IS IT A PROBLEM? TAKEAWAYS FROM RESEARCH INTO THE USE AND EFFECTIVENESS OF AVALANCHE PROBLEMS

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ABSTRACT: Over the past 20 years, avalanche safety operations in North America adopted common standards for assessing avalanche hazard, including the North American Public Avalanche Danger Scale, avalanche problems, and the conceptual model of avalanche hazard. While these systems aim to provide a consistent, structured way to assess and communicate avalanche hazard, practical experience and several studies have shown that there is considerable variability in how the standards are understood and applied. To examine their use and effectiveness more systematically, the Simon Fraser University Avalanche Research Program has conducted several projects focused on how forecasters apply danger ratings and avalanche problems. This paper synthesizes the key results of this research, with a focus on the practical implications for avalanche forecasters. We begin with a brief review of the individual projects, which span from statistical modelling of large datasets to qualitative interviews with forecasters. We then synthesize common themes found throughout the research, which include inconsistencies between forecasters, limitations of the published standards, and complications arising from the contextual nature of hazard assessments. Recommendations to increase quality and consistency include clarifying published standards, developing evidence-based decision aids, improving training and communication amongst forecasters, and further research into how danger ratings and problems are used to manage risk.

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KEYWORDS: hazard assessment, avalanche problems, danger ratings, conceptual model

1. INTRODUCTION

Hazard assessments are essential in the management of avalanche risk and are central to risk communication among practitioners and the public (CAA, 2016). In North America, practitioners have made significant efforts to establish consistent standards for evaluating avalanche hazard using danger ratings (Statham et al., 2010) and avalanche problems (Haegeli et al., 2010; Statham et al., 2018), along with a structured workflow known as the conceptual model of avalanche hazard (CMAH, Statham et al., 2018). These systems aim to provide a uniform and structured approach to assess and communicate avalanche hazard. However, practical experience and several studies have revealed considerable variability in how these standards are understood and applied, both in North America (e.g., Clark, 2019; Lazar et al., 2016; Statham et al., 2018b) and Europe (Techel et al., 2018).

To systematically examine the use and effectiveness of these standards, the Simon Fraser University Avalanche Research Program (SARP) conducted several projects focusing on how avalanche forecasters apply danger ratings and problems. The research started in 2015 with statistical analysis of large hazard assessment data sets and eventually evolved to incorporate more qualitative exploratory approaches to find the "why" behind the observed patterns and gain further insights into how forecasters use problems. The goal of this paper is to present a synthesis of the key findings from these studies, with the objective of sharing overarching themes that we believe have practical implications for improving hazard assessments.

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2. RESEARCH SUMMARY

2.1 Characterizing hazard situations

Our initial research into avalanche problems applied a statistical method known as self-organizing maps (Kohonen, 2001), an unsupervised clustering technique well suited for high-dimensional datasets, to analyze public avalanche forecasts and identify common avalanche hazard situations based on the combination of problems on a given day (Shandro, 2017). Characterizing hazard with this approach allowed Shandro and Haegeli (2018) to describe regional avalanche climates across western Canada in a more detailed way than had been done previously. Focusing on the prevalence of avalanche problem types, Haegeli et al. (2021) examined the impact of atmos-

phere-ocean oscillations, such as El Niño–Southern Oscillation and Pacific Decadal Oscillation, on seasonal patterns in avalanche hazard in different parts of western Canada.

2.2 Forecaster inconsistency

Analyses of hazard assessments quickly revealed inconsistencies caused by forecasters' interpretations and biases. Statham et al. (2018b) quantified inconsistencies between individuals within the same agency and between bordering agencies by examining the number of identified avalanche problems, the ordering of the listed avalanche problems, and agreements between the forecasted danger ratings and the subsequent day's nowcast. The study found that it was common to describe similar avalanche conditions with different danger ratings and problems.

2.3 Relationship between problems and danger

Clark (2019) used conditional inference trees (Hothorn et al., 2006), a type of classification tree based on statistical tests, to explore the relationship between avalanche problems and danger ratings. Using public forecasts from 2012 and 2018, the classification trees explained danger ratings based on the type, size, and likelihood of avalanche problems as well as their vegetation band, aspect, mountain range, and forecast agency. The results can be explored interactively at https://www.avalanchere-search.ca/pubs/2019_mrm_clark. As expected, avalanche size and likelihood had a strong impact on danger ratings (Figure 1), however there were notable influences of problem types and vegetation band. For example, identical combinations of size and likelihood yielded different danger ratings depending on the problem type, with storm slab problems generally resulting in higher danger ratings than other problem types. Similarly, danger ratings tended to be higher in the alpine. The danger associated with storm slab problems was most sensitive to the assessed size, while persistent slab problems were more sensitive to likelihood. There was substantial variability not explained by the statistical models, which was partly attributed to inconsistent application of problems and danger ratings by forecasters.

2.4 Relationship between observations and problems

Towell (2019) and Horton et al. (2020b) also used conditional inference trees to explore relationships between weather and snowpack conditions with the presence or absence of avalanche problems in Glacier National Park, Canada. Some problem types were explained with intuitive relationships such as 3-day snowfall explaining storm slab problems (Figure 2), air temperature explaining wet loose problems, and weak layer grain size and slab density explaining persistent slab problems. However, many of the splits in the classification trees were less intuitive and suggested forecasters considered additional or contextual factors when choosing problems. For example, wind slab and cornice problems were poorly explained by weather and snowpack variables. The classification trees also revealed clearer rules for adding new problems to assessments compared to removing old problems from assessments.

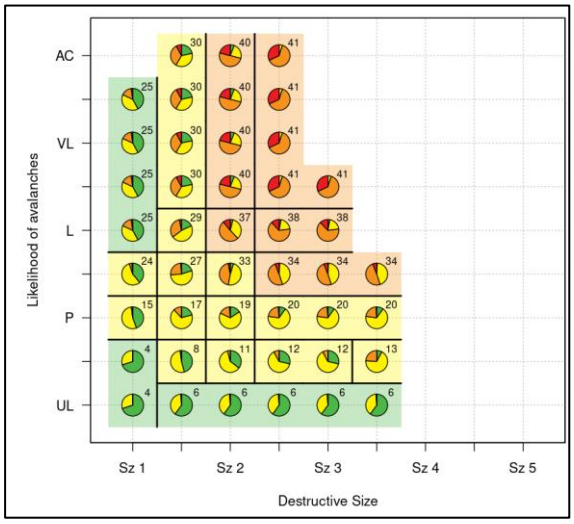

Figure 1. Results from conditional inference trees predicting the danger rating based on the size and likelihood of avalanche problems (Clark, 2019). Pie charts show the distribution of danger ratings for each combination of size and likelihood following the standard colour scheme of green for 1-Low, yellow for 2-Moderate, orange for 3-Considerable, and red for 4-High.

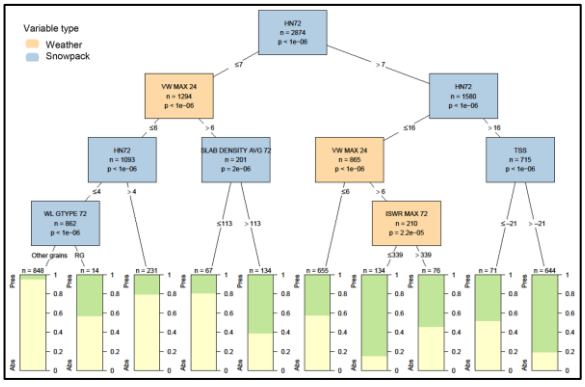

Figure 2. Conditional inference tree explaining the presence or absence of storm slab problems based on weather and snowpack variables (Horton et al., 2020b). Variables in the tree include heigh of snow in the past 72 h (*HN72*), maximum wind speed in past 24 h (*VW MAX 24*), grain type beneath snow deposited in past 72 h (*WL GTYPE*

72), average density of snow deposited in past 24 h (*SLAB DENSITY AVG 72*), maximum incoming shortwave radiation in past 72 h (*ISWR MAX 72*), and the snow surface temperature (*TSS*). Terminal nodes show the proportion of cases with storm slab problems (green) and without (yellow).

2.5 How forecasters choose problems

Hordowick (2022) followed up on these statistical analyses by performing 22 in-depth interviews with public forecasters to understand their decision processes. The study focused on decisions involving storm slab, wind slab, persistent slab, and deep persistent slab problems. While intuitive weather and snowpack variables were found to be influential, forecasters differed in terms of the weight and threshold values attributed to different variables. Furthermore, the interviews clearly emphasized that in addition to the physical characteristics, public risk communication considerations also played an important role when choosing problems, with forecasters making decisions based on assumptions about what best communicated the avalanche hazard to the public. Other considerations also factored into their decisions including differing ways of handling uncertainty and operational constraints such as time and software limitations.

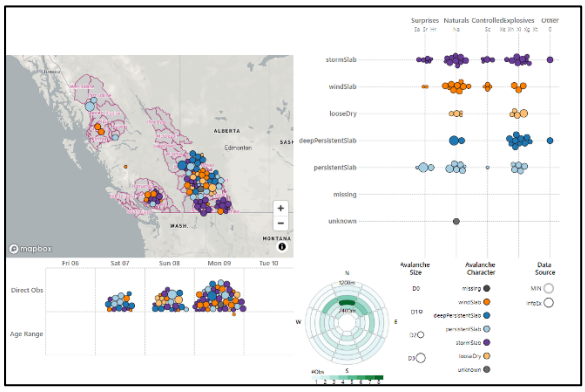

Figure 3. Screenshot of Avalanche Canada's interactive avalanche observation dashboard, which was designed to establish links between avalanche occurrences and avalanche problems as well as highlight uncertainty and gaps in the data.

2.6 Ambiguity and uncertainty

A series of research projects have been conducted around visualizing and communicating uncertainty in hazard assessments. Horton et al. (2020a) developed visualization design principles to visually map snowpack properties to avalanche problems, which has helped to presentation of snowpack model output. Nowak et al. (2020) and Nowak and Bartram (2022) closely observed, recorded, and reflected on the daily workflow of avalanche forecasters and highlight issues related to the interpretation of weather, snowpack, and avalanche data, as well as how interpretations are communicated between them. They have proposed software designs to better document and communicate interpretations and ambiguities (Figure 3).

2.7 Numerical derivation of problems

Attempts to numerically derive avalanche problems from simulated snowpack models have been explored by Reuter et al. (2021) and Herla et al. (2023). These approaches take advantage of the complete spatial and temporal coverage of snowpack models to calculate the depth and stability of all weak layers. The reliability of these methods is challenged by the accuracy of snowpack simulations as well as the lack of objective training data, since archived avalanche problem datasets are inconsistent and subjective.

3. COMMON THEMES

These studies highlight several main themes about the application of avalanche problems and danger ratings. It is evident that the adoption of avalanche problems and the conceptual model of avalanche hazard offers a more comprehensive description of avalanche hazard compared to previous methods that solely relied on ordinal ratings like stability or danger. Avalanche problems serve as a valuable tool for organizing data during the assessment process and facilitate effective communication among avalanche professionals.

Conducting research with hazard assessment data sets has proven challenging due to the inherent complexity of the data. Inconsistencies arise from variations in the practices of individual forecasters and operations, leading to messy and inconsistent data. While hazard assessment data tends to be more complete than field observations because it is produced daily irrespective of weather and avalanche conditions, the level of confidence in the assessments can vary greatly. Unfortunately, assessments are rarely reanalyzed to create complete and verified records. These issues severely limit the development of statistical models for predicting problems and will continue to pose challenges as we look ahead to computer-assisted forecasting.

Avalanche problems are assessed using a combination of objective environmental factors and subjective contextual factors. In Europe, avalanche problems are primarily defined based on meteorological conditions that influence the snowpack structure. On the other hand, the North American definitions emphasize the distinct risk mitigation strategies required for each problem (detailed descriptions of these are provided by

Haegeli et al. (2010) at https://www.avalancheresearch.ca/avalanche-problem-types). The intended motivation for avalanche problems came from their direct link to risk mitigation strategies (Atkins, 2004). However, since their introduction, a significant portion of attention has gravitated towards the physical attributes of the snowpack, inadvertently creating confusion and inconsistencies.

Our research demonstrates a clear influence of weather and snowpack conditions on selecting avalanche problems, but also the influence of these risk mitigation considerations. For example, the selection of a specific problem can be shaped by operational objectives, the elements at risk, risk tolerance, and the management of uncertainty. Consequently, relying solely on field observations to predict avalanche problems falls short, as it fails to capture the broader context within which assessments are conducted. Our experience suggests there could be clearer separation between the objective hazard assessment and risk mitigation considerations.

4. RECOMMENDATIONS

While our research publications provide specific and detailed recommendations, we can summarize them into the following broad themes.

4.1 Clarify standards and definitions

Certain aspects of the hazard assessment workflow appear to be subject to interpretation, such as how problems are defined, determining when problems should be removed, and establishing how danger ratings should be assigned based on the problems. Furthermore, better separation between hazard assessment and risk mitigation strategies could make the hazard assessments themselves more accurate and consistent, and then the subsequent risk mitigation guidance can be more context specific.

4.2 Consistency through improved training and communication

Public forecasting agencies in Canada implemented better practices for interagency communication after the findings of Statham et al. (2018b) highlighted the degree of inconsistency. There should be ongoing efforts to improve communication among forecasters to ensure consistency. One approach is developing tools that facilitate the documentation and communication of interpretations and contextual considerations. Also, given that avalanche problems are relatively new to the industry, there is potential to enhance the level of training in professional courses to ensure all professionals have a grounded understanding of how problems are defined and should be applied.

4.3 Validation and training datasets

Most operations have limited feedback loops to validate past analyses, which could be a valuable opportunity to learn and reflect. Furthermore, if we want to harness the capabilities of machine learning techniques, we need to develop proper validated datasets for training these models.

4.4 Implement evidence-based decision aids

Many professions rely on decision aids to enhance the accuracy and consistency of human assessments, such as checklists, decision trees, and nearest neighbour models (CAA, 2016). Some decision aids have already been developed to help with avalanche problems, including the European Avalanche Warning Service matrix and workflow for selecting danger ratings (EAWS, 2023), and a classification tree for selecting problems suggested by Lazar et al. (2012). Further development and implementation of these types of aids could promote consistency.

4.5 Numerical modelling of hazard

Developing tools based on physical principles, such as numerical weather and snowpack models, could provide added value that is independent of past datasets or human judgment.

4.6 Research the impact of assessments on risk management decisions

Research on avalanche problems in the context of public forecasting has revealed how substantial emphasis is placed on risk communication strategies. However, these considerations are largely based on assumptions about how backcountry recreationists use problems and danger ratings to manage their risk, rather than grounded in empirical research on their perceptions and behaviours. Furthermore, while not extensively studied, we suspect that similar operational considerations influence the application of problems in other contexts, such as backcountry guiding, ski areas, and industrial avalanche work. Conducting research to investigate what operational factors affect hazard assessments in various contexts would offer valuable insights for improving consistency and communication across industry segments.

5. CONCLUSIONS

Research on the adoption and application of avalanche problems and danger ratings in Canada illustrate the advantages of these standardized

practices. Focusing avalanche problems on risk mitigation strategies offers clear benefits for overall risk management goals, but it introduces additional contextual factors and interpretations that pose a challenge for consistent application and communication. To address these issues, it is important for operational practices to stay up to date with evidence-based research findings. The research done by SARP has informed several projects underway in Canada, including the development of interactive dashboards that effectively communicate critical data with uncertainties and context, as well as the advancement of numerical snowpack models that provide independent decision support. Moreover, future research should explore the role of avalanche problems in supporting risk management decisions across diverse contexts, allowing for a more comprehensive understanding of their practical application.

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