of avalanche frequency and magnitude

4.1.2 Scale

A thorough understanding of scale issues is fundamental for avalanche forecasting (Haegeli and McClung 2004). Many complexities and uncertainties involved in avalanche prediction are due to the spatially and temporally variable nature of the snow cover. LaChapelle (1980) and McClung and Schaerer (1993) discuss three spatial scales for avalanche forecasting rooted in meteorology: synoptic, meso and micro. In practice, avalanche forecasters assess spatial scale in ways that refer directly to the spatial extent of the terrain they are analyzing (Table 2).

Avalanche forecasting accuracy also depends on temporal scale, with predictions having increasing uncertainty farther into the future. Because fluctuations in avalanche hazard are dependent upon weather, the quality of weather and climate predictions strongly affects the quality of avalanche hazard forecasts. In general, the shorter the time span, the more accurate the forecast. Table 3 shows the common time spans that avalanche forecasters and planners work under.

Scale has a dominant influence on the scope of an avalanche hazard assessment. The extent of an assessment in both space and time determines such fundamental parameters as data requirements, how much uncertainty is acceptable and estimates of likelihood, to name just a few. A clear awareness of the relevant spatial and temporal scales is imperative for every avalanche hazard assessment.

4.2 Avalanche problem framework

The CMAH is organized around the central concept of an *avalanche problem* (Haegeli et al. 2010; Lazar et al. 2012), which has been defined as a 'set of factors that describe the avalanche hazard' (CAA 2013). Figure 1 illustrates the structure of an avalanche problem and shows how these factors combine to create an avalanche hazard. Often, more than one problem will exist, and each different problem represents an actual operational concern about potential avalanches in terms of their *type*, *location*, *likelihood* and *size*. This concept has been used informally for years by avalanche forecasters, who often focus on one or two specific issues for their assessment. Assessing distinct avalanche problems that are described by key factors is similar to the use of scenarios in traditional risk analysis (Jamieson et al. 2010b).

The premise of the CMAH is that (1) identifying and assessing different types of avalanche problems is more relevant than solely assessing the ease of triggering avalanches when managing backcountry avalanche risk (Atkins 2004) and (2) integrating avalanche size with likelihood is a fundamental rule of avalanche hazard assessment (Meister 1994). Previous formal approaches in North America and Europe for assessing backcountry avalanche hazard were focused primarily on avalanche probability and snowpack stability

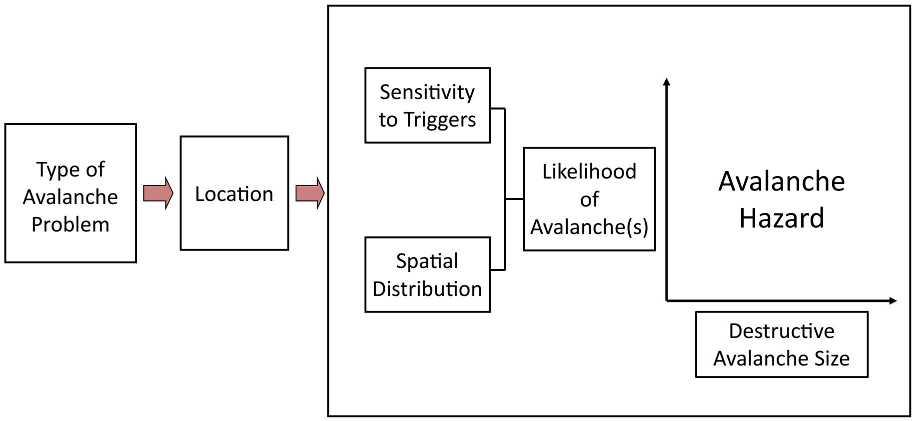

Fig. 1 Structure of an avalanche problem. Each problem is defined by its *type*, *location*, *likelihood* and *size*

(Dennis and Moore 1996), with little or no consideration given to different types of avalanche problems or their potential magnitude. Only recently has avalanche size been formally incorporated into the Bavarian Matrix (Müller et al. 2016b).

When assessing avalanche hazard, forecasters consider four sequential questions:

1. *What* type of avalanche problem(s) exists?
2. *Where* are these problems located in the terrain?
3. *How likely* is it that an avalanche will occur?
4. *How big* will the avalanche be?

These questions address the key components of an avalanche problem, and answering them constitutes the process of avalanche hazard assessment. While assessments at different operations may use different techniques (e.g., individual judgment, consensus teamwork, software, checklists), the components and their sequence are universal. For example, a lone ski guide making decisions in real-time at the top of a slope considers the same questions as an office-based avalanche forecaster producing a 24-h forecast for a broad geographic region. The following four subsections describe the formal assessment of these questions in detail.

4.2.1 Type of avalanche problem

Different snowpack structures create different types of avalanche problems. For example, a *dry loose* avalanche problem presents a completely different pattern of avalanche release than a *storm slab* avalanche problem, despite the fact that they are both formed by an overload of new snow. Similarly, a *wind slab* avalanche problem is a fundamentally different type of problem than a *persistent slab* avalanche problem, notwithstanding they are both slab avalanches. These different types of avalanche problems are repeatable patterns, formed from a disparate set of snowpack, weather and even terrain factors that require distinct risk management techniques. Recognizing these patterns and distinguishing between the different types of avalanche problems is a fundamental tenet of effective avalanche risk management, and the first step toward characterizing an avalanche problem in the CMAH.

Atkins (2004), who first introduced the concept of avalanche problems in North America, separated avalanche activity into 27 different regimes, such as 'wind slabs near ridge tops' or 'small slab avalanches in storm snow,' and postulated that terrain choices were in fact most strongly influenced by these regimes. In Europe, Harvey et al. (2009) suggested four different kinds of 'avalanche situations,' or patterns of avalanche characteristics and distribution, mainly based on the meteorological conditions that produce the avalanche situation. Finally, Mair and Nairz (2010) introduced ten avalanche danger patterns to highlight conditions that frequently lead to avalanche accidents. Statham et al. (2010b) refined the ideas presented by Atkins (2004) and introduced eight different Avalanche Characters, which were described in detail by Haegeli et al. (2010) in terms of their development, avalanche activity patterns, recognition and assessment in the field, and risk management strategies. While there are considerable similarities and overlap between the kinds of avalanche problems identified by these different authors, there is a fundamental difference among the perspectives. The descriptions of the European classifications primarily focus on the meteorological factors creating the condition, whereas the North American perspective is foremost tied to how the different types of avalanche problems require different risk mitigation strategies.

The CMAH builds on the eight Avalanche Characters introduced by Statham et al. (2010b), but calls them *types of avalanche problems*, as the characterization of avalanche problems also includes information about their location in the terrain, likelihood and size. The nine different *types of avalanche problems* included in the CMAH (Table 4) represent typical, repeatable and observable patterns in the formation, persistence, underlying weak layer, overlying slab, potential fracture propagation and size of the avalanche, along with common risk mitigation actions. Although classified as discrete choices, the boundaries between the different types of avalanche problems are soft, and problems can transition from one type to another as the snowpack changes over time.

Identifying and tracking specific types of avalanche problems is a critically important part of the hazard assessment process because it provides an overarching filter (Haegeli et al. 2010) that sets expectations (e.g., typical locations and patterns of avalanche activity) and influences all subsequent choices, including what type of observations are most relevant for the assessment (Jamieson et al. 2010b) and effective approaches for risk management. For example, terrain selection and/or explosive placement differs substantially between a *deep persistent slab* and a *storm slab* problem. Often, more than one type of avalanche problem will exist, in which case they are usually prioritized according to the most dominant type(s). Lazar et al. (2012) provide a decision tree to assist forecasters in prioritizing. The concept of different types of avalanche problems has quickly gained broad acceptance in the professional and recreational avalanche communities in North America. Lazar et al. (2012), Statham et al. (2012) and Klassen et al. (2013) all describe the introduction of avalanche problems as central to public warnings and risk management.

4.2.2 Location in the terrain

Terrain influences all weather and snowpack processes, whether broadly at the scale of a mountain range, or locally on an individual terrain feature (e.g., Birkeland 2001; Grünewald et al. 2013). Changes in terrain correspond with changes in snowpack structure, and the resulting spatial variability is a major source of uncertainty in avalanche forecasting (Haegeli and McClung 2004). Static terrain factors such as slope angle, shape, aspect and elevation directly influence both in situ snowpack development, and the impact of weather factors such as precipitation, air temperature and wind. Terrain is the constant modifier on all factors that influence avalanche formation (Schweizer et al. 2008), and understanding where a particular avalanche problem is located in the terrain is crucial for effectively managing the associated risk. For backcountry travel, the exposure component of risk (people's time and position in terrain) is the single most important consideration for controlling risk (Statham 2008). Accordingly, avalanche forecasters must possess an in-depth understanding of the interaction between terrain and snowpack processes. Schweizer et al. (2008) describe that forecasters develop sophisticated, inductive processing techniques that search for terrain correlated patterns, and relate them to avalanche formation processes.

Therefore, the second step toward characterizing an avalanche problem in the CMAH is determining where in the terrain the problem can typically be found. Terrain is identified and described using common terminology and methods that differ depending on the context and scale of the assessment. For example, regional avalanche forecasters discuss terrain in terms of aspect, elevation or vegetation bands, highway forecasters reference named avalanche paths, ski area forecasters refer to designated operating zones, and professional guides describe ski runs and individual terrain features.

Table 4 Types of avalanche problems

Name	Description[a]	Formation	Persistence	Typical physical characteristics					Typical risk mitigation
				Weak layer type[b]	Weak layer location	Slab hardness[c]	Propagation potential	Relative size potential[d]	
Dry loose avalanche problem	Cohesionless dry snow starting from a point. Also called a sluff or point release	Surface layers of new snow crystals that lack cohesion, or surface layers of faceted snow grains that lose cohesion	Generally lasts hours to days when associated with new snow, and longer when associated with facets	–	–	–	Downslope entrainment	R1-2	Avoid terrain traps where avalanche debris can concentrate, exposure above cliffs where small avalanches have consequence, and steep terrain overhead where sluffs can start
Wet loose avalanche problem	Cohesionless wet snow starting from a point. Also called a sluff or point release	Snow becomes wet and cohesionless from melting or liquid precipitation	Persistence correlates with warm air temperatures, wet snow or rain, and/or solar radiation	–	–	–	Downslope entrainment	R1-3	Avoid gullies or other confined terrain features when water from melting or precipitation is moving through the snowpack

Table 4 continued

Name	Description[a]	Formation	Persistence	Typical physical characteristics					Typical risk mitigation
				Weak layer type[b]	Weak layer location	Slab hardness[c]	Propagation potential	Relative size potential[d]	
Storm slab avalanche problem	Cohesive slab of soft new snow. Also called a direct-action avalanche	Cohesive slab of new snow creates short-term instability within the storm snow or at the old snow interface	Peaks during periods of intense precipitation and tends to stabilize within hours or days following	DF, PP	In new snow or at new/old snow interface	Very soft to medium (F-1F)	Path	R1-5	Avoid avalanche terrain during periods of intense precipitation, and for the first 24–36 h following. Assess for crack propagation potential in all avalanche terrain during and in the days following a storm

Table 4 continued

Name	Description[a]	Formation	Persistence	Typical physical characteristics					Typical risk mitigation
				Weak layer type[b]	Weak layer location	Slab hardness[c]	Propagation potential	Relative size potential[d]	
Wind slab avalanche problem	Cohesive slab of locally deep, wind-deposited snow	Wind transport of falling snow or soft surface snow. Wind action breaks snow crystals into smaller particles and packs them into a cohesive slab overlying a nonpersistent weak layer	Peaks during periods of intense wind loading, and tends to stabilize within several days following. Cold air temperatures can extend the persistence	DF, PP	Upper snowpack	Soft to very hard (4F-K)	Terrain feature to path	R1-4	Identify wind-drifted snow by observing sudden changes in snow surface texture and hardness. Wind erodes snow on the upwind side of an obstacle, and deposits it on the downwind side. They are most common on the lee side of ridge tops or gullies and are most unstable when they first form and shortly after

Table 4 continued

Name	Description[a]	Formation	Persistence	Typical physical characteristics					Typical risk mitigation
				Weak layer type[b]	Weak layer location	Slab hardness[c]	Propagation potential	Relative size potential[d]	
Persistent slab avalanche problem	Cohesive slab of old and/or new snow that is poorly bonded to a persistent weak layer and does not strengthen, or strengthens slowly over time. Structure is conducive to failure initiation and crack propagation	Weak layer forms on the snow surface and is buried by new snow. The overlying slab builds incrementally over several storm cycles until reaching critical threshold for release.	Often builds slowly and then activates within a short period of time. Can persist for weeks or months but generally disappears within six weeks.	SH, FC, FC/CR combo	Mid- to upper snowpack	Soft to hard (4F-P)	Path to adjacent paths	R2-4	Complex problem that is difficult to assess, predict and manage. Typically located on specific aspects or elevation bands but sometimes widespread. Identification and tracking of weak layer distribution and crack propagation propensity is key, along with a wide margin for error and conservative terrain choices

Table 4 continued

Name	Description[a]	Formation	Persistence	Typical physical characteristics					Typical risk mitigation
				Weak layer type[b]	Weak layer location	Slab hardness[c]	Propagation potential	Relative size potential[d]	
Deep persistent slab avalanche problem	Thick, hard cohesive slab of old snow overlying an early-season persistent weak layer located in the lower snowpack or near the ground. Structure is conducive to failure initiation and crack propagation. Typically characterized by low likelihood and large destructive size	Weak layer metamorphoses within the snowpack forming facets adjacent to an early-season ice crust, depth hoar at the base of the snowpack, or facets at the snow-glacier ice interface. The overlying slab builds incrementally over many storm cycles until reaching critical threshold for release	Develops early in the winter and is characterized by periods of activity followed by periods of dormancy, then activity again. This on/off pattern can persist for the entire season until the snowpack has melted	DH, FC, FC/CR combo	Basal or near-basal	Medium to very hard (1F-K)	Path to adjacent paths	R3-5	The most difficult avalanche problem to assess, predict and manage due to a high degree of uncertainty. Low probability/high consequence avalanches. Triggering is common from shallow, weak snowpack areas, with long crack propagations and remote triggering typical. Weak layer tracking and wide margins for error are essential, with seasonal avoidance of specific avalanche terrain often necessary

Table 4 continued

Name	Description[a]	Formation	Persistence	Typical physical characteristics					Typical risk mitigation
				Weak layer type[b]	Weak layer location	Slab hardness[c]	Propagation potential	Relative size potential[d]	
Wet slab avalanche problem	Cohesive slab of moist to wet snow that results in dense debris with no powder cloud	Slab or weak layer is affected by liquid water which decreases cohesion. Crack propagation occurs before a total loss of cohesion produces a wet loose avalanche problem	Peaks during periods of rainfall or extended warm air temperatures. Persists until either the snowpack refreezes or turns to slush.	Various but often FC or DH	Any level	Soft to hard wet grains (4F-P)	Path	R2-5	Rainfall, strong solar radiation, and/or extended periods of above-freezing air temperatures can melt and destabilize the snowpack immediately. Timing is key regarding slope aspect and elevation, and overnight re-freezing of the snow surface can stabilize the snowpack

Table 4 continued

Name	Description[a]	Formation	Persistence	Typical physical characteristics					Typical risk mitigation
				Weak layer type[b]	Weak layer location	Slab hardness[c]	Propagation potential	Relative size potential[d]	
Glide slab avalanche problem	Entire snowpack glides downslope then cracks, then continues to glide downslope until it releases a full-depth avalanche	Entire snowpack glides along smooth ground such as grass or rock slab. Glide crack opens, slab deforms slowly downslope until avalanche release results from a failure at the lower boundary of the slab	Can appear at any time in the winter and persists for the remainder of the winter. Avalanche activity is almost impossible to predict	WG, FC	Ground	Medium to very hard (1F-K)	Path	R3-5	Usually localized, visible and easy to recognize, the presence of a glide crack does not indicate imminent release. Predicting a glide slab is almost impossible, so avoid slopes with glide cracks and overhead exposure to glide slabs

Table 4 continued

Name	Description[a]	Formation	Persistence	Typical physical characteristics					Typical risk mitigation
				Weak layer type[b]	Weak layer location	Slab hardness[c]	Propagation potential	Relative size potential[d]	
Cornice avalanche problem	Overhanging mass of dense, wind-deposited snow jutting out over a drop-off in the terrain	Wind transport of falling snow or soft surface snow develops a horizontal, overhanging build out of dense snow on the leeward side of sharp terrain breaks	Persists all winter on ridge crests and tends to collapse spontaneously during periods of warming, or following intense wind loading events	–	–	–	Path	R1-5	Avoid overhead exposure to cornices whenever possible, particularly during storms or periods of warmth and/or rain. Cornices are heavy and can trigger slabs on the slopes below. Use great care on ridge crests to stay on solid ground, well away from the root of the cornice

[a]Haegeli et al. (2010); [b] Fierz et al. (2009, p. 4); [c]Fierz et al. (2009, p. 6); [d]AAA (2016, p. 54)

4.2.3 Likelihood of avalanche(s)

Likelihood of avalanche(s) is the chance of an avalanche releasing within a specific location and time period, regardless of avalanche size. While probability is dependent on scale, in practice forecasters express their likelihood judgments independently of scale, using qualitative terms such as *possible* or *almost certain* (Statham 2008) across different scales. The CMAH considers two factors that contribute to the likelihood: *sensitivity to triggers* and *spatial distribution*.

Sensitivity to triggers assesses snowpack instability separately from the size of the avalanche by gauging the triggers necessary for avalanche release. Table 5 shows the four-level ordinal scale for expressing *sensitivity to triggers* and offers examples of artificial and natural triggers associated with each different level. Assessing the *sensitivity to triggers* for each avalanche problem isolates the evaluation of snowpack instability so that even very small, inconsequential avalanches are properly considered in the assessment.

Spatial distribution considers the spatial density and distribution of an avalanche problem and the ease of finding evidence to support or refute its presence. We developed a three-level ordinal scale to express *spatial distribution* (Table 6); rare and hard-to-find evidence contributes to a lower *likelihood of avalanche(s)* than evidence that is everywhere and easy to find.

Avalanche forecasters combine their analysis of sensitivity and distribution to provide an overall estimate of the *likelihood of avalanche(s)* (Fig. 2), which expresses their degree of certainty that an avalanche of any size will release. The CMAH uses the terms 'unlikely,' 'possible,' 'likely,' 'very likely' and 'almost certain' on an ordinal scale to express the *likelihood of avalanche(s).* Although many studies of quantified verbal probability expressions have identified consistent probability ranges for these terms (e.g., Kent 1964; Reagan et al. 1989; Mosteller and Youtz 1990; Mastrandea et al. 2010), the scale dependence of probability values and the scale independence of this likelihood terminology rule out associating probability values for this multi-scale approach.

Table 5 Sensitivity to triggers

Sensitivity	Natural releases	Human triggers	Explosive triggers		Cornice triggers
			Size	Result	
Unreactive	No avalanches	No avalanches	Very large explosives in several locations	No slab	No slab from very large cornice fall
Stubborn	Few	Difficult to trigger	Large explosive and air blasts, often in several locations	Some	Large
Reactive	Several	Easy to trigger with ski cuts	Single hand charge	Many	Medium
Touchy	Numerous	Triggering almost certain	Any size	Numerous	Any size
Description of observation	*Natural avalanche occurrence*	*Ease of triggering by a single human*	*Size of explosive and effect*		*Size of cornice that will trigger a slab*

Table 6 Spatial distribution

Distribution	Spatial density	Evidence
Isolated	The avalanche problem is spotty and found in only a few terrain features	Evidence is rare and hard to find
Specific	The avalanche problem exists in terrain features with common characteristics	Evidence exists but is not always obvious
Widespread	The avalanche problem is found in many locations and terrain features	Evidence is everywhere and easy to find
Comment	*How is the evidence distributed?*	*How hard is it to find?*

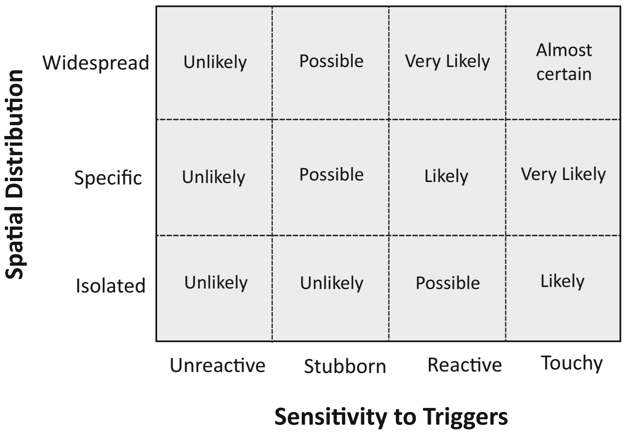

Fig. 2 Likelihood of avalanche(s) results from the integration of spatial distribution and sensitivity to triggers (after Müller et al. 2016a)

When a single slope that is *possible* to trigger is treated in isolation, it might be considered an unacceptably high risk. Yet when the entire drainage is considered, the possibility of triggering an avalanche on a single slope might then be acceptable due to the many other terrain options available to mitigate exposure. The probability of an avalanche on a single slope of 0.01 could be considered *likely*, while the probability of an avalanche across an entire region of 0.1 could be considered *unlikely*. This dichotomy, combined with a lack of valid data and the impracticality of calculating probabilities during real-time operations, is the main reasons forecasters do not usually work with probabilities, but instead rely on inference and judgment (LaChapelle 1980) to estimate likelihood. Numeric probabilities can be assigned when the spatial and temporal scales are fixed (e.g., CAA 2002; AGS 2007; Jamieson et al. 2009) and the data are available, but given the time constraints and variable scales of avalanche forecasting, probability values are not commonly used.

4.2.4 Destructive avalanche size

Determining the magnitude of a potential avalanche requires calculating or estimating its size in terms of destructive potential, which is a function of the mass, speed and density of the avalanche, as well as the length and cross section of the avalanche path. For operational avalanche forecasting applications, destructive potential is most commonly estimated using the destructive force classification system, resulting in a subjective estimate of size between 1 and 5 (Table 7). This qualitative assessment requires an avalanche forecaster to estimate the harm the avalanche could cause to hypothetical objects located in the avalanche track (CAA 2014; AAA 2016).

4.3 Hazard assessment: putting the pieces together

Combining *likelihood of avalanche(s)* with *destructive avalanche size* gives an estimate of avalanche hazard, which is a qualitative counterpart to the frequency–magnitude matrices used to map avalanche hazard (BFF and SLF 1984; CAA 2016). The CMAH combines these two ordinal variables into a hazard chart that plots likelihood on the y-axis against size on the x-axis to visualize the avalanche hazard for each avalanche problem (Fig. 3). The resulting data point or range is an estimate of the most common condition for both likelihood and size, and the resulting rectangle is a graphical representation of the avalanche hazard.

When more than one type of avalanche problem is identified, the results can be overlain on a single chart to visualize the total avalanche hazard (Haegeli et al. 2014) as shown in Fig. 3, or multiple charts to isolate each avalanche problem (Statham et al. 2012). Multiple avalanche problems require the forecaster to prioritize. In the example shown in Fig. 3, the *persistent slab* avalanche problem (avalanches between size 2–4 possible) might be prioritized in front of the concurrent *storm slab* avalanche problem (avalanches around size 2 are likely to almost certain) because the *persistent slab* has more uncertainty and is more destructive, making it harder to deal with from a risk management perspective.

4.4 Link to risk assessment and mitigation

The CMAH is an assessment of avalanche potential, and although it implies an effect on people, facilities or things of value, the model does not incorporate the exposure or vulnerability of an element-at-risk. An assessment using the CMAH is independent of anything being at-risk; thus, the next step after completing an assessment is to connect it with

Table 7 Destructive avalanche size classification system (CAA 2014; AAA 2016)

Destructive size	Avalanche destructive potential	Typical mass (t)	Typical impact pressure (kPa)	Typical path length (m)
1	Relatively harmless to people	< 10	1	10
2	Could bury, injure or kill a person	10^2	10	100
3	Could bury and destroy a car, damage a truck, destroy a wood frame house or break a few trees	10^3	100	1000
4	Could destroy a railway car, large truck, several buildings or a forest area of approximately 4 hectares	10^4	500	2000
5	Largest snow avalanche known. Could destroy a village or a forest area of approximately 40 hectares	10^5	1000	3000

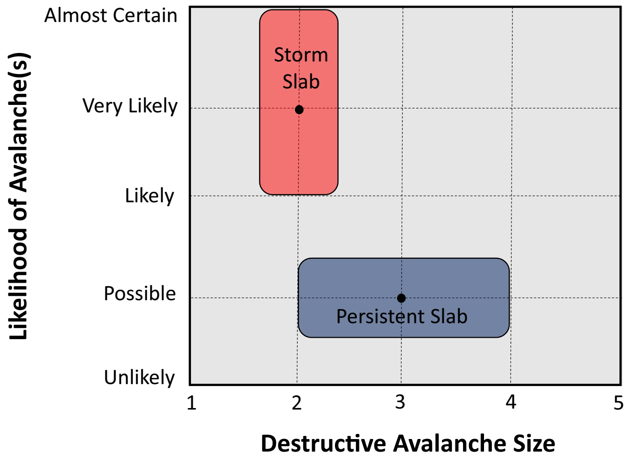

Fig. 3 An avalanche hazard chart showing two avalanche problems. In this example, *persistent slab* avalanches are possible from size 2 to 4, while *storm slabs* near to size 2 are likely to almost certain

an element-at-risk to determine the degree of risk and decide on mitigation strategies. This occurs in different ways depending on the operational application (Table 1). In the case of public forecasting, danger ratings are published to accompany an avalanche bulletin, and the public at-large manages their own exposure and vulnerability. In operations where an element-at-risk is being managed (e.g., transportation corridor, ski area, backcountry guiding), the hazard assessment, which may or may not be expressed with a hazard rating, is then combined with scenarios that estimate the exposure and vulnerability of the element-at-risk and result in specific tactics to mitigate the risk to an acceptable level within the operational risk band (McClung 2002a). Mirroring the hazard assessment process, the risk assessment process also typically follows an iterative cycle (LaChapelle 1980) and proceeds in stages through progressively smaller scales starting from regional, long-range desktop assessments down through to decision making in real-time situations on individual terrain features.

4.5 Operational advantages of the CMAH approach to hazard assessment

The CMAH has considerable practical benefits when implemented into an operational avalanche forecasting application.

4.5.1 Structured workflow

The step-wise nature of the CMAH creates a logical and consistent workflow that walks avalanche forecasters through a progression of choices. The model is flexible enough to accommodate a variety of scales, applications and perspectives and provides a common, standardized approach for communicating critical avalanche hazard information between diverse operations who manage different elements-at-risk (Haegeli et al. 2014). Within individual teams, the CMAH provides a platform for debate and decision making that is independent of any individual. The workflow of the CMAH naturally lends itself to software development and database capture, which facilitates operational record keeping and future data analysis. The rich dataset that results from the CMAH may form the foundation of future decision aids that could be derived from patterns found within these assessments.

For public avalanche warnings and education, the components of the CMAH can be presented in a simplified format that provides the public with the same structured avalanche hazard information that the forecasters have assessed (Statham et al. 2012). This strengthens the link between forecasting methods and public communication. The structured workflow of the CMAH also provides a natural platform for education, with each component of the model supplying valuable lessons on the overall composition of avalanche hazard. Further, the CMAH's explicit distinction between hazard and risk promotes a better understating of how to manage exposure and vulnerability when interacting with avalanche hazard.

4.5.2 Systematic breakdown of avalanche problems

Avalanche hazard assessments using the CMAH offer rich evaluations of current and future avalanche conditions that go beyond single ratings and are highly informative for risk mitigation decisions. Breaking down the complexity of avalanche prediction into a series of smaller, more manageable analyses of avalanche problems allow forecasters to isolate the individual components of avalanche hazard in order to study them specifically, and in more detail. This results in a more thorough analysis and understanding of the overall hazard conditions, which can guide communication and the choice of risk mitigation strategies more meaningfully. When undertaken in a group environment, the debate and consensus around each hazard component draws out many important, detail-oriented elements of the avalanche hazard.

Single danger or hazard ratings primarily serve as a tool for summarizing the avalanche conditions and communicating them to a broader audience. Several different rating systems exist (e.g., CAA 2014, 2016; EAWS 2016b), each of them providing a relative measure of avalanche hazard that corresponds with a set of definitions for each hazard level. The five-level avalanche danger scale (Statham et al. 2010a; EAWS 2016a) is the most commonly used in public warnings (Fig. 4). For avalanche forecasters, any single rating represents the end of the hazard assessment process, while for the public it may signal the beginning.

The CMAH provides a foundation for rating systems in North America similar to how the 'information pyramid' does in Europe (SLF 2015). Although the North American avalanche danger scale's criteria for avalanche likelihood, size and distribution map qualitatively from the CMAH, the link is not deterministic. Instead, the CMAH's model provides the platform for a detailed assessment, and a framework for data analysis and collection. This was done deliberately to support future empirical analyses (e.g., Haegeli et al. 2012; Shandro et al. 2016) in establishing more robust links between assessment methods and any operational rating systems. This is in contrast to the Bavarian Matrix (Müller et al. 2016b), which was designed specifically to determine a danger rating and provide consistency in the use of the European avalanche danger scale.

4.5.3 Clear illustration of uncertainty

Uncertainty is inherent in all avalanche hazard and risk assessments; it can be reduced, but never eliminated (LaChapelle 1980; Jamieson et al. 2015). Uncertainty creates doubt, and doubt (or lack of it) manifests itself in people and their actions. High uncertainty leads to low confidence and vice versa (Willows and Connell 2003). For these reasons, it is

North American Public Avalanche Danger Scale Avalanche danger is determined by the likelihood, size and distribution of avalanches.			
Danger Level	**Travel Advice**	**Likelihood of Avalanches**	**Avalanche Size and Distribution**
5 Extreme	Avoid all avalanche terrain.	Natural and human-triggered avalanches certain.	Large to 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.
Safe backcountry travel requires training and experience. You control your own risk by choosing where, when and how you travel.			

Fig. 4 North American public avalanche danger scale (Statham et al. 2010a)

essential to recognize, accommodate and communicate uncertainty in avalanche assessments.

The CMAH shows uncertainty in hazard assessments by illustrating ranges of likelihood and size for each avalanche problem. Starting from an initial data point, each parameter is given a range to show what could be possible. Figure 3 illustrates a *persistent slab* problem where the potential avalanche is unlikely to possible and could range from size 2–4. The size and shape of the resulting rectangles provide an indication of the degree of uncertainty. This approach is similar to Jamieson et al. (2015) who show quantitative uncertainty expressed as confidence intervals (whiskers) that illustrate a range of values.

5 Existing operational implementations

Since the development of the initial version of the CMAH in 2008, the framework has been implemented in various applications in both Canada and the USA. While the adoption of the CMAH by practitioners can be interpreted as an indication of its practical value, this operational testing also produced valuable feedback that resulted in many important refinements.

5.1 Examples from Canada

In 2008, the Canadian Avalanche Association's Industry Training Program incorporated the CMAH as core curriculum for their Level 3—Applied Avalanche Risk Management course. Haegeli (2008) developed a database-driven online tool for facilitating the operational use of the CMAH, providing the foundation for the first statistical examination of relationships between its components (Haegeli et al. 2012). In 2011, Parks Canada developed Aval*X* to integrate the CMAH into the daily workflow of avalanche forecasters from different agencies (Statham et al. 2012). Aval*X* provided the first standardized forecasting method between different agencies and forecasters in Canada and delivered a consistent format for avalanche safety information to the Canadian public. In 2013, the CMAH was integrated into the InfoEx^{TM}, the daily exchange of avalanche information among avalanche safety services hosted by the Canadian Avalanche Association (Haegeli et al. 2014). This effectively embedded the CMAH process into the daily workflow of all Canadian avalanche forecasters.

5.2 Examples from the USA

Incorporating the CMAH into professional training programs for avalanche workers began in 2008. Currently, all four programs providing avalanche worker training in the USA use the CMAH framework. The American Avalanche Institute and the American Institute for Avalanche Research and Education both run Level 3 courses where avalanche workers from a variety of disciplines use the CMAH to assess the avalanche hazard and ISO 31000 to manage risk for workers and clients. The American Avalanche Association's AVPRO course and the National Avalanche School both include the CMAH as the basis for assessing avalanche hazard for ski area operations.

In the USA, the US Forest Service (USFS) and the Colorado Avalanche Information Center (CAIC) produce public safety information for backcountry recreation. The USFS program is composed of 12 regional avalanche centers, while the CAIC runs a statewide program that also provides highway avalanche forecasts. All US operations utilize elements of the CMAH in an informal way, though the Utah Avalanche Center began using a communication tool that included avalanche character, likelihood of triggering, and avalanche size in their products in 2004. Many other USFS avalanche centers incorporated these ideas into their products over the next decade. The CAIC formally adopted the CMAH into its daily operations in 2012. It is embedded into the daily workflow as well as documentation of forecast process and operational decisions. The CMAH forms the foundation for communication between CAIC forecasters in different offices and focused on different avalanche safety applications.

6 Conclusions

Although the existing literature on avalanche forecasting has provided a good overview of the general nature of the assessment process and its inputs, it is missing tangible guidance on how to undertake and assemble a hazard or risk assessment for avalanche forecasting and backcountry operations. Our objective was to address this knowledge gap by eliciting the essence of the avalanche forecasting process from avalanche forecasters and then describing it within a risk-based framework that is consistent with other natural hazards disciplines. The resulting conceptual model illustrates the key components of avalanche hazard and structures them into a systematic, consistent workflow for hazard and risk assessment.

Based on our experience with the CMAH to-date, we believe that the main benefits are:

1. It provides a logical framework for organizing and analyzing crucial data and evidence that contributes to the avalanche hazard and informs risk mitigation decisions.
2. It is universally applicable to all types of avalanche forecasting operations, and the underlying principles can be applied at any scale in space or time.
3. It formalizes the concept of an *avalanche problem* and that different types of problems directly influence the assessment and management of avalanche hazard and risk.

4. It aligns avalanche forecasters with a consistent methodology and language and streamlines the communication of hazard information between different avalanche operations.
5. Its risk-basis brings the practice of avalanche forecasting into line with the concepts and methods employed in land-use planning, bridging these two disciplines of the avalanche industry.

Although the CMAH is a step forward in the description of the avalanche hazard assessment process, numerous challenges remain. For example, although the identification of different types of avalanche problems (Table 4) is fundamental to avalanche forecasting, agreeing on the specific type of problem and when to transition from one problem to another is challenging. Furthermore, the lack of quantitative links between the components of the CMAH—or any existing hazard rating system—leaves the process highly susceptible to human error and bias. It is our hope that by capturing these judgments in a structured manner, the CMAH will help to facilitate the development of evidence-based decision aids that can address these challenges. Future research into the intuitive, judgment-based processes used in conventional avalanche forecasting may yield important practical results that allow forecasters to check their assessments against a model output.

Avalanche forecasting has always been difficult to explain and fraught with uncertainty. With little in the way of rational guidance, it ultimately remains a task for human judgment with support from technology and process. The CMAH resulted from our investigation into the underlying, intuitive processes that forecasters have developed from thousands of days spent observing avalanches in the mountains.

Acknowledgements We thank Roger Atkins, Steve Conger, Bruce Jamieson, Karl Klassen and Brian Lazar for their thoughtful insights and important contributions to this work, as well as two anonymous reviewers whose comments greatly improved the quality of this manuscript. This work was supported by the Canadian Avalanche Association and Avalanche Canada through their management of project funding provided by the Government of Canada’s National Search and Rescue Secretariat’s New Initiatives Fund (SAR-NIF).

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