# Exploring the link between the Conceptual Model of Avalanche Hazard and the North American Public Avalanche Danger Scale

**by**

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# Approval

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## Abstract

In 2010, Statham, Haegeli, et al. (2018) introduced the Conceptual Model of Avalanche Hazard (CMAH) to improve transparency and consistency of avalanche bulletin production in North America. However, since the CMAH has no explicit link to the avalanche danger scale, forecasters must rely on their own judgment to assign danger ratings, which can lead to inconsistencies in public avalanche risk communication. My research aims to address this missing link by exploring the relationship between avalanche hazard assessments and danger rating assignments in public avalanche bulletins. Using conditional inference trees, key decision rules and components of the CMAH influencing danger rating assignments are extracted. While the analysis offers insights into the assignment rules, it also highlights substantial variability that cannot be explained by components of the CMAH. The results from this study offer a foundation for critically reviewing existing forecasting practices and developing evidence-based decision aids to increase danger rating consistency.

**Keywords**: Danger Rating; Avalanche Hazard, Forecasting, Decision Trees

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## List of Acronyms

| | |
|---|---|
| AC | Likelihood of avalanches rating: Almost Certain |
| AUC | Area Under the receiver operator characteristic Curve |
| BM | Bavarian Matrix |
| CART | Classification and Regression Tree |
| CIT | Conditional Inference Tree |
| L | Likelihood of avalanches rating: Likely |
| P | Likelihood of avalanches rating: Possible |
| POLR | Proportional Odds Logistic Regression |
| ROC | Receiver Operator characteristic Curve |
| UL | Likelihood of avalanches rating: Unlikely |
| VL | Likelihood of avalanches rating: Very Likely |

# Chapter 1. Introduction

Backcountry skiers, mountain snowmobilers, out-of-bound skiers, ice climbers and snowshoers from all over the world are drawn to Western Canada because of its world-renowned mountains and powder snow. However, enjoying the backcountry in the winter time is not without risk as these activities are associated with the exposure to natural hazards, such as snow avalanches, tree wells, cliffs or crevasses, that can lead to accidental injury or death. On average, avalanches claim the lives of approximately 14 recreationists in Canada every winter (Avalanche Canada, 2017). The majority of these fatalities involve non-guided backcountry recreationalists who are responsible for their own decisions while traveling in avalanche terrain (Jamieson, Haegeli, & Gauthier, 2010).

In comparison to skiers in ski resorts or guests at mechanized skiing operations, where the risk from avalanches is managed by ski patrollers and professional mountain guides, non-guided backcountry recreationalists are responsible for their own risk management decisions (Statham, 2008). Since avalanche hazard cannot be physically controlled in the backcountry (e.g., through the use of explosives), the primary risk mitigation method of recreationists is their decision of when and where to expose themselves to the existing hazard (Statham, 2008; Statham, Haegeli, et al., 2018).These decisions are made at various stages before and during a backcountry trip (Haegeli & Strong-Cvetich, in press). First, recreationists need to decide whether to go on a backcountry trip at all or not. If the decision is made to go, they need to find an appropriate destination under the given conditions. Once at the trailhead or staging area, they have to choose an appropriate route, which is subsequently continuously adjusted in response to the local avalanche hazard conditions.

For most recreationists, public avalanche bulletins (Figure 1.1) are the first and primary place for getting information about avalanche hazard when planning a trip into avalanche terrain. In Canada, Avalanche Canada and Parks Canada produce daily avalanche bulletins for regions in key mountain regions throughout British Columbia (BC) and Western Alberta from mid-November until the end of April.

Panel A)

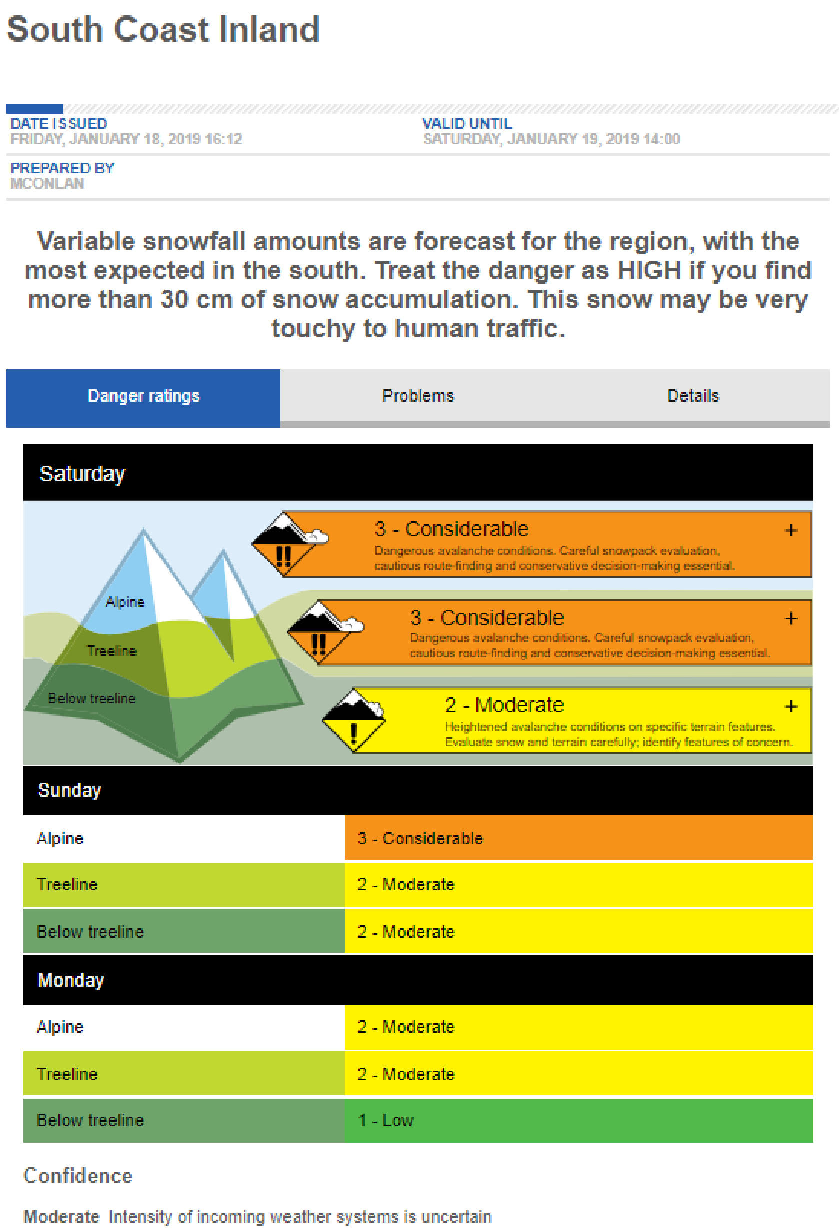



**Figure 1.1** **Public avalanche bulletin for the South Coast Inland forecast region on January 18th, 2019 describing the danger ratings for three elevation bands (Panel A) and a description of the avalanche problems (Panel B) including where the problem is located as well as the expected size and chances of avalanches, and detailed background on weather, snowpack and avalanche conditions (Panel C).**

Panel B)

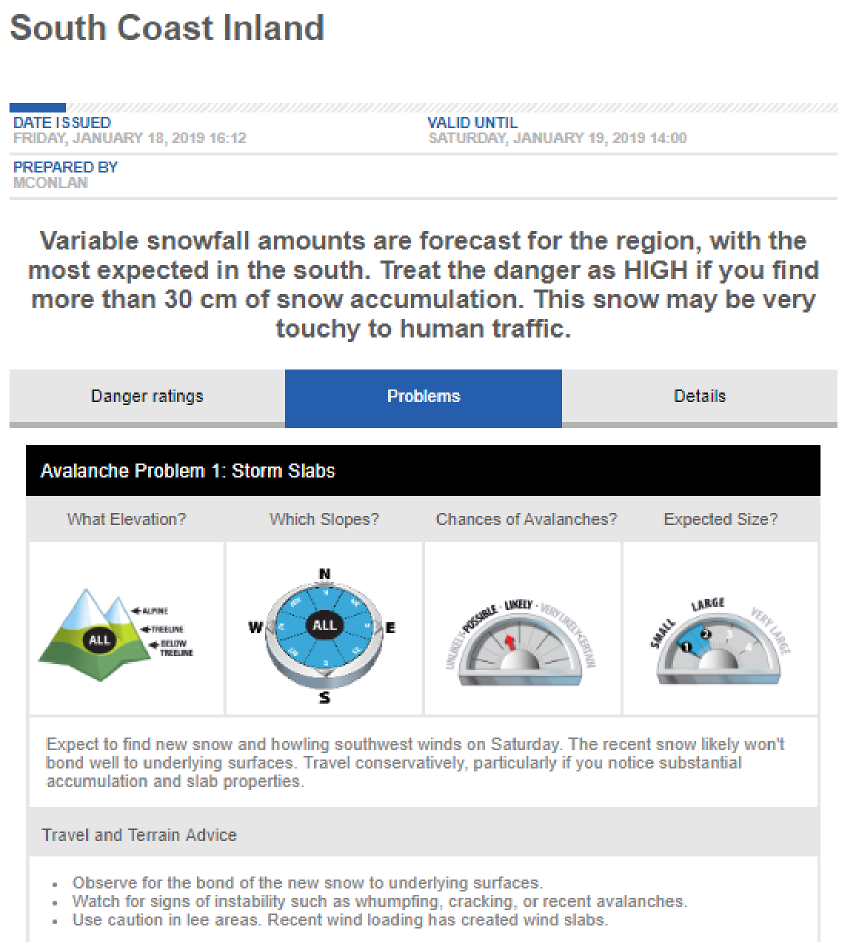
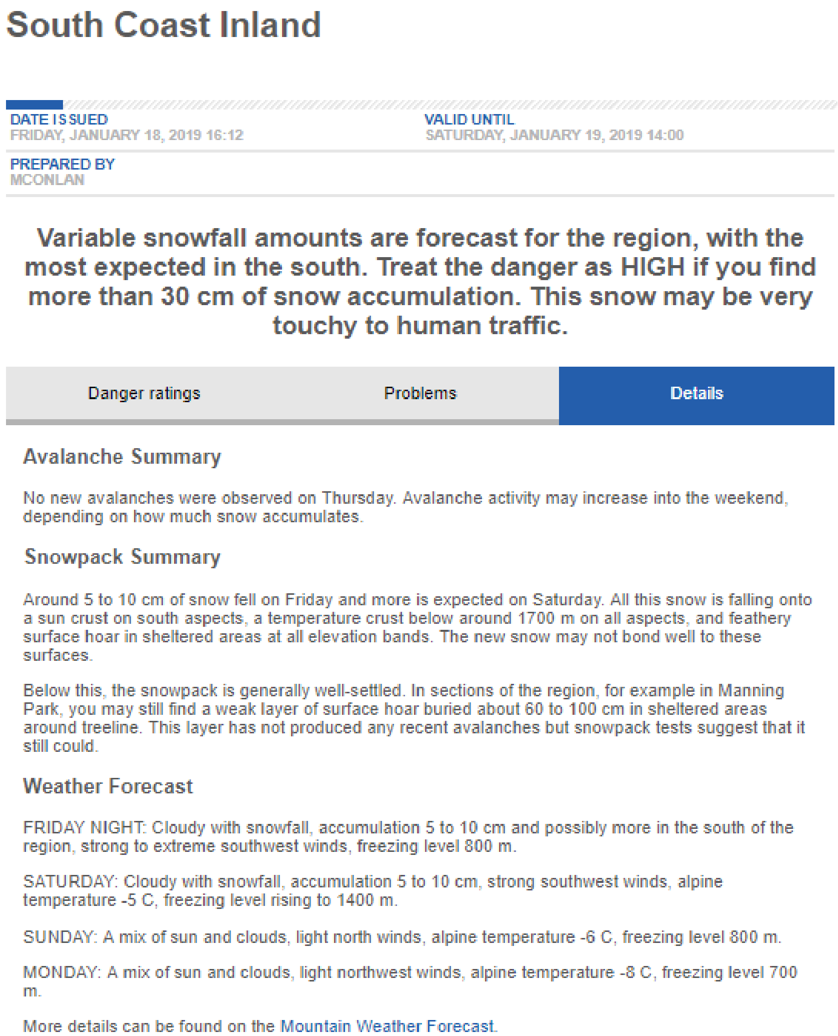



**Figure 1.1 Continued**

Canadian avalanche bulletins are structured according to an information pyramid, which presents avalanche hazard information from the most succinct to the most detailed. At the top of the pyramid, danger ratings at three elevation bands (alpine, treeline, below treeline) describe conditions using the North American Public Avalanche Danger Scale (Statham et al., 2010) (Figure 1.1 – Panel A). The scale consists of five ordinal levels, colour coded from green (Low) to black (Extreme) illustrating overall avalanche danger (Figure 1.2). A similar five level scale exists in Europe, called the European Avalanche Danger Scale, but definitions of individual levels differ slightly (Statham et al., 2010). The middle of the information pyramid describes the nature of the existing avalanche hazard in more detail using the concept of avalanche problems (Statham, Haegeli et al., 2018). Each avalanche problem is characterized in terms of

Panel C)


South Coast Inland

DATE ISSUED
FRIDAY, JANUARY 18, 2019 16:12

VALID UNTIL
SATURDAY, JANUARY 19, 2019 14:00

PREPARED BY
MCONLAN

**Variable snowfall amounts are forecast for the region, with the most expected in the south. Treat the danger as HIGH if you find more than 30 cm of snow accumulation. This snow may be very touchy to human traffic.**

Danger ratings | Problems | Details

**Avalanche Summary**

No new avalanches were observed on Thursday. Avalanche activity may increase into the weekend, depending on how much snow accumulates.

**Snowpack Summary**

Around 5 to 10 cm of snow fell on Friday and more is expected on Saturday. All this snow is falling onto a sun crust on south aspects, a temperature crust below around 1700 m on all aspects, and feathery surface hoar in sheltered areas at all elevation bands. The new snow may not bond well to these surfaces.

Below this, the snowpack is generally well-settled. In sections of the region, for example in Manning Park, you may still find a weak layer of surface hoar buried about 60 to 100 cm in sheltered areas around treeline. This layer has not produced any recent avalanches but snowpack tests suggest that it still could.

**Weather Forecast**

FRIDAY NIGHT: Cloudy with snowfall, accumulation 5 to 10 cm and possibly more in the south of the region, strong to extreme southwest winds, freezing level 800 m.

SATURDAY: Cloudy with snowfall, accumulation 5 to 10 cm, strong southwest winds, alpine temperature -5 C, freezing level rising to 1400 m.

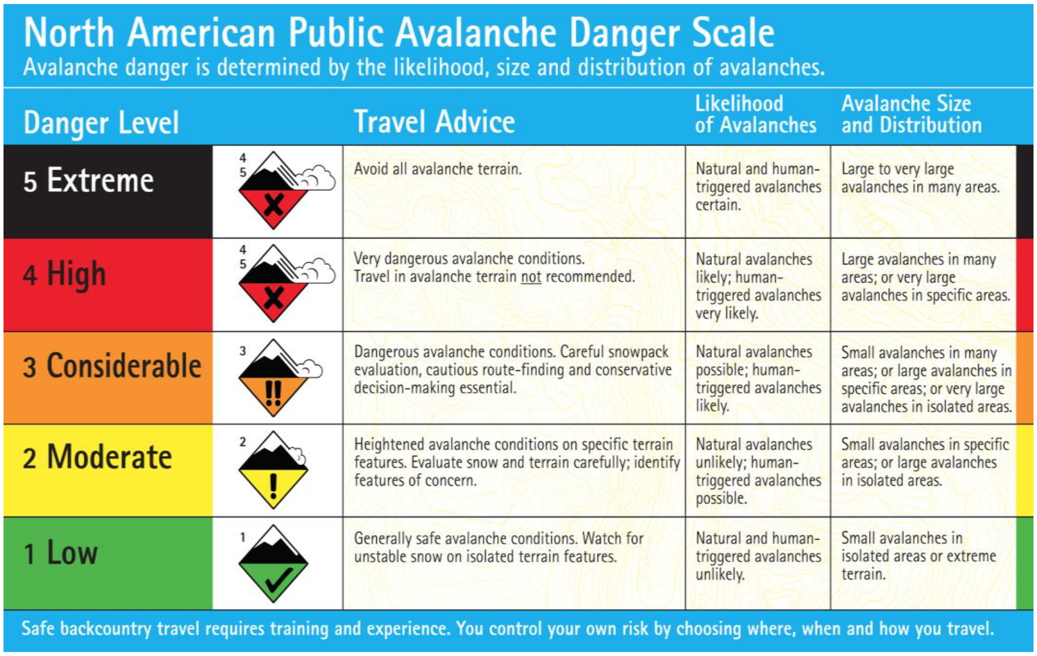
SUNDAY: A mix of sun and clouds, light north winds, alpine temperature -6 C, freezing level 800 m.

MONDAY: A mix of sun and clouds, light northwest winds, alpine temperature -8 C, freezing level 700 m.

More details can be found on the Mountain Weather Forecast.

**Figure 1.1 Continued**

avalanche problem type, location of where the problem is likely found (elevation bands and aspects), likelihood of triggering and the expected destructive size (Figure 1.1 – Panel B). This provides users with specific characteristics of the avalanche problem(s) that will likely be encountered while in avalanche terrain. At the very bottom of the information pyramid is more detailed information about past avalanche conditions, critical snowpack features and relevant information from the weather forecast (Figure 1.1 – Panel C). While the information provided in avalanche bulletins gives backcountry users pivotal information for planning a trip into avalanche terrain, this information needs to be verified and supplemented with direct field observations once out in the field.



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.

**Figure 1.2 The North American Public Avalanche Danger Scale describing the danger rating, travel advice for each level along with the likelihood of avalanches, destructive size and distribution (Statham et al., 2010).**

The foundation of Canadian avalanche bulletins is the Conceptual Model of Avalanche Hazard (CMAH) (Statham, Haegeli, et al., 2018) which organizes the avalanche forecasting process around four sequential questions:

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

In 2011, Parks Canada developed the avalanche forecasting software *AvalX* (Statham, Campbell and Klassen, 2012) to integrate the CMAH into the workflow of public avalanche forecasters in Canada. *AvalX* provided the first standardized forecasting method and delivered a consistent format for the presentation of avalanche safety information in Canada (Statham, Haegeli, et al., 2018).

While the CMAH standardized and streamlined the avalanche hazard assessment process, it does not provide explicit guidance on what levels on the North American Avalanche Danger Scale are associated with what type of avalanche hazard conditions. This missing link leaves danger rating assignments up to forecaster judgement, which can lead to inconsistencies in published danger ratings. This is a problem as Murphy (1993) expresses that consistency is one of three characteristics that contribute to the overall goodness of a forecast, allowing users to attain maximum benefit and inform the decision making (risk mitigation) process. The same point was previously made by Mileti and Sorensen (1990), who also stress consistency as a key attribute for effective risk communication products.

To highlight the inconsistency challenge, Lazar et al. (2016) conducted a survey where avalanche forecasters were asked to assign danger ratings from the North American Public Avalanche Danger Scale to ten different snowpack and weather scenarios. The study found that although there was much consensus at the extreme ends of the danger rating scale (Low and Extreme), substantial differences in judgment were observed when the danger rating was in the middle of the danger scale (i.e., moderate or considerable).

A first attempt to provide a quantitative link between the CMAH and the danger rating scale was conducted by Haegeli, Falk, and Klassen (2012), who used two years of CMAH-based hazard assessment data from Avalanche Canada that was collected with a precursor system of *AvalX*. Their analysis showed that maximum likelihood of triggering and maximum destructive size had the strongest influence on danger ratings. Their analysis also showed considerable variation in danger rating assessments among forecasters.

The operational use of the *AvalX* software by both Avalanche Canada and Parks Canada since 2012 has produced a rich, CMAH-based hazard assessment dataset, which provides a unique opportunity for examining the relationship between the North American Public Avalanche Danger Scale and hazard assessments in more detail. The objective of my research is to explore this connection and identify the assessment rules used by avalanche forecasters in Canada. More specifically, my research is driven by the following research questions:

- How are the core components of the CMAH used to describe the nature of avalanche hazard—likelihood of avalanches and destructive size—linked to avalanche danger ratings?
- Are avalanche danger rating assignments influenced by other factors?

The intent is that the results from my research will provide the foundation for establishing a formal decision aid to address the issue of inconsistent danger rating assignments in public avalanche bulletins. In comparison to the European Bavarian Matrix[1] (European Avalanche Warning Services, n.d.) (Appendix A), which was designed by a small group of experts, the decision aid based on my results would represent the assessment expertise of the entire Canadian public avalanche forecasting community.

[1] The Bavarian Matrix is a danger rating assessment aid used by public avalanche forecasters in Europe.

# Chapter 2. Background

## 2.1. Conceptual Model of Avalanche Hazard

When assessing threats from avalanches, it is important to clearly distinguish between hazard and risk. Statham (2008) defines avalanche hazard as *“The potential for an avalanche(s) to cause damage to something of value”*, which represents the condition of the natural system is independent of any elements at risk. In the same paper, risk is defined as *”The probability or chance of harm resulting from interactions between avalanche hazard and a specific element at risk”* (e.g., building, infrastructure, person) (Statham, 2008). Hence, risk combines hazard with exposure and vulnerability, which are both properties of the element at risk. In the case of backcountry travel, the risk from avalanches is kept at an acceptable level by constantly adjusting exposure in response to the local hazard.

In 2010, a group of avalanche professionals developed the Conceptual Model of Avalanche Hazard (CMAH) to provide a streamlined, generic and consistent workflow for assessing avalanche hazard (Figure 2.1). The conceptual model is based around four key questions regarding the avalanche hazard:

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

Together, the components of the conceptual model describing the hazard are combined in a way that structures and focuses the hazard assessment process to inform risk management decisions. Avalanche forecasters use the details provided to determine the avalanche danger rating while providing backcountry users with interpretable information to help manage their own risk.

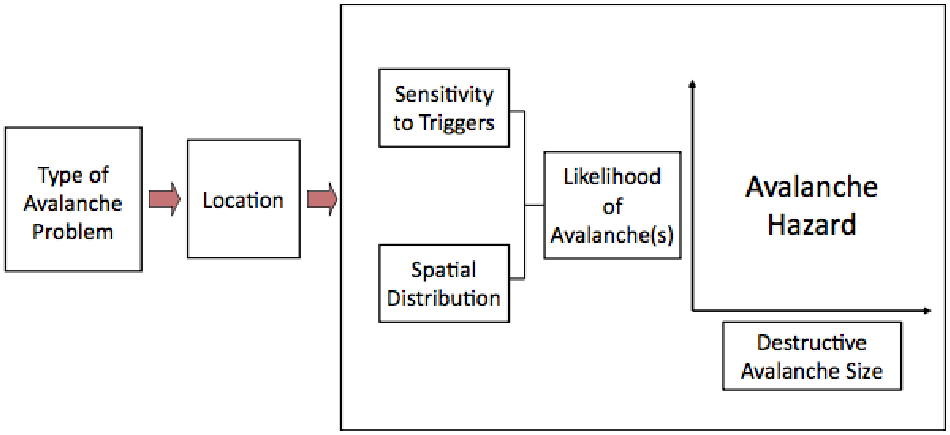



**Figure 2.1: The workflow process of the conceptual model outlining the avalanche problem type, its location, likelihood of avalanche(s) and destructive size (Statham, Haegeli et al., 2018*)*.**

The CMAH framework starts by identifying the type of avalanche problems present based on current weather, snowpack and avalanche observations. An avalanche problem type represents a repeatable avalanche hazard situation that develops under distinct conditions and requires specific avalanche risk management approaches (Haegeli, et al. 2010). Statham, Haegeli, et al. (2018) describe nine different avalanche problem types that are encountered in avalanche terrain (Table 2.1). A *Storm slab avalanche problem*, for example, forms when new snow is deposited onto an old surface where bonding has yet to occur resulting in a slab that is relatively easy to trigger and size depending on the amount new snow. An appropriate risk mitigation strategy for this avalanche problem type is to avoid avalanche terrain all together for a period of time allowing the storm snow to stabilize (Haegeli, et al., 2010). In contrast, *Persistent slab avalanche problems* form as a result of snow metamorphism changing the structure of snow crystals creating a weak layer that can fracture when stressed. Managing this problem type requires avoiding specific areas, slopes or elevation bands. Multiple avalanche problem types can coexist at any given time, and the CMAH accounts for this by prioritizing and assessing each individually through the framework.

**Table 2.1 The nine avalanche problem types encountered within avalanche terrain along with a short description of the problem and risk mitigation strategies (after Haegeli et al., 2010; Statham, Haegeli, et al., 2018).**

| Avalanche Problem | Description of problem | Risk mitigation strategies |
|---|---|---|
| Cornice | Overhanging deposit of snow formed on leeward slopes overtop of cliff or steep drop. | Limit exposure where cornices are present and use caution on ridges. |
| Deep persistent slab avalanche problem | Thick cohesive slab overlying an early season persistent weak layer in the lower existing snowpack. | Approach new terrain cautiously and be conservative with terrain choices. |
| Dry loose avalanche problem | Dry, powdery surface snow released from specific point. | Avoid steep slopes and terrain traps. |
| Glide avalanche problem | Snowpack destabilizes at the ground causing cracks to form potentially releasing entire snowpack. | Avoid areas where glide cracks are visible. |
| Persistent slab avalanche problem | Consolidated slab of snow overtop of poorly bonded persistent weak layer in the existing snowpack. | Avoid specific locations (elevation bands, aspects) where weak layers are present. |
| Storm slab avalanche problem | Unconsolidated soft slab formed by newly fallen snow. | Avoid avalanche terrain during and for up to a day after the storm. |
| Wet loose avalanche problem | Wet surface snow released from a specific point. | Avoid terrain traps, avalanche paths and start zones. |
| Wet slab avalanche problem | Consolidated slab of wet snow. | Avoid start zones and avalanche paths especially during daytime heating. |
| Wind slab avalanche problem | Consolidated slab of wind deposited snow. | Avoid areas where wind drifted snow is deposited, most commonly on leeward slopes. |

After the types of the existing avalanche problem(s) are identified, forecasters describe the location where the problem(s) can be found in the terrain. Terrain characteristics such as slope angle, slope shape, orientation to the sun and wind, as well as elevation band influence the development of avalanche problems. In public avalanche bulletins, the location of an avalanche problem is expressed with respect to elevation bands and sides of the mountain (aspect) since the information is synoptic in nature and provided at a regional scale. Elevation band describes elevation in three distinct bands, from highest to lowest being alpine, treeline and below treeline. The alpine elevation band contains little to no vegetation where multiple avalanche paths exist over open slopes and ridges compared to the below treeline elevation band where vegetation is dense towards valley bottoms (Avalanche Canada, 2019). The treeline elevation band is a transition zone between below treeline and alpine where vegetation begins to become sparse leading into the alpine and is relatively narrow compared to the two other bands (Avalanche Canada, 2019). Aspect has a direct influence on weather factors such as wind and temperature (McClung & Schaerer, 2006). These factors create different avalanche problems based on the difference in air temperature between solar and non-solar aspects while wind created problems are more present on leeward slopes. For example, *Wet slab avalanche problems* and *Wet loose avalanche problems* are more present on solar aspects due to increased temperatures, melting the surface snow on sunny days whereas *Wind slab avalanche problems* and *Cornices* are problems most likely found on leeward aspects due to the prevailing wind direction. Identification of the problem location is crucial in making decisions about risk mitigation strategies.

Once the location of avalanche problem is identified, forecasters describe the likelihood of avalanches, which represents the probability or chance that avalanches of the particular type will release (Statham, 2008), in a qualitative way. Likelihood of avalanches is a function of the spatial distribution of the problem and its sensitivity to triggering. The spatial distribution refers to the spatial density of the avalanche problem and the presence of related evidence (e.g., relevant snowpack observations, associated avalanche activity) within the location of the avalanche problem previously specified in terms of elevation band and aspect. The distribution of the problem is expressed in qualitative terms ranging from *widespread* (the problem is in many locations and terrain features) to *isolated* (certain locations and specific terrain features) on a three-level ordinal scale. Sensitivity to triggers describes the instability of the problem based on its ease of triggering naturally or by humans. The terms used to express sensitivity range from *touchy* (almost certain human triggered and numerous natural avalanches) to *unreactive* (no human or naturally triggered avalanches). Forecasters then combine their spatial distribution and sensitivity rating into a single, qualitative rating for likelihood of avalanches, which is described using a five-level ordinal scale ranging from Unlikely to Almost Certain (Figure 2.2). Half steps can be used to be more specific. For example, an avalanche problem’s likelihood of avalanche that is greater than Possible but less than Likely can be referred to as Possible-Likely.

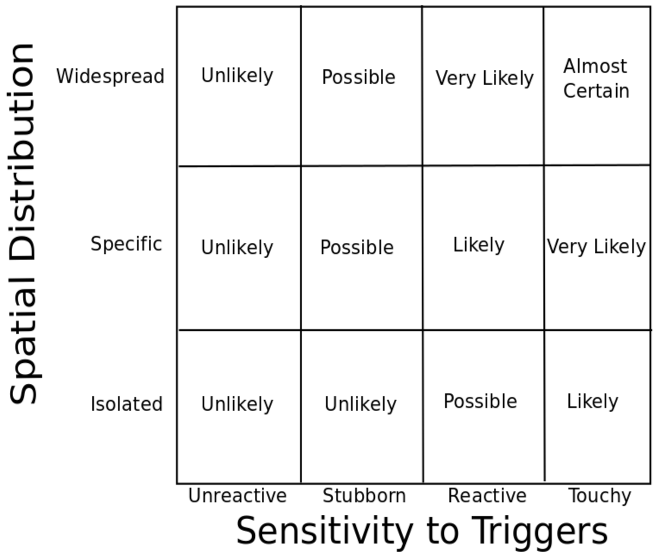



**Figure 2.2 Matrix describing the likelihood of an avalanche as a function of its spatial distribution and sensitivity to triggers (Statham, Haegeli, et al., 2018)**

Estimating the destructive size of the associated avalanches is the last component in the CMAH assessment process. Destructive size is expressed using the Canadian avalanche size classification (Canadian Avalanche Association, 2014). This five-level scale ranges from size 1, which represents avalanches that are relatively harmless to people, to size 5, which is used to describe the largest known avalanches (Table 2.2). Similar to the likelihood scale, sizes can be described in half sizes.

**Table 2.2: Canadian Avalanche Size Classification (Canadian Avalanche Association, 2014)**

| Size | Destructive Potential | Typical mass | Typical path length | Typical impact pressure |
|---|---|---|---|---|
| 1 | Relatively harmless to people. | < 10 t | 10 m | 1 kPa |
| 2 | Could bury, injure, or kill a person. | $10^2$ t | 100 m | 10 kPa |
| 3 | Could bury and destroy a car, damage a truck, destroy a wood-frame house of break a few trees. | $10^3$ t | 1 000 m | 100 kPa |
| 4 | Could destroy a railway car, large truck, building or a forest of approximately 4 ha. | $10^4$ t | 2 000 m | 500 kPa |
| 5 | Largest snow avalanche known. Could destroy a village or a forest area of approximately 40 ha. | $10^5$ | 3 000 m | 1 000 kPa |

After the likelihood of avalanches and destructive size are specified for all avalanche problems, the overall hazard assessment is summarized by visualizing the described avalanche problem(s) on a hazard chart (Figure 2.3). To represent uncertainty from spatial and temporal variability as well as lack of forecaster knowledge, both likelihood of avalanches and destructive size are expressed through a value triplet that consists of the maximum, typical and minimum values (Statham, Haegeli et al., 2018). The center of the plotted square represents the typical estimated likelihood and size of the avalanche problem(s), whereas the upper left and lower right corners outline the maximum and minimum values.

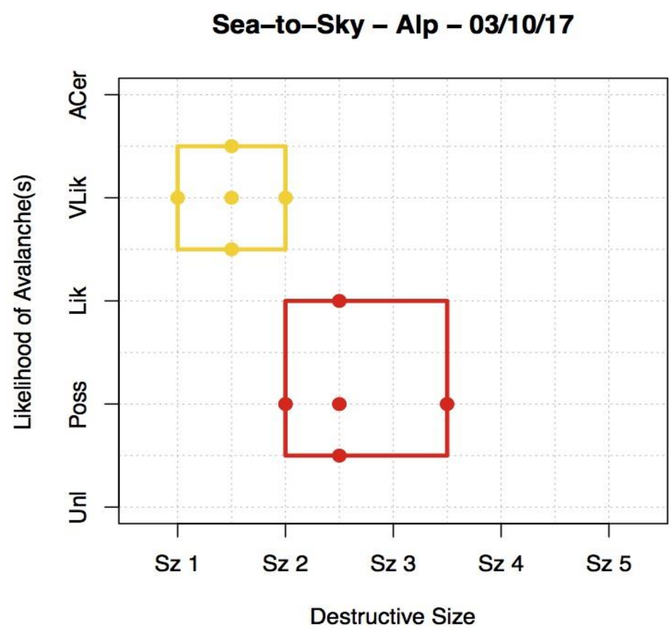



**Figure 2.3 Example of the CMAH hazard chart output for the Sea-to-Sky forecast region for March 10th, 2017. The yellow rectangle represents a Storm slab avalanche problem while the yellow rectangle represents a Persistent slab avalanche problem. The point in the middle describes the typical value of the size and likelihood of the problem avalanching while the outer edges represent the maximum and minimum values.**

Since the CMAH was designed as a generic framework for avalanche hazard assessment, it does not specify the nature of the subsequent risk management actions. In the case of public avalanche forecasting, avalanche forecasters publish avalanche danger ratings in public avalanche bulletins, which recreationists then use to make their own avalanche risk management decisions. Ski guides, on the other hand, use the information from the hazard assessment directly to make terrain choices in the backcountry. Avalanche professionals responsible for the safety of a transportation corridor use the information from the hazard assessment to decide whether to close the road or leave it open and/or whether to use explosives to manage the existing hazard.

## 2.2. Existing statistical models for avalanche hazard assessment

There have been several studies that have modeled avalanche hazard. These studies differ from each other with respect of a) the type of input parameters, b) how the dependent variable of avalanche hazard is operationalized in the model, and c) what method is employed to describe the relationship between the predictor and dependent variables.

Discriminant analysis was used as one of the earlier methods to identify the most powerful parameter for distinguishing between avalanche and non-avalanche days along a highway corridor or within a ski area (Floyer & McClung, 2003; McClung & Tweedy, 1994; Obled & Good, 1980). Floyer and McClung (2003) used a one way analysis of variance and canonical discriminant analysis to determine important physical variables related to avalanche prediction based on manually recorded snowpack and weather data from four sections of Bear Pass, British Columbia. Using these two methods, important variables were extracted that distinguished between avalanche and non-avalanche days such as amount of new precipitation, temperature and snowpack depth. The models were able to classify 73% of avalanche days and 72% of non-avalanche days.

The nearest neighbour approach emerged as a successful approach for modelling avalanche hazard in several different operational contexts. The approach was first introduced by Obled and Good (1980), who used it to estimate the probability of avalanches within the Parsenn ski area in Davos, Switzerland, based on how similar the current conditions are to observed conditions in the past. Building on their success, Brabec and Meister (2001) used the method to develop a nearest neighbour model for assessing regional avalanche danger. Given observations on slope stability, elevation, slope aspect, avalanche activity and weather data, the NXD-2000 assessed regional avalanche danger in terms of the European Public Avalanche Danger Scale.

Schirmer, Lehning, and Schweizer (2009) used a variety of different statistical methods—classification trees, the nearest neighbour approach, artificial neural networks, support machine vectors and hidden Markov models—to predict regional avalanche danger ratings based on simulated snowpack observations. The study used a variety of measures to assess prediction accuracy to determine which method worked best. Overall the nearest neighbour approach proved to be the most reliable model, predicting danger rating correctly 73% of the time. The classification tree analysis showed the lowest performance of all models but was able to predict changes in the danger rating reasonably well.

Pozdnoukhov et al. (2011) used a support vector machine approach to predict avalanche danger ratings for a small forecast region in Scotland based on 39 parameters including local weather observations, modeled snowpack parameters and avalanche observations. The system was applied to a grid with 10 m resolution to produce avalanche forecasts at a high resolution. Although this approach showed the ability to model avalanche hazard at a high spatial resolution using support vector machines, the hazard ratings used as the target variable were not based on a danger scale. Rather the model assumed the probability of an avalanche occurring within the grid space from unlikely (0) to certain (1) given local conditions.

Bellaire and Jamieson (2013) used classification trees to derive danger ratings from simulated snowpack conditions in Rogers Pass, Canada. Snowpack simulations were done on a single grid point location closest to a well-known study plot at Mt. Fidelity. They used a multivariate classification analysis to determine the most important variables, which where then used in a classification tree analysis to predict the danger rating. Danger ratings were based on the North American Public Avalanche Danger Scale and forecasted danger ratings from the 2012-2013 winter season for Glacier National Park were used for validation. The classification model provided 77% of alpine, 76% of tree line, and 70% of below tree line danger rating classifications correctly.

Hendrikx, Murphy, and Onslow, (2014) used 28 years of weather, snowpack and avalanche activity variables on the Seward Highway in Alaska to identify key parameteters responsible for significant avalanche activity. They described an avalanche day as one day or more where avalanches ran 90% of their path length where 100% of the path length was the road itself. Using two different classification tree methods (one with an equal, one with unequal misclassification rate), the proabability of detecting an avalanche day was between 74% and 94% based on the number of input parameters used to grow each tree model. Many of the variables that gave high probability of detection were based on weather measurements such as the highest temperature in a 24 hour period. The trees developed for this study were then combined with forecasting practices along the road to aid as an operational forecasting tool.

Most recently, Blattenberger and Fowles (2016) used Bayesian additive trees to model whether avalanches would cross the road in the Little Cottonwood Canyon in Utah using daily winter data from 1995 to 2011. The ensemble method provided a flexible way of dealing with the abundance of variables with small bits of information being gained over numerous model iteration to provide synthesized information of whether or not to close the road. The model out performed many traditional approaches as well as forecaster data provided by guard stations along the road. It proved to be an effective method addressing avalanche prediction within this area and context.

While all of the mentioned studies aimed to model the physical pathways between avalanche hazard and its contributing factors, an alternative approach is to imitate the human forecasting process by processing data based on decision rules determined by avalanche experts. This type of model is generally referred to as expert systems. Météo France, for example, uses MÉPRA (Giraud, 1992) as part of their operational avalanche forecasting model chain to interpret simulated snow profile data and derive an avalanche hazard rating on a four-level scale. Schweizer and Föhn (1996) created two expert system models using CYBERTEK-COGENSYS software to evaluate the degree of avalanche hazard according to the altitude and aspect of dangerous slopes based on weather, snowpack and snow cover data around Davos, Switzerland.

The study closest to the present research is Haegeli, Falk and Klassen (2012), who examined public avalanche bulletin data captured through the CMAH framework from two winters produced by Avalanche Canada and Parks Canada. Using a proportional odds logistic regression model (POLR), a type of ordinal logistic regression model, 3073 hazard assessments were used to predict danger rating based on avalanche problems. The model predicted the correct danger rating 75% of the time. Analysis found that the maximum values of likelihood of avalanches had the most influence on danger rating, while maximum expected size and avalanche problem(s) were respectively second and third most important. While the POLR model analysis by Haegeli, Falk and Klassen (2012) offered valuable quantitative insights into the relationship between the components of the CMAH and avalanche hazard ratings, their model approach has some weaknesses that fundamentally inhibit its ability to accurately represent forecaster expertise. The model assumed a linear relationship between avalanche problem characteristics and danger rating and did not incorporate any interaction terms between variables. In addition, the dataset at the time only included two winter seasons of public avalanche bulletins, which only covers a limited range of possible avalanche hazard conditions.

While all of the mentioned studies have contributed to our ability to predict avalanche hazard, there are a number of shortcomings that might prevent these models from achieving higher prediction accuracies for regional avalanche hazard. First, the pathway from weather and snowpack observations to an avalanche hazard rating is complex and involves many interactions that can be difficult to incorporate in statistical models. Second, predicting regional avalanche hazard from weather and snowpack observations at point locations might be challenged by scale issues (Haegeli & McClung, 2004) as there is a mismatch between the small-scale nature of observations (e.g., temperature observation, snowfall observation) and the regional-scale nature of danger ratings. Third, large-scale operational avalanche forecasting datasets can be quite messy as it is difficult to collect consistently complete observations over large areas. For example, large-scale avalanche datasets are inherently incomplete as it is never possible to comprehensively monitor large areas and limited visibility can temporarily prevent observations completely.

The CMAH dataset offers a unique opportunity to potentially overcome these challenges. By having human avalanche forecasters interpret the existing conditions and distilling them into the key components of avalanche hazard addresses the complexity of the pathway between observations and avalanche hazard as well as the incompleteness of observations. Furthermore, the forecaster assessment process also overcomes the scale issue as the hazard components are assessed at the same scale as the danger rating. Hence, the CMAH has the potential to offer a much cleaner dataset for predicting avalanche danger ratings than what was available to previous studies.

# Chapter 3. Methodology

## 3.1. Study area and dataset

In Canada, Avalanche Canada and Parks Canada are the main agencies responsible for providing public avalanche safety information. Together, these agencies publish daily avalanche bulletins for 17 different forecast regions in western Canada during the winter months (approx. mid-November to the end of April). While Parks Canada produces bulletins for five forecast regions covering the mountain national parks (Banff-Yoho-Kootenay, Little Yoho, Jasper, Glacier and Waterton), Avalanche Canada produces daily forecasts for 12 regions in western Canada (Figure 3.1).

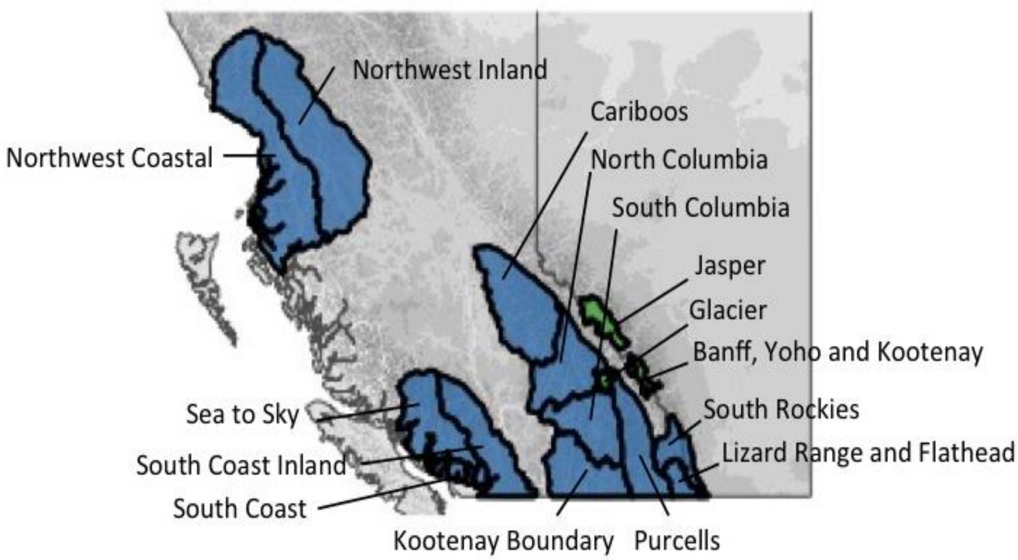



**Figure 3.1 Public avalanche bulletin regions of western Canada, 2018. Blue areas represent Avalanche Canada forecast regions while green areas show Parks Canada regions.**

The mountains regions in western Canada covered by avalanche bulletins can be grouped into three main mountain ranges that include the Coast Mountains along the Pacific coast, the Columbia Mountains in the interior and the Rocky Mountains along the BC-Alberta border. Each of these mountain ranges has a distinct snow climate and is known for particular avalanche hazard patterns (McClung & Schaerer, 2006; Shandro &

Haegeli, 2018). The Coast Mountains are characterized by a maritime snow climate as winters consist of heavy snowfall, moderate temperatures and deep snowpacks. The majority of avalanches in this area are typically storm slab avalanches that occur during or following storms. The continental snow climate of the Rocky Mountains shows lower snowfalls, colder temperatures and much thinner snowpacks that are often unstable due to persistent structural weaknesses within the snowpack. Deep persistent slabs and wind slabs are the dominant avalanche problems in this area. The Columbia Mountains exhibit a transitional climate with characteristics of both continental and maritime, which result in distinct problems due to surface hoar layers and crust-facet combinations (Haegeli & McClung, 2007; Shandro & Haegeli, 2018). While these snow climate classifications describe the general snow and avalanche characteristics of the main mountain ranges in Western Canada, considerable variations can exist within these regions and from year to year (Shandro & Haegeli, 2018).

## 3.2. Dataset content and structure

Forecasters at Avalanche Canada and Parks Canada use the software *AvalX* to produce their daily avalanche forecasts during winter months (Statham, Campbell, & Klassen, 2012). *AvalX* structures forecasters' workflow process according to the CMAH and gives them a convenient workspace to assimilate observations, develop public avalanche bulletins and document their process in a structured way (Statham, Haegeli et al., 2018). Prior to the implementation of *AvalX* at Avalanche Canada and Parks Canada in 2012, Avalanche Canada used the avalanche hazard assessment website provided by Avisualanche Consulting (http://avalanchehazard.avisualanche.ca/) for two winters to document the production of their avalanche bulletins according to the CMAH framework, This website was used to test the practical value of the CMAH for operational avalanche forecasting and served as a prototype for the development of *AvalX.*

For the present analysis, I only used avalanche bulletins that were stored in *AvalX*. To maximize consistency between forecast regions, I limited my analysis dataset to only bulletins that were published between December 1st and April 15th. This resulted in a complete analysis dataset of 14,265 bulletins that span all forecast regions within western Canada during seven winters (2012 to 2018). The information stored for each bulletin consists of three main components; metadata, characteristics of avalanche problems and avalanche danger ratings. Bulletin metadata includes information on the date of publication, which region and mountain range the bulletin was produced for, the agency that produced the bulletin, and the initials of the forecaster authoring the bulletin. Each avalanche problem included in a bulletin is characterized with its maximum, typical and minimum values of likelihood of avalanches and destructive size, the location of the problem according to elevation band (alpine, treeline and below treeline), aspects the problem is present on, as well as sensitivity to triggering and spatial distribution. The avalanche danger ratings included in an avalanche bulletin represent the overall assessment of the hazard at each elevation band and are given for the day the bulletin is released and forecasted three days into the future. Each of these three components are stored in separate database tables in *AvalX*.

For the present analysis, I processed the dataset in the following manner. To allow the linking of hazard ratings at individual elevation bands with relevant avalanche problem characteristics, I first merged the *AvalX* bulletin database tables and converted them into a single table of hazard assessments by splitting up each bulletin into its three elevation bands. The resulting table consisted of 42,589 hazard assessments and had columns for all of the metadata, avalanche problem characteristics and avalanche danger ratings. The hazard assessment table had a wide table format as each of the nine avalanche problem types was represented by a set of columns expressing the problems characteristics assessed through the conceptual model. Sensitivity, distribution, minimum, typical and maximum values of likelihood of avalanches and destructive size of each problem type were represented with ordinal categories, whereas the aspects the problem was present on were stored in eight binary columns, one for each cardinal and intermediate directions.

Whereas this wide data format is efficient for the analysis of the dataset, it does not support circumstances when the same avalanche problem type is listed multiple times within the same assessment. However, these situations were rare, and I handled them by only including the avalanche problem instance with the higher value for likelihood of avalanches and/or destructive size. The assumption behind this approach is that under these circumstances, the hazard assessment is likely dominated by the more severe instance of the same avalanche problem type.

## 3.3. Decision tree approach

### 3.3.1. Why decision trees?

Modern machine learning methods offer powerful and flexible approaches for modeling complex non-linear relationships (Bishop, 2006) and represent a promising avenue for overcoming the limitations of the POLR model presented by Haegeli, Falk and Klassen (2012). While many of today's machine learning approaches, such as support vector machines or other ensemble methods, focus on predictive performance (Hothorn, Hornik, & Zeileis, 2006), the limited interpretability of the model prediction or output is a substantial limitation of these methods for providing deeper insight (Russell & Norvig, 2010). I chose decision trees, a supervised machine learning technique that classifies attributes according to specified output values (Russell & Norvig, 2010), to be the main modeling approach for my analysis as they combine the ability to model complex non-linear relationships while offering tangible and easy to interpret insights into the underlying decision rules. Furthermore, research in cognitive science postulates that decision trees are closely linked to models of the human decision making process (Martignon et al., 2012). Two main types of decision trees exist; classification trees for modelling ordinal or nominal dependent variables, and regression trees for modelling numeric dependent variables (Bishop, 2006). Since the avalanche danger rating is an ordinal data type, my analysis requires a classification tree approach.

### 3.3.2. Conditional inference trees

Several avalanche research studies have used decision trees in the past such as Schirmer, Schweizer and Lehning (2010), Bellaire and Jamieson (2013). All of these studies used the well-established Classification and Regression Tree (CART) approach by Breiman et al. (1998), which uses the Gini index as the splitting criteria to recursively partition the dataset into increasingly homogeneous nodes (Kuhn & Johnson, 2013). While the CART approach is well established, it has a number of weaknesses. First, it can lead to overfitting as there are no stopping criteria in the CART approach (Hothorn, Hornik & Zeileis, 2006). To overcome this issue, CART models require pruning based on interpretation of performance indicators to establish effective models (Kuhn & Johnson, 2013). Furthermore, the CART approach can lead to biased splits when the response variable is unevenly distributed (Hothorn, Hornik & Zeileis, 2006).

Conditional inference trees (CIT, Hothorn, Hornik & Zeileis, 2006) avoid the issues of CART models by recursively splitting the dataset based on statistical hypothesis testing (Hothorn et al., 2008). In a CIT analysis, the splitting process starts by calculating a quadratic linear test statistic (Hothorn, Hornik & Zeileis, 2006) for the differences in dependent variable distributions for all possible partitions in the dataset (i.e., using all values of all the independent variables as possible splitting rules). Since little information can be determined for the possible split based on the test statistic alone, permutation framework tests are used to put the test statistic values into perspective. Permutation tests shuffle a sample of the dataset numerous times and calculate corresponding test statistics for each of these random splits. This creates a distribution of a variables quadratic linear test statistics. The original test statistic is then compared to the distribution to derive a p-value and assess the statistical significance of a proposed split. The p-values for all possible splits are then ranked accordingly and the dataset is split on the variable and value with the overall lowest p-value (i.e., highest statistical significance). This splitting process is done recursively until no variables remain that result in a statistically significant split. Once the splitting process is complete, the terminal nodes at the end of each branch contain a distribution of the dependent variable, which can then be used to make predictions. There are multiple ways to convert the distributions of the dependent variable into categorical predictions. By default, the CIT algorithm uses the mode of the distribution to predict a specific danger rating, but the product-sum (i.e., weighted average) can be a meaningful alternative.

The CIT approach differs from the traditional CART methodology as splits are based on a variable's influence (statistical significance) on the dependent variable rather than the node purity gained through each split. The CIT splitting criteria bypasses the limitations of the CART approach by producing unbiased splits of the dataset and avoiding performance indicator interpretation to achieve an adequate model (Hothorn et al., 2006). This means that CIT models do not require any pruning.

Similar to the CART method, the results of a CIT analysis can be visualized in the form of a decision tree diagram that offers an intuitive interpretation of how the model partitioned the dataset. Splits that are shown higher on the tree diagram are found to be more statistically significant than those found lower on the tree. Further, the tree visualization allows decision rules to be interpreted and extracted while terminal nodes describe the results of the decision rules that partitioned the dataset.

## 3.4. Analysis steps

### 3.4.1. Dataset overview

To begin the analysis, general descriptive statistics were calculated to provide insight into the general nature of the dataset. Depending on the class of the variable, I either used the Pearson’s Chi-squared test (nominal data), the Wilkoxon rank sum test (comparing ordinal data of two groups) or Kruskal-Wallis test (comparing ordinal data of more than two groups). I considered p-values < 5% to indicate statistically significant differences. I paid particular attention to examining the distributions of each parameter I intended to include in the CIT model with respect to avalanche problem type to understand the specific characteristics of each avalanche problem type and their differences. This information would provide critical information for guiding the analysis and interpreting the results in a meaningful way.

### 3.4.2. Splitting the dataset

Because of the high dimensionality of the avalanche hazard assessment dataset (311 parameters in total), applying a CIT analysis to the entire dataset would results in an overwhelming and extremely difficult to interpret decision tree. To maximize my ability to provide insight, I divided the dataset into three different types of situations according to the number of avalanche problems present. Hazard assessments that contained no avalanche problems were omitted from the analysis as they offer no information about decision rules and their connection to the danger rating. Hazard assessments with only a single avalanche problem were split into their own dataset. In these situations, the avalanche danger rating is fully determined by the characteristics of that single problem. The third and final split included the remaining hazard assessments with multiple avalanche problems. *AvalX* allows public avalanche bulletins to contain up to three avalanche problems and the resulting danger rating representing the combined hazard of all included problems.

### 3.4.3. Hazard assessments with single avalanche problems

The main goal of analyzing single avalanche problems first was to extract decision rules for individual avalanche problem types and compare them in a tangible way. In addition to exploring the effect of avalanche problem characteristics on avalanche danger ratings, I also used this analysis to explore how danger ratings are affected by other input parameters such as elevation band, mountain range or the agency that produced the assessment. The insight gained from this analysis would provide the foundation for examining the combined effect of multiple avalanche problems on avalanche danger ratings.

For this step in the analysis, the wide format data table was converted into long format by stacking the avalanche problem columns of all avalanche problem types into a single set. To maintain the information on the avalanche problem type, and additional avalanche problem type column was added. This data table format allowed me to create a single CIT model for all single avalanche problems combined. While the dataset of single avalanche problems contains sufficiently large samples for most avalanche problem types to allow meaningful analyses, avalanche problem types with particularly low number of data points where eliminated from the analysis.

According to the conceptual model of avalanche hazard, likelihood of avalanche and destructive size of an avalanche problem are the primary determinants of avalanche hazard. In *AvalX*, forecasters are asked to assign minimum, typical and maximum values for both of these parameters. The typical value is intended to represent the best possible estimate for the existing conditions, while the minimum and maximum values aim to describe the expected range of conditions based on a qualitative assessment of the expected variability in space and time (i.e., natural uncertainty) as well as assessment uncertainty (Canadian Avalanche Association, 2014). Since the likelihood and size value triplets are internally highly correlated, including all six parameters in the analysis would result in convoluted decision rules. A key decision for a meaningful analysis is how to best represent likelihood of avalanches and destructive size in the CIT models.

To address this issue, I created three base decision trees that only included the avalanche problem type and one of three possible parameter combinations representing the avalanche problem:

a) typical values of likelihood and size only

b) maximum values of likelihood and size only

c) typical + (maximum – typical) values of likelihood and size

While the typical value combination represents the best possible assessment of the hazard situation, the maximum value combination reflects a worst-case scenario as represented by the upper right extent of the hazard rectangle on the hazard chart, and the typical + (maximum – typical) combination represents a combination that incorporates both the best possible estimate and the size of the upper right corner of the hazard rectangle on the hazard chart.

To make an informed decision on how to best include likelihood of avalanches and destructive size in my CIT analysis, the single avalanche problem dataset was randomly split into training (75%) and testing (25%) sets. While the training set was used to build baseline CIT models for each representation option, the testing set was subsequently used to validate each model using hit rate and multi-class area under the receiver operator characteristic curve (multi-class AUC) as performance measures. Hit rate (also known as accuracy) refers to how often the model was able to correctly predict the danger rating category given the testing set and is expressed as a percentage (Wilks, 2006). It is a straightforward measure to understand but lacks a clear understanding of how well the model is able to predict each category (Harrell, 2011). Multi-class AUC was used to supplement the hit rate and assess how well the model is able to predict a given danger rating category. Obtaining this performance indicator required the calculation of a receiver operator characteristic curve (ROC), which explains how well a model predicts one category over another (Fawcett, 2005). ROC curves are calculated for each danger rating class compared to all others (e.g., low rating compared to moderate, considerable, high/extreme) and the area under the curve (AUC) is simply the area underneath the ROC curve (Fawcett, 2005). A diagonal line (0.5) represents the model predicting classes similar to random chance while scores above the diagonal show that the model can predict a given class better (Wilks, 2006). The multi-class AUC score is the average of all AUC scores for each class prediction and gives a realistic understanding of how well the model predicted each danger rating category (Hand & Till, 2001). In addition to performance indicators, public avalanche forecasters were asked to explain how they use minimum, typical and maximum values in *AvalX* to describe the existing conditions. I combined the results from the performance measure analysis with the perspectives of the forecasters to determine the best input parameter representation for the base CIT model.

Once the parameter representation for likelihood of avalanches and destructive size was chosen, I created a single Master CIT model for all single avalanche problems with agency, mountain range, elevation band and aspects of where the problem was present as additional parameters. Since most avalanche problems in my dataset were present on all (eight) aspects and only *Wind slab* and *Wet loose avalanche problems* exhibited more distinct aspect distributions, I simplified aspect into a binary parameter that depicts whether the problem was present on all aspects (1) or fewer (0). The influence of the variables included in the CIT model was assessed based on whether the variable was used to split the dataset. Additionally, simplified CIT models with fewer input parameters were calculated to assist the interpretation of specific research questions.

### 3.4.4. Visualization, decision rule extraction and model interpretation

Once the Master CIT model was created, I visualized the model using tree diagrams to facilitate interpretation and extract decision rules found by the model. To enhance interpretability, I extracted decision rules for each avalanche problem type from the Master CIT model and presented them as individual decision trees. This approach offered a straightforward comparison of relevant decision rules for each avalanche problem scenario.

To present the results of the analysis in a way that is more familiar to avalanche forecasters, I visualized the decision rules for specific scenarios (e.g., storm slab avalanche problems in the alpine assessed by Avalanche Canada in the Columbia Mountains) by drawing them onto the hazard chart. For these scenarios, the terminal nodes were identified for each likelihood of avalanches and destructive size combination where observations were present, and the danger rating distributions at each of these combinations were plotted as pie charts on the hazard chart. Furthermore, I used the predicted danger rating (mode of distribution) at each combination to colour in the background. Comparisons between the scenarios were based on the differences in terminal nodes found by the decision rules within the tree model. However, since the Master CIT model includes a large number of input parameters, the scenarios required for the hazard chart visualizations become too specific to highlight general patterns found in the data. To overcome this issue, I calculated additional, simpler CIT models (e.g., storm slab avalanche problems regardless of elevation band, agency and mountain range) that target specific relationships and facilitate their visualization on the hazard chart. Since these models are simplifications of the Master CIT model, the decision nodes and danger rating distributions presented in these hazard chart visualizations generally do not explicitly match with the decision nodes and danger rating distributions included in the Master CIT model.

## 3.5. Hazard assessments with avalanche problem combinations

Using the insight gained from the single avalanche problem CIT model, the analysis was then expanded to hazard situations that involved avalanche problem combinations. The goal of this analysis was to assess how the presence of an additional avalanche problem affects the decision rules and danger rating assignment of another avalanche problem. Frequencies of all avalanche problem combinations were calculated to identify the most common avalanche problem combinations. I then calculated individual, avalanche problem combination specific CIT models for each of the most common problem combinations using the same variable parameters as in the individual avalanche problem trees.

Due to the increased complexity of the resulting models, the visualization, rule extraction and interpretation was conducted differently than with the single avalanche problems. The higher dimensionality of these models (i.e., at least four dimensions due to two likelihoods of avalanches and two destructive sizes) also prevents their visualization on single hazard charts. However, to illustrate the tree models in a similar way to the single avalanche problem situations, I created a series of hazard charts. In these visualizations, the decision rules, terminal nodes and predicted danger ratings are plotted onto the hazard charts of one avalanche problem under a series of specific combinations of likelihood of avalanches and destructive size of the second avalanche problem. The resulting series of hazard charts allow the viewer to explore how the decision rules and danger rating assignments change in the hazard chart space of the first problem as a function of the nature of the second problem.

# Chapter 4. Results

## 4.1. Dataset overview

The complete available dataset contains 42,589 elevation band specific avalanche hazard assessments produced by Avalanche Canada and Parks Canada from all 17 forecast regions within BC and western Alberta. The dataset was unevenly split between Avalanche Canada (79%) and Parks Canada (21%), which is simply a reflection of the different number of forecast areas covered by the two agencies. Out of the available hazard assessments, 6,490 (15%) did not include any avalanche problems, 15,020 (35%) only included a single avalanche problem, and the remaining 21,079 (50%) represented hazard situations with multiple avalanche problems. These proportions differed significantly between agencies (Pearson's chi-squared test: p-value < 0.01) with single avalanche problem situations being slightly more prevalent in Avalanche Canada hazard assessments (36% versus 32%) and multiple avalanche problem situations being more common in the Parks Canada dataset (52% versus 49%). Proportions also differed significantly among mountain ranges (Pearson's chi-squared test: p-value < 0.01) with the Coast Mountains exhibiting both the highest proportion of single avalanche problem situations (42%) and the lowest proportion of multiple avalanche problem situations (42%). The proportion of hazard situations with no avalanche problems was highest in the Rocky Mountains (18%), followed by the Coast Mountains (16%) and the Columbia Mountains (12%). However, the most dramatic differences in the proportions were identified with respect to elevation band (Kruskal-Wallis test: p-value < 0.01). In general, hazard situations with fewer avalanche problems were more common below treeline (39% of all below treeline assessments had no avalanche problems), whereas hazard situations with multiple avalanche problems were most common in the alpine (69% of all alpine assessments had multiple avalanche problems). Of the 15,020 hazard situations with single avalanche problems, 30% were alpine assessments, 31% were from treeline and 44% originated from below treeline. Of the 21,079 hazard situations with multiple avalanche problems, 46% were from the alpine, 43% were treeline assessments and 11% were below treeline assessments.

## 4.2. Analysis of hazard situations with a single avalanche problem

### 4.2.1. Dataset overview

The dataset of single avalanche problem hazard situations consisted of 15,020 hazard assessments, 81% originated from Avalanche Canada and 19% came from Parks Canada. The split among the main mountain ranges was pretty even with 32% of the assessments being from the Coast Mountains, 39% from the Columbia Mountains and 29% from the Rocky Mountains.

There were considerable differences in the prevalence of avalanche problem types in the single avalanche problem dataset (Table 4.1). *Storm slab avalanche problems* were the most common avalanche problem type, closely followed by *Wind slab avalanche problems*. Together, these two problems accounted for 59% of the single problem dataset and 21% of the complete dataset. *Cornice* and *Wet slab avalanche problems* occurring on their own accounted for less than 1% of hazard assessments. Since these samples were too small for producing meaningful decision rules, I omitted these two problems from the CIT analysis.

**Table 4.1 Frequency of single avalanche problem types from the single avalanche problem dataset.**

| Avalanche problem | Number of assessments | |
|---|---|---|
| Storm slab | 4467 | 30% |
| Wind slab | 4359 | 29% |
| Persistent slab | 2797 | 19% |
| Wet loose avalanche | 1771 | 12% |
| Deep persistent slab | 975 | 6% |
| Dry loose avalanche | 530 | 4% |
| Cornice* | 66 | <1% |
| Wet slab* | 55 | <1% |
| Total | 15020 | 100% |

* omitted from CIT analysis

**Table 4.2 Frequency of single avalanche problems within mountain ranges of British Columbia and western Alberta.**

| Avalanche problem | Coast Mountains | | Columbia Mountains | | Rocky Mountains | |
|---|---|---|---|---|---|---|
| Storm slab | 1915 | 40% | 1769 | 30% | 783 | 18% |
| Wind slab | 1623 | 34% | 1496 | 25% | 1240 | 28% |
| Persistent slab | 465 | 10% | 1526 | 26% | 806 | 18% |
| Wet loose avalanche | 535 | 11% | 641 | 11% | 595 | 11% |
| Deep persistent slab | 118 | 2% | 180 | 3% | 677 | 15% |
| Dry loose avalanche | 37 | 1% | 216 | 4% | 277 | 6% |
| Cornice* | 30 | 1% | 24 | <1% | 12 | <1% |
| Wet slab* | 21 | <1% | 19 | <1% | 15 | <1% |
| Total | 4744 | 100% | 5871 | 100% | 4405 | 100% |

* omitted from CIT analysis

Avalanche problems were found to have differing frequencies for each mountain range (Table 4.2), and elevation band (Table 4.3). The Coast and Columbia Mountains were dominated by *Storm slab avalanche problems*, while *Wind slab avalanche problems* were the most prominent single avalanche problem type in the Rocky Mountains. An examination with respect to elevation bands showed that most hazard assessments with single *Wet loose avalanche problems* and *Persistent slab avalanche problems* came from below treeline. These problems became less prevalent at higher elevation bands. In contrast, most of the assessments involving *Wind slab avalanche problems* came from the alpine elevation band with a smaller proportion coming from treeline and hardly any from below treeline. While the largest number of *Storm slab avalanche problem* assessments came from below treeline, this avalanche problem was the most evenly distributed among the elevation bands.

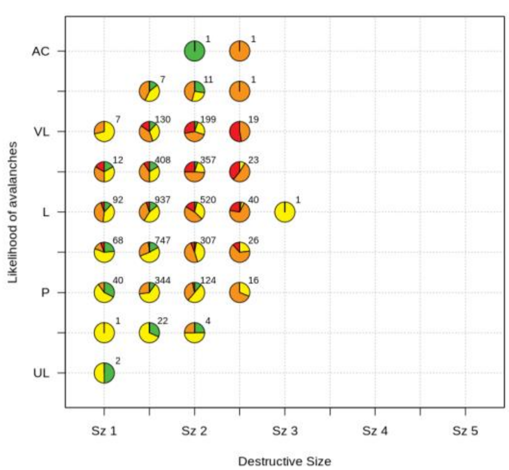
**Table 4.3 Frequency of single avalanche problems within the single avalanche problem dataset based on occurrence at each elevation band.**

| Avalanche problem | Below treeline | | Treeline | | Alpine | |
|---|---|---|---|---|---|---|
| Storm slab | 1889 | 30% | 1260 | 29% | 1309 | 30% |
| Wind slab | 176 | 3% | 1846 | 42% | 2337 | 54% |
| Persistent slab | 2009 | 32% | 495 | 11% | 293 | 7% |
| Wet loose avalanche | 1405 | 22% | 311 | 7% | 55 | 22% |
| Deep persistent slab | 429 | 7% | 339 | 8% | 207 | 7% |
| Dry loose avalanche | 341 | 5% | 143 | 3% | 46 | 1% |
| Cornice* | 1 | <1% | 2 | <1% | 63 | 1% |
| Wet slab* | 38 | 1% | 14 | <1% | 3 | <1% |
| Total | 6297 | 100% | 4410 | 100% | 4313 | 100% |

* omitted from CIT analysis

Avalanche problem types also showed differences in the space they occupied on the avalanche hazard chart (Figure 4.1). Overall, the typical values of likelihood of avalanches covered close to the full range of the likelihood scale, whereas the typical destructive size assessments primarily occupied the lower half of the scale. All problems spanned the scale of the likelihood of avalanches from Unlikely to Very Likely. *Storm slab avalanche problems* had the highest likelihoods out of all problems with some observations rated Almost Certain. Typical destructive sizes showed less of a range and varied from size 1 to size 3.5. *Deep persistent slab avalanche problems* were the only problem that did not have any hazard assessments at typical destructive of sizes 1 and had the largest number of observations at 3.5.

a) Storm slab avalanche problem




b) Wind slab avalanche problem

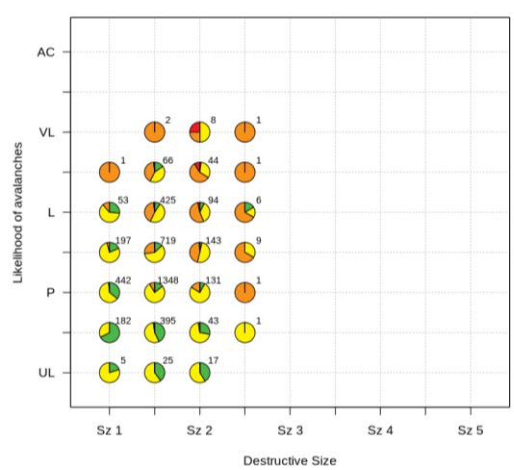
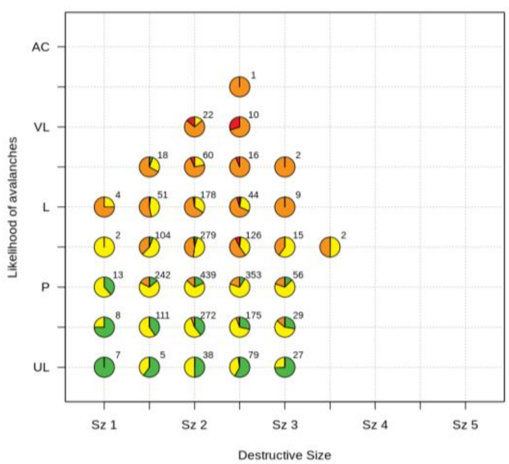
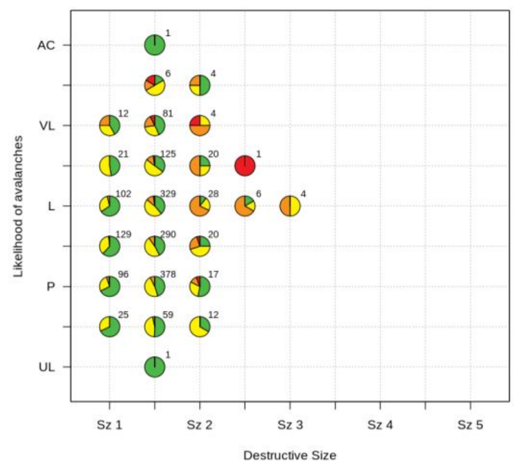



**Figure 4.1 Avalanche problem observations for both Avalanche Canada and Parks Canada assessments based on typical likelihood of avalanches and destructive size for each avalanche problem type with the exception of the omitted Cornice and Wet slab avalanche problem types. The pie chart denotes the danger rating distribution at the combination of typical likelihood of avalanches and destructive size while the number on the upper right shows the number of observations at that point.**

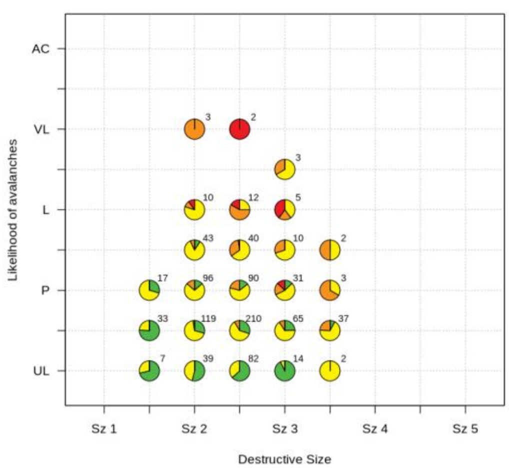
c) Persistent slab avalanche problem




d) Wet loose avalanche problem




e) Deep persistent slab avalanche problem




f) Dry loose avalanche problem

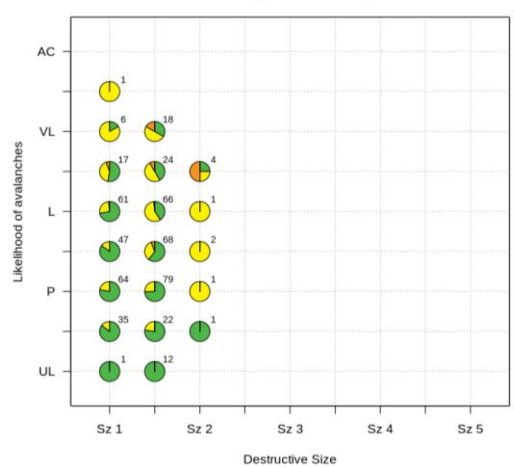



**Figure 4.1 Continued.**

Avalanche danger ratings associated with single avalanche problem hazard situations were not evenly distributed and different problems were found to have different danger rating distributions (Kruskal-Wallis test: $p$-value < 0.01; Table 4.4). Overall, *Storm slab avalanche problems* were the most severe and *Dry loose avalanche problems* the least severe avalanche problem. Pairwise Wilcoxon rank-sum tests with Bonferroni correction revealed significant differences in danger rating distributions between almost all avalanche problem comparisons except *Cornices* and *Deep persistent slab avalanche problems* ($p$-value = 0.27), *Cornices* and *Wet loose avalanche problems*, *Persistent slab* and *Wet slab avalanche problems*, and *Storm slab* and *Wet* *slab avalanche problems* (all p-value = 1.00). All of these non-significant differences are caused by the small sample sizes of either the *Cornice* or *Wet slab avalanche problem*. Moderate was the most common rating for most avalanche problems except for *Dry loose avalanche* and *Wet loose avalanche problems* where Low was the dominant danger rating level. Considerable ratings were assigned second most frequent, with *Storm slab avalanche problems* being assigned this rating the most. High/Extreme was assigned the least during the study period with many problems having this rating in less than 2% of their assessments. The main exceptions of this pattern are *Storm slab* and *Wet slab avalanche problems* that received High/Extreme ratings 9% (407 of 4467) and 4% (2 of 55) of the time.

**Table 4.4: Danger rating distributions and overall ranking for each avalanche problem type within the single avalanche problem dataset.**

| Avalanche problem | Rank | Low | | Moderate | | Considerable | | High/Extreme | |
|---|---|---|---|---|---|---|---|---|---|
| Storm slab | 1 | 507 | 11% | 1839 | 41% | 1714 | 38% | 407 | 9% |
| Wind slab | 4 | 890 | 20% | 2732 | 63% | 715 | 16% | 22 | 1% |
| Persistent slab | 3 | 493 | 18% | 1543 | 55% | 729 | 26% | 32 | 1% |
| Wet loose avalanche | 6 | 807 | 46% | 755 | 43% | 185 | 10% | 24 | 1% |
| Deep persistent slab | 5 | 272 | 28% | 582 | 60% | 109 | 11% | 12 | 1% |
| Dry loose avalanche | 8 | 349 | 66% | 167 | 32% | 14 | 3% | 0 | 0% |
| Cornice* | 7 | 25 | 38% | 40 | 61% | 1 | 1% | 0 | 0% |
| Wet slab* | 2 | 14 | 26% | 18 | 33% | 21 | 38% | 2 | 4% |
| Total | | 3357 | 22.3% | 7676 | 51% | 3488 | 23% | 499 | 3% |

* omitted from CIT analysis

### 4.2.2. Representation of likelihood of avalanche and destructive size

The three CIT models used to determine the best representation of likelihood of avalanches and destructive size for single avalanche problems revealed similar performances based on the randomly selected testing dataset (25% of single problem dataset). Hit rates only varied within a percentage point and the multi-class AUC scores only ranged within 0.06 (Table 4.5). These results indicate that each of these representations is suitable to represent the avalanche problem adequately with the *Maximum* model producing the best hit rate and the *Typical + (Maximum – Typical)* model resulting in the highest multi-class AUC value. However, consultations with avalanche forecasters at Avalanche Canada (S. Horton, personal communication) and Parks Canada (G. Statham, personal information) indicated that the *Typical* values are often used as a starting point for hazard assessments and there is the impression that they are used more consistently among forecasters than *Maximum* values. To make my analysis as relevant for operational forecasters as possible, I therefore chose the *Typical* values of likelihood of avalanches and destructive size to represent avalanche problems for my CIT analyses.

**Table 4.5 Performance indicators of CIT models to assess which variable to represent the hazard assessment within the final CIT model for the single avalanche problem dataset.**

| Parameter representations | Hit rate | Multi-class AUC |
|---|---|---|
| Typical | 57.8% | 0.740 |
| Maximum | 58.2% | 0.740 |
| Typical + (Maximum – Typical) | 58.0% | 0.746 |

### 4.2.3. Overall CIT model

#### *General structure of classification tree*

The CIT analysis of the single avalanche problem situations found 124 decision rules that split the dataset into 125 distinct terminal nodes. The performance indicators of this model showed an overall hit rate of 63% and a multi-class AUC score of 0.805. The importance of an individual parameter on the danger rating assessment is a combination of both the position of where the splits occur within the decision tree and the total number of splits. While decision rules located higher on the tree reflect the most significant splits in the danger rating distributions, the decision rules further down are responsible for fine-tuning.

The first, and therefore most significant split in the Master CIT model for single avalanche problems was avalanche problem type separating *Storm slab avalanche problems* from all other avalanche problem types included in the analysis (i.e., *Deep persistent slab*, *Persistent slab*, *Wind slab*, *Wet loose avalanche* and *Dry loose avalanche problems*). Following the *Storm slab avalanche problem* branch of the decision tree, elevation band made the next split separating below treeline from treeline and alpine hazard assessments, followed by a concurrent destructive size split (size 1.5) for both elevation bands. For all other avalanche problem types, likelihood of avalanches was found to be the next most statistically significant split, separating problems based on likelihoods of Possible. This was followed by a second likelihood split based on Unlikely-Possible for problems with likelihoods of less than Possible, while problems with greater than Possible likelihoods showed an avalanche problem split separating *Wet loose avalanche* and *Dry loose avalanche problems* from *Deep persistent slab*, *Persistent slab* and *Wind slab avalanche problems*.

Overall, the results of the single avalanche problem CIT model confirmed that typical likelihood of avalanches and destructive size are fundamental parameters linking avalanche problems to avalanche danger ratings. Both typical likelihood of avalanches and destructive size were found to be responsible for some of the largest number of splits in the dataset. Likelihood of avalanches was responsible for a total of 24 (19%) splits, while destructive size contributed 22 (18%) splits. For *Deep persistent slab*, *Persistent slab*, *Wind slab*, *Wet loose avalanche* and *Dry loose avalanche problems*, likelihood of avalanches was found to be the more significant contributor towards the danger rating as it was used for splits higher in the decision tree. For these avalanche problem types, destructive size was often used further down on the CIT model affecting the distribution of danger ratings rather than the level of the predicted danger rating (i.e., mode of distribution). In contrast, destructive size was found to be more influential than likelihood of avalanches for *Storm slab avalanche problems* as destructive size was used to split the dataset much higher in the *Storm slab avalanche problem* branch of the CIT model.

Avalanche problem type was the most statistically significant (i.e., first) split found by the CIT model and was used for a total of 17 splits (14%) throughout the entire tree. While some of the avalanche problem types shared considerable sections of CIT branches, this result highlights that each avalanche problem type has a somewhat unique set of decision rules for assigning avalanche danger ratings. Splits were mainly focused around three main avalanche problem groups: a) *Storm slab avalanche problems*, which were assigned their own branch in the CIT model, b) *Deep persistent slab*, *Persistent slab* and *Wind slab avalanche problems*; and c) *Wet loose avalanche* and *Dry loose avalanche problems*.

In addition to likelihood of avalanches and destructive size, elevation band emerged as a significant contributor to danger rating assignment and was tied with likelihood of avalanches for the greatest number of splits (24, 19% of all splits) in the single avalanche problem CIT model. It was identified as one of the main determining factors for the danger rating distributions of *Storm slab avalanche problems* as it was responsible for some of the dominant splits in the upper part of that section of the decision tree (Figure. 4.6). For all other avalanche problems, elevation band was typically used further down on the tree, and the assessments from the below treeline elevation band were often separated from the alpine and treeline hazard assessments, which stayed together for longer.

The remaining parameters included in the model—agency, mountain range and the binary aspect variable—were all found to be less significant contributors to the danger rating for most avalanche problem types. Agency was used to split the dataset a total of 13 (10%) times, while the mountain range and aspect were used 12 (10%) and 11 (9%) times respectively. Since most of these splits were found much further down on the decision tree than the splits associated by the likelihood of avalanches, destructive size or the elevation band, these partitions were used to fine tune the danger rating distributions rather than highlighting big splits.

### *Hazard chart visualizations*

These charts aim to assist the interpretation of the CIT model by visualizing the effect of specific model parameters on danger rating assignments more comprehensively. However, it is important to remember that the CIT models used for these visualizations do not include all of the model parameters included in the Master CIT model for single avalanche problems.

#### Influence of likelihood of avalanches and destructive size

Projecting a decision tree with only likelihood of avalanches and destructive size (i.e., all avalanche problem types combined) onto a hazard chart showed that danger rating assignments relate to these parameters as expected (Figure 4.2). The distribution of danger ratings (visualized with pie charts) and its mode (background colour) shifted towards higher levels in response to increases in both likelihood and size parameters. It is important to note that the hazard chart presented in Figure 4.2 represents a simplified CIT model that only includes likelihood of avalanches and destructive size. The detailed patterns of the displayed decision rules (black lines) should therefore not be over interpreted.

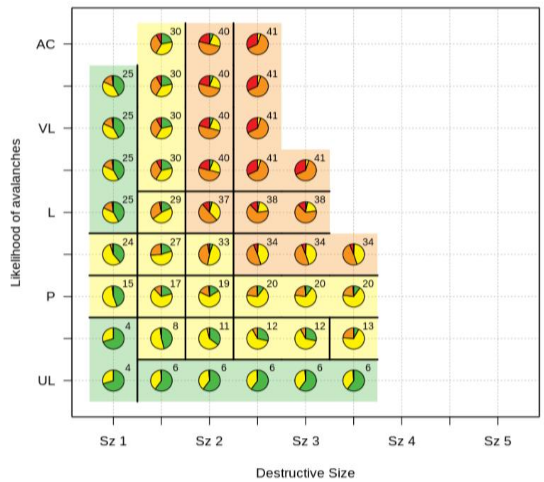



**Figure 4.2 Results of the single avalanche problem CIT model with only typical likelihood of avalanches and typical destructive size projected on the hazard chart. Decision rules are outlined in black while the pie chart denotes the danger rating distribution of the terminal node based on the CIT model. The numbers above the pie charts correspond to the identifier of the respective terminal nodes.**

**Influence of avalanche problem type**

The hazard chart visualizations for the different avalanche problem types (Figure 4.3) clearly reflected the role of the avalanche problem type parameter in the single avalanche problem CIT model and the observed differences in avalanche danger rating distributions between avalanche problem types (Table 4.2).

The hazard chart visualization for *Storm slab avalanche problems* (Panel a) showed that this avalanche problem type occupied a more severe part of the hazard chart than other problem types. In addition, the visualizations illustrated that the same combinations of typical likelihood of avalanches and destructive size generally resulted in higher danger ratings for *Storm slab avalanche problems* compared to other problem types. These two observations together were responsible for *Storm slab avalanche problems* to have the most severe danger rating distribution of all avalanche problem types. The hazard chart visualization for *Storm slab avalanche problems* also illustrated that the typical destructive size affects the danger rating more than the likelihood as only few likelihood of avalanches decision rules existed and increases in the destructive size increased the danger rating more dramatically.

a) Storm slab avalanche problem b) Wind slab avalanche problem

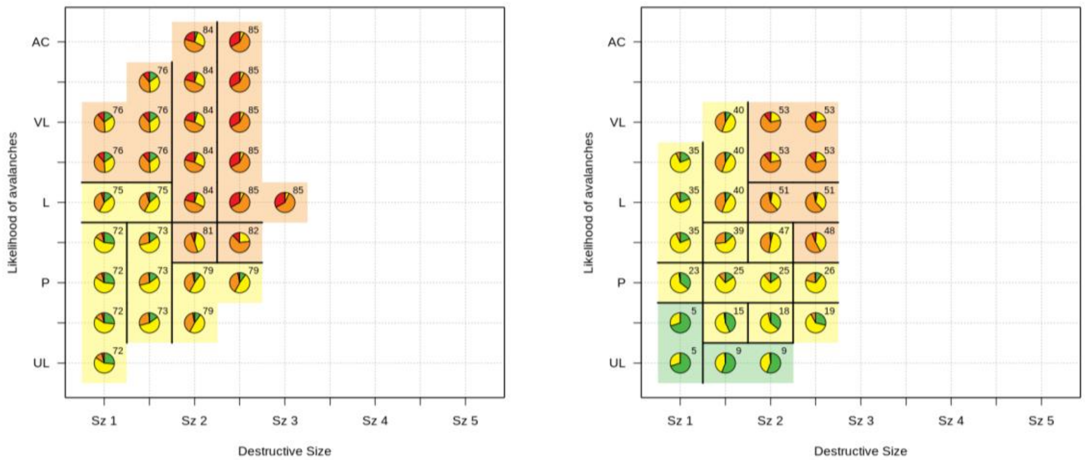
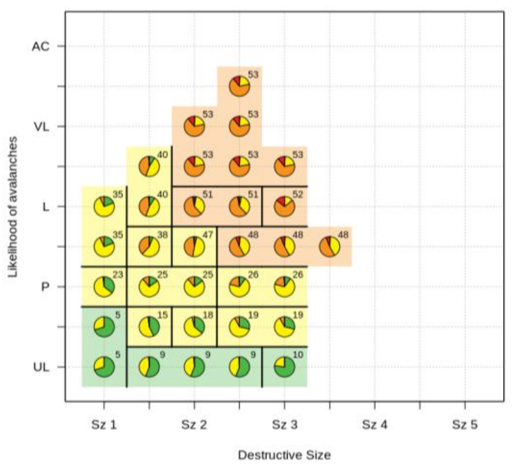
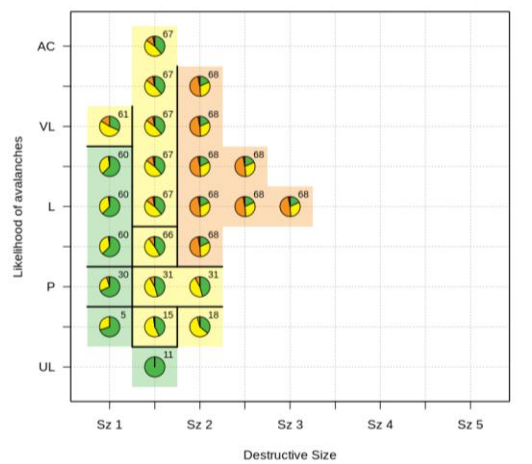



**Figure 4.3** **Results of single avalanche problem CIT model with only avalanche problem type, typical likelihood of avalanches and typical destructive size projected on the hazard chart for each avalanche problem type seperately. Same presentation as Figure 4.2.**

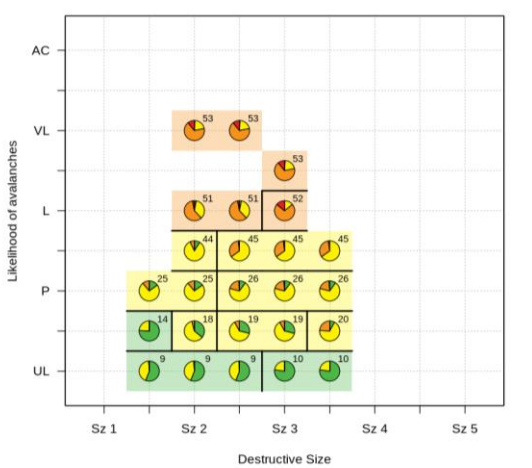
c) Persistent slab avalanche problem




d) Wet loose avalanche problem




e) Deep persistent slab avalanche problem




e) Dry loose avalanche problem

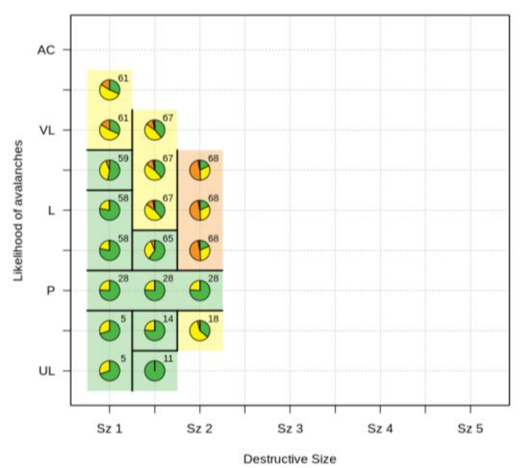



**Figure 4.3 Continued.**

The hazard chart visualizations also confirmed that the avalanche forecasters treated *Deep persistent slab*, *Persistent slab* and *Wind slab avalanche problems* distinctly different from *Storm slab avalanche problems*. Both of the persistent avalanche problem types had decision rules in similar locations (Panel c and e), but there were slight differences in the associated avalanche danger ratings as the likelihood of avalanches approaches Possible-Likely. The danger rating for *Persistent slab avalanche problems* increased slightly sooner in response to changes in likelihood of avalanches than for *Deep persistent slab avalanche problems*. Furthermore, the danger rating of *Deep persistent slab avalanche problems* was affected more strongly by likelihood of avalanches decision rules as it had fewer destructive size decision rules than *Persistent slab avalanche problems*.

*Wind slab avalanche problems* shared considerable similarities with *Deep persistent slab* and particularly *Persistent slab avalanche problems* as this avalanche problem type was split from the persistent slab avalanche problems in the lower portions of the Master CIT model. The decision rules for *Wind slab avalanche problems* shown in the hazard chart (Panel b) illustrated that both likelihood of avalanches and destructive size influence the danger rating for this avalanche problem type. This was shown as increases in likelihood of avalanches and destructive size result in comparable changes in the danger rating.

In the Master CIT model, the two loose avalanche problems—*Wet loose avalanche problems* and *Dry loose avalanche problems*—were separated from *Deep persistent slab*, *Persistent slab* and *Wind slab avalanche problems* in a split at the third level of the tree. The two loose avalanche problems then stayed together until they split apart much further down on the decision tree and only for scenarios with likelihoods of avalanches lower than Likely-Very Likely and destructive sizes smaller than 2. Hence, the danger rating assignments for these two avalanche problems shared many similarities and were distinct from the others, which is apparent in the hazard chart visualizations (Panels d and e). For example, the charts showed that the danger rating assessments for both loose avalanche problem types were more sensitive to the destructive size than likelihood of avalanches. However, *Wet loose avalanche problems* were generally assessed more seriously than *Dry loose avalanche problems* of the same likelihood and size.

### *Influence of elevation band*

Elevation band emerged as one of the key parameters in the Master CIT model, especially for *Storm slab avalanche problem* assessments. The visualization of the general relationship between elevation band and danger rating on the hazard chart (Figure 4.4) highlights that while the general pattern of danger rating distributions was similar in all elevation bands, forecasters assessed the same combinations of likelihood of avalanches and destructive size more seriously at higher elevation bands.

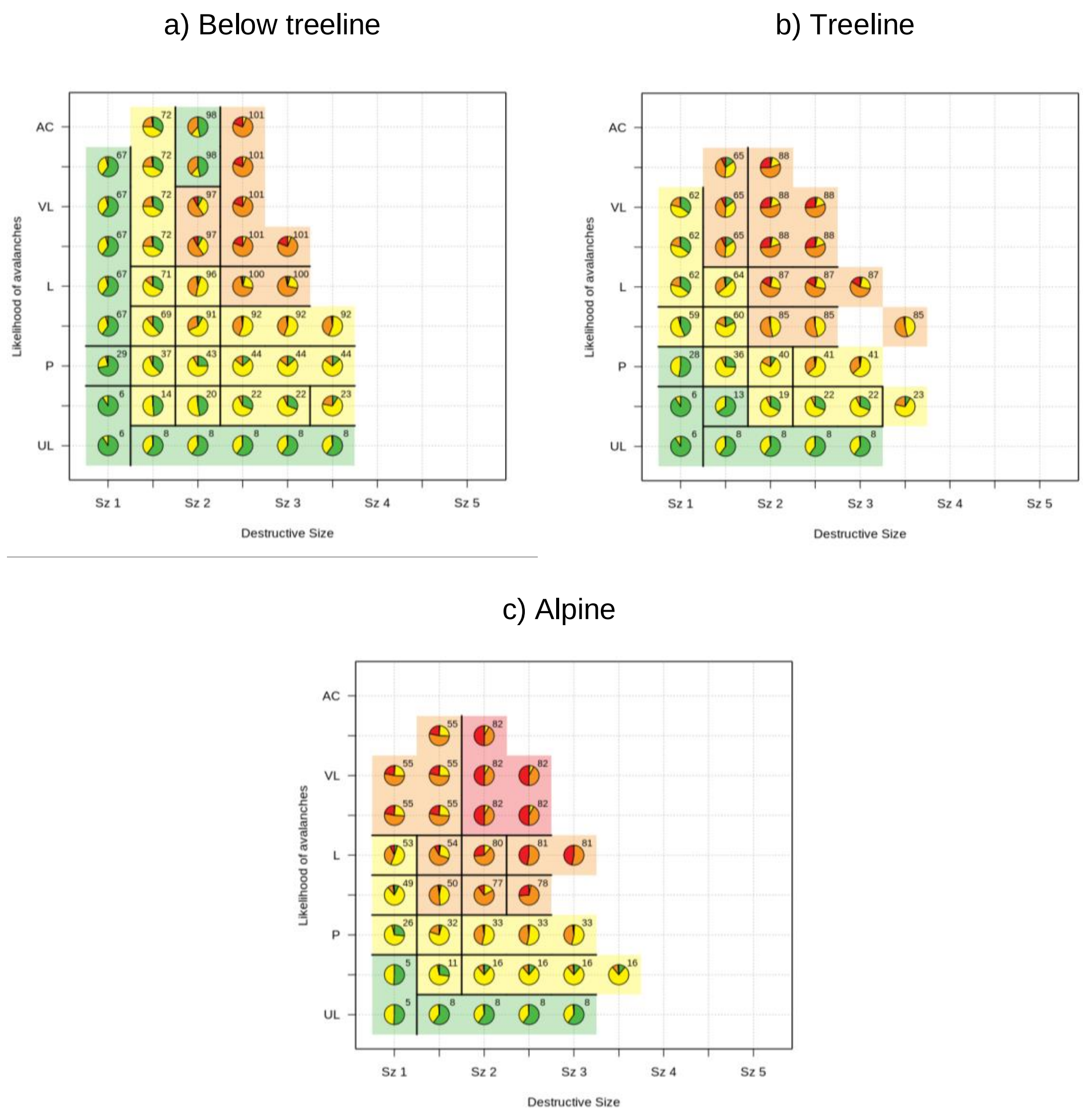



**Figure 4.4** **Hazard assessment decision rules and danger rating distributions for each elevation band according to observed typical likelihood of avalanches and typical destructive size. Same presentation as Figure 4.2.**

### *Influence of other variables*

Although some splits in the Master CIT model were based on aspect, agency and mountain range, these variables show a limited influence on assigned avalanche danger ratings. *Wind slab avalanche problems* and *Wet loose avalanche problems* were the only problem types that have substantial proportions of assessments where the problem did not exist on all eight aspects (66% and 56% respectively). For all other avalanche problem types, problems on fewer than eight aspects only occurred in less than 20% of the assessments. While the CIT analysis did not detect any decision rules with respect to aspect for *Wind slab avalanche problems*, *Wet loose avalanche problems* exhibited significant differences in danger rating assignments with respect to this variable (Figure 4.5). Whereas the locations of many likelihood and size decision rules were similar regardless of the number of aspects, *Wet loose avalanche problems* that existed on fewer than eight aspects are generally assessed less seriously. Aspect was also found to split the *Storm slab avalanche problem* section of the decision tree three times. However, these splitting rules only apply to a small part of the dataset since *Storm slab avalanche problems* were only identified on fewer than eight aspects on 143 of 4457 assessments (3%).

a) Wet loose avalanche problem
Present on fewer than eight aspects

b) Wet loose avalanche problem
Present on all eight aspects

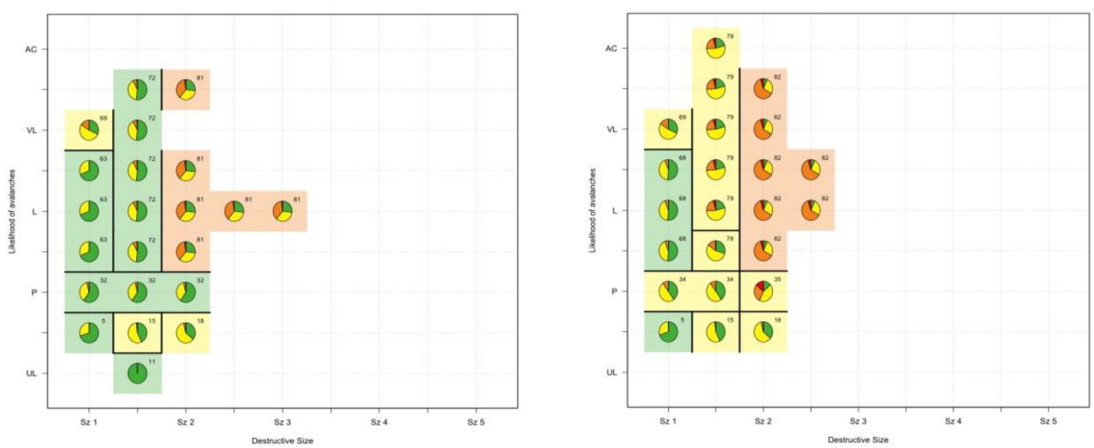



**Figure 4.5 Hazard assessment decision rules and danger rating distributions for Wet loose avalanche problems based on the problem being on less than eight aspects and the problem being on eight aspects according to observed typical likelihood of avalanches and typical destructive size. Same presentation as Figure 4.2.**

Since the Master CIT model revealed that agency and mountain range only had minor effects on avalanche danger rating assignments for single avalanche problem situations, I did not further explore these relationships with hazard chart visualizations.

## 4.2.4. Detailed look at specific individual avalanche problems

To provide deeper insight into how the various parameters included in the Master CIT model interact, I will now discuss the decision rules for the three most prevalent single avalanche problem types—*storm slab avalanche problems*, *persistent slab avalanche problems* and *wind slab avalanche problems*—in more detail. Decision trees for the other avalanche problem types are presented in Appendix B.

### *Storm slab avalanche problems*

The *Storm slab avalanche problem* branch of the decision tree consisted of 23 decision rules that divided the dataset into 24 terminal nodes (Figure 4.6). The first and most important decision rule related to elevation band, which separated alpine and treeline hazard assessments from below treeline. Next, destructive size was used to split both elevation band branches on destructive sizes of 1.5. Likelihood of avalanches made the most splits with ten (42%), elevation band making four (17%), and agency, destructive size and aspect each making three splits (13%). Mountain range was only responsible for a single split (4).

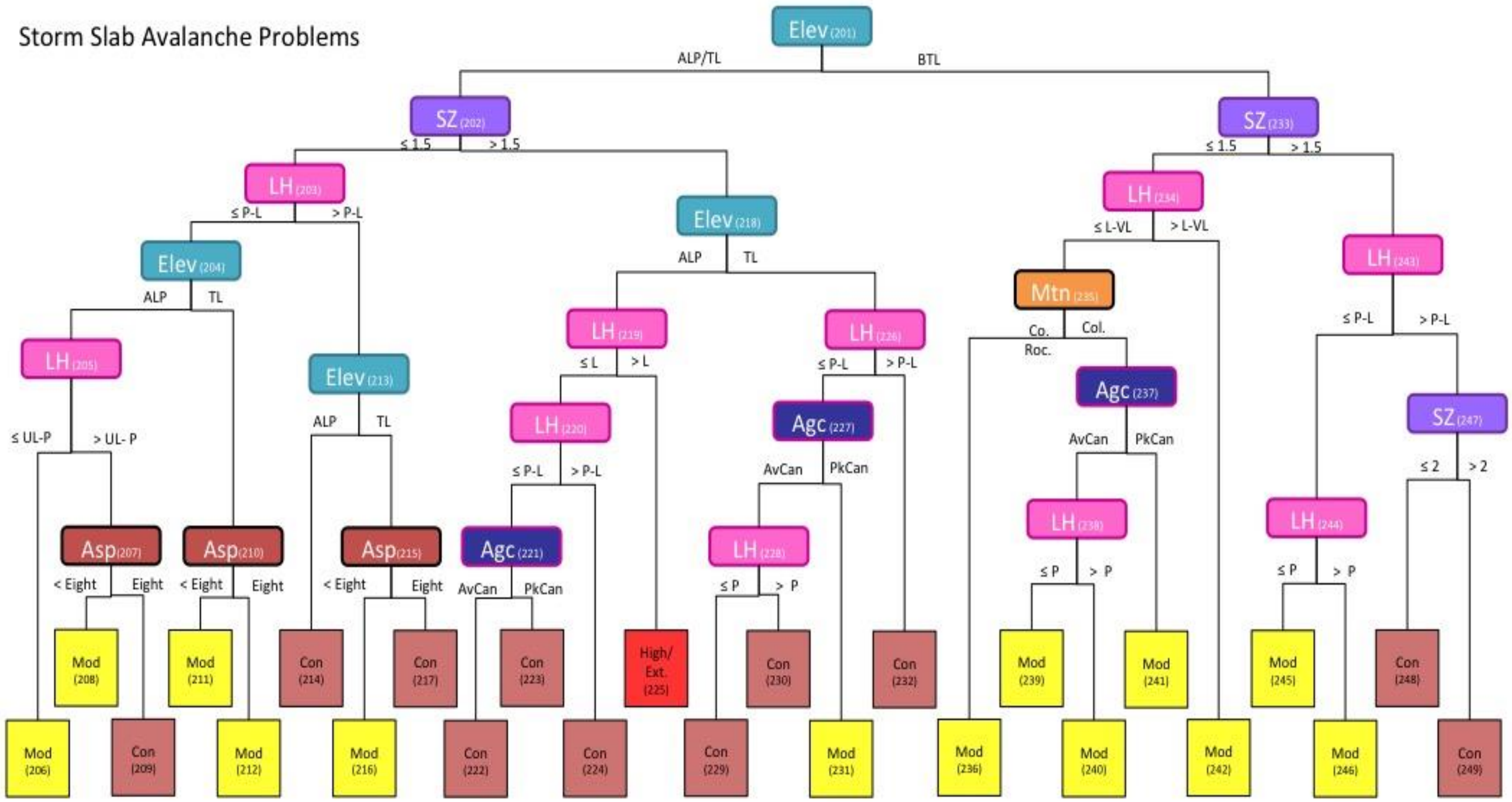



**Figure 4.6** **Storm slab avalanche problem section of the single avalanche problem CIT describing the decision rules and corresponding terminal nodes based on the most common danger rating assigned based on those rules.**

Since the influence of a parameter is reflected in both the position and the number of associated splits, destructive size was found to influence the danger rating for *Storm slab avalanche problems* substantially more than likelihood of avalanches. The main contributing factor to danger rating assignments for *Storm slab avalanche problems* was based on size of 1.5. This is shown through higher danger ratings when the *Storm slab avalanche problem* was assessed higher than size 1.5 where the most common danger ratings were Considerable, while less than 1.5 were commonly assigned Moderate danger ratings (Figure 4.6). Since the splits associated with likelihood were lower down on the tree, they affected the danger rating distributions to a lesser degree.

Elevation band being the first split of the dataset showed that alpine and treeline hazard assessments were more similar than below treeline. The effect of elevation band on *Storm slab avalanche problems* exhibited the same general pattern as discussed previously with progressively increasing danger ratings from below treeline to alpine (Figure. 4.7). The decision rule of size 1.5 appeared in all elevation bands, which highlights the prominence of this rule for danger rating assignments of *Storm slab avalanche problems*. While alpine and treeline did not display any further splits on destructive size, below treeline exhibited another splitting rule at size 2 when likelihood of avalanches was assessed greater than Possible-Likely (Figure 4.6). However, this rule did not change the mode of the danger rating distribution. Below treeline showed Moderate danger ratings as most common, while treeline and alpine were generally assigned Considerable ratings. In the alpine, High/Extreme was predicted within the upper right area of the hazard chart where the likelihood of avalanches was greater than Likely and destructive size was greater than size 1.5. High/Extreme ratings were not a common danger rating assignment at treeline or below, but they were part of the danger rating distributions in higher likelihood of avalanches and destructive size scenarios.

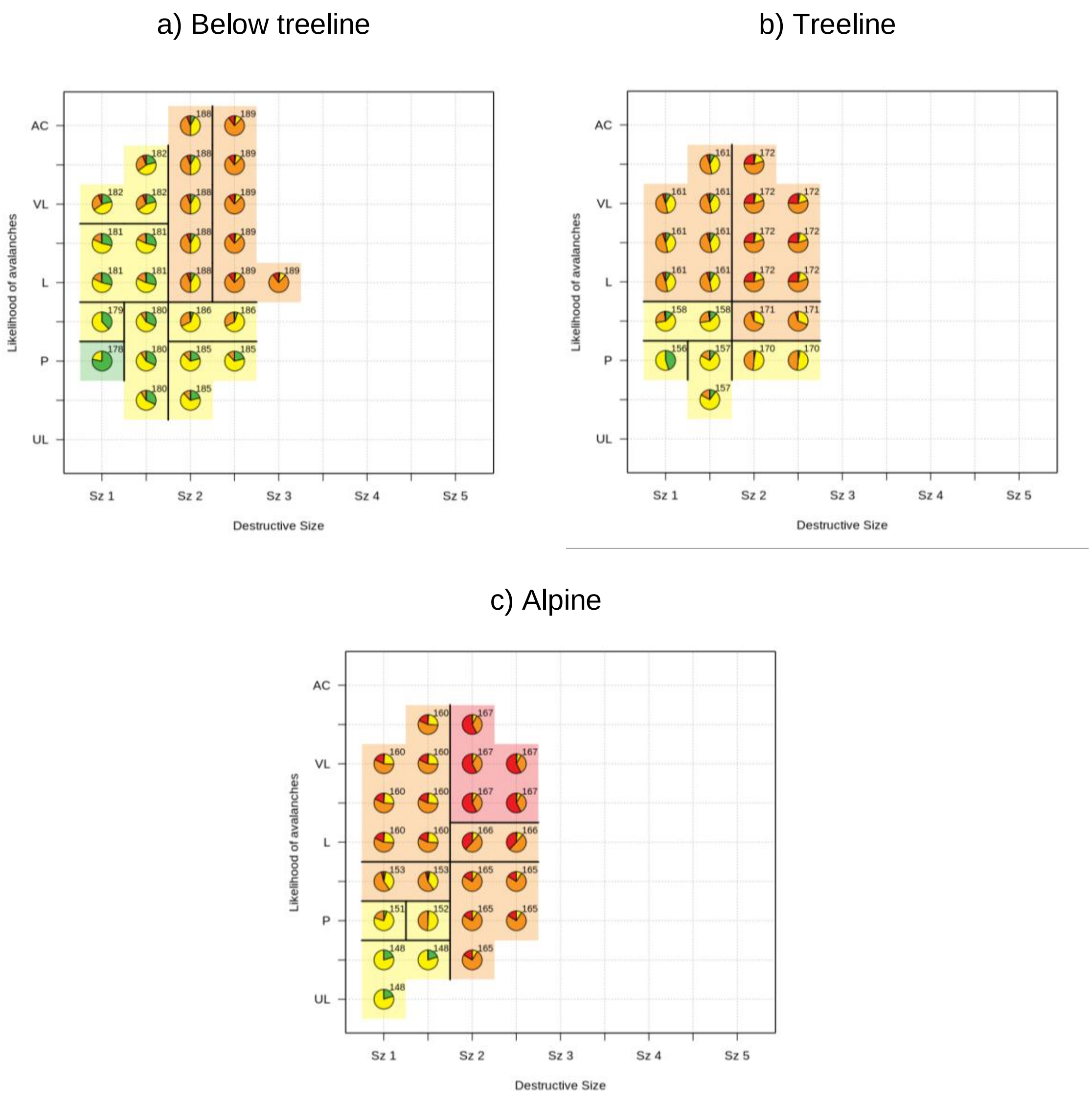



**Figure 4.7 Hazard assessment decision rules and danger rating distributions for Storm slab avalanche problems at each elevation band according to observed typical likelihood of avalanches and typical destructive size. Same presentation as Figure 4.2.**

Since the *Storm slab avalanche problem* branch of the Master CIT model only included a single decision rule with respect to mountain range (Figure 4.6), the danger rating assessments were found to be generally consistent between mountain ranges. This consistency was also reflected in the mountain range specific hazard charts for *Storm slab avalanche problems* (Figure 4.10).

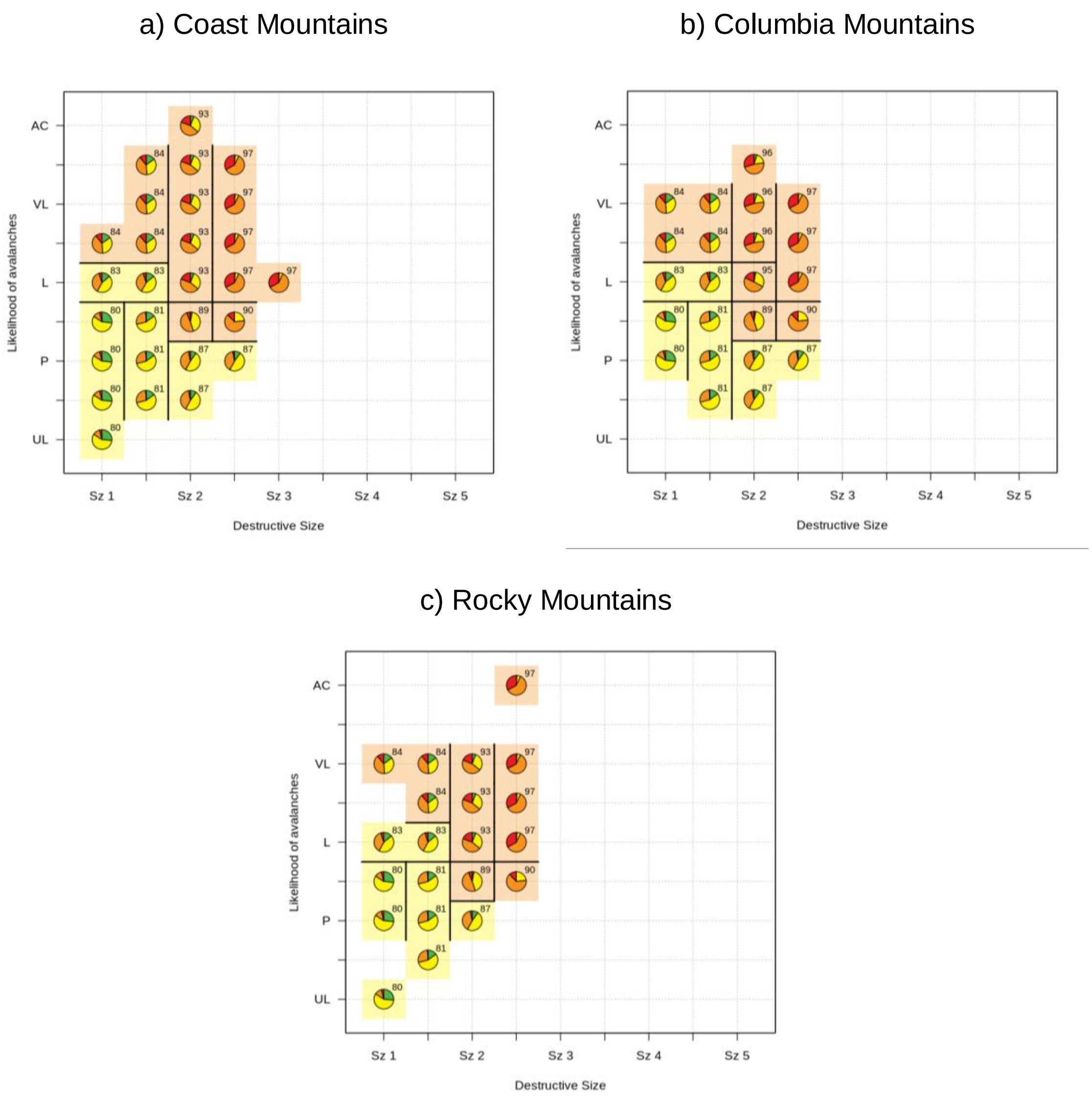



**Figure 4.8** **Hazard assessment decision rules and danger rating distributions for Storm slab avalanche problems in each mountain range according to observed typical likelihood of avalanches and typical destructive size. Same presentation as Figure 4.2.**

Although aspect and agency were responsible for a few splits in the *Storm slab avalanche problem* branch of the Master CIT tree (Figure 4.6), hazard chart visualizations that focus on the effect of these parameters for *Storm slab avalanche problems* did not further illustrate these differences.

### *Persistent slab avalanche problems*

The *Persistent slab avalanche problem* section of the decision tree consisted of a total of 41 decision rules and 42 terminal nodes (Figure 4.9). There was considerable overlap in the decision tree sections among *Deep persistent slab*, *Persistent slab* and *Wind slab avalanche problem* types. Twenty-two (55%) of the terminal nodes included in the *Persistent slab avalanche problem* section of the Master CIT model were also part of the *Wind slab avalanche problem* part of the tree indicated by terminal nodes outlined with dashed orange lines.

Most splits in the *Persistent slab avalanche problem* part of the Master CIT model were based on elevation band with a total of 11 (27%), followed by destructive size (10, 24%) and likelihood of avalanches (7, 17%). However, despite being responsible for fewer splits, likelihood of avalanches was the more significant parameter for the assessment of *Persistent slab avalanche problems* as it produced splits higher up on the tree. The main decision rule for *Persistent slab avalanche problems* was based on likelihood of avalanches at Possible separating higher danger ratings (Moderate and Considerable) from lower ones (Low and Moderate). This split at the top of the tree was also shared by *Deep persistent slab*, *Wind slab*, *Wet loose avalanche* and *Dry loose avalanche problem* types.

The hazard chart visualization of *Persistent slab avalanche problems* by elevation band (Figure 4.10) helps to illustrate the effect of elevation on the danger rating assessments on this avalanche problem type. Similar to the elevation pattern exhibited by *Storm slab avalanche problems* discussed in the previous section, *Persistent slab avalanche problems* were also assessed consistently more seriously at higher elevation bands. The danger rating was most different in the alpine as this elevation band was consistently split off first (Figure 4.9). Even though the *Persistent slab avalanche problem* branch of the CIT model only included four splits that separate treeline from below treeline at the final level, two of these splits resulted in danger rating distributions with different modes.

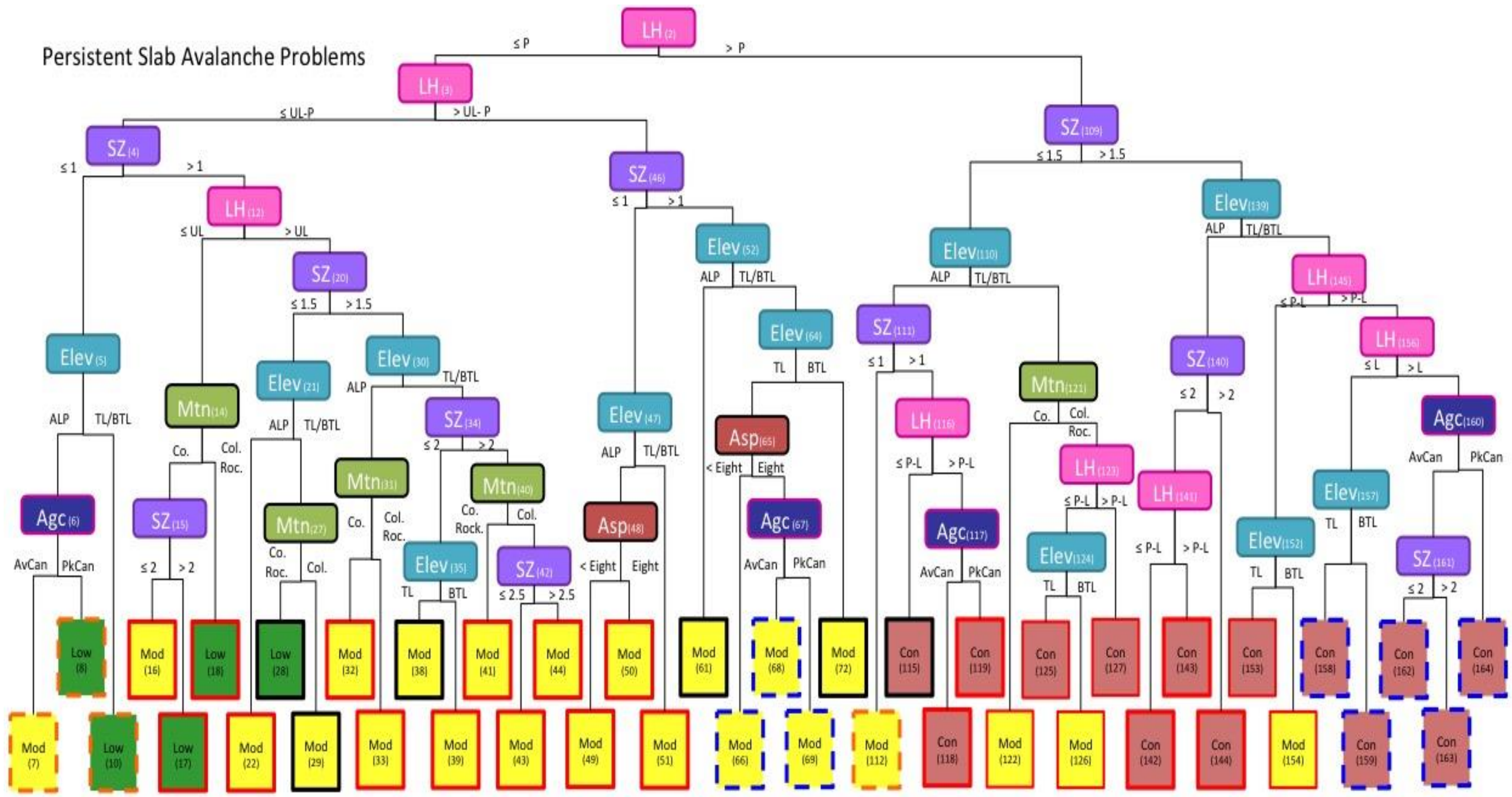



**Figure 4.9 Persistent slab avalanche problem section of the single avalanche problem CIT describing the decision rules and corresponding terminal nodes based on the most common danger rating assigned based on those rules. Red outlined terminal nodes are shared between Persistent slab, Deep persistent slab and Wind slab avalanche problems, blue dashed outlined terminal nodes are shared between Persistent and Deep persistent slab problems, orange outlined terminal nodes are shared between Persistent and Wind slab avalanche problems, and black outlined terminal nodes are unique to Persisient slab avalanche problems.**

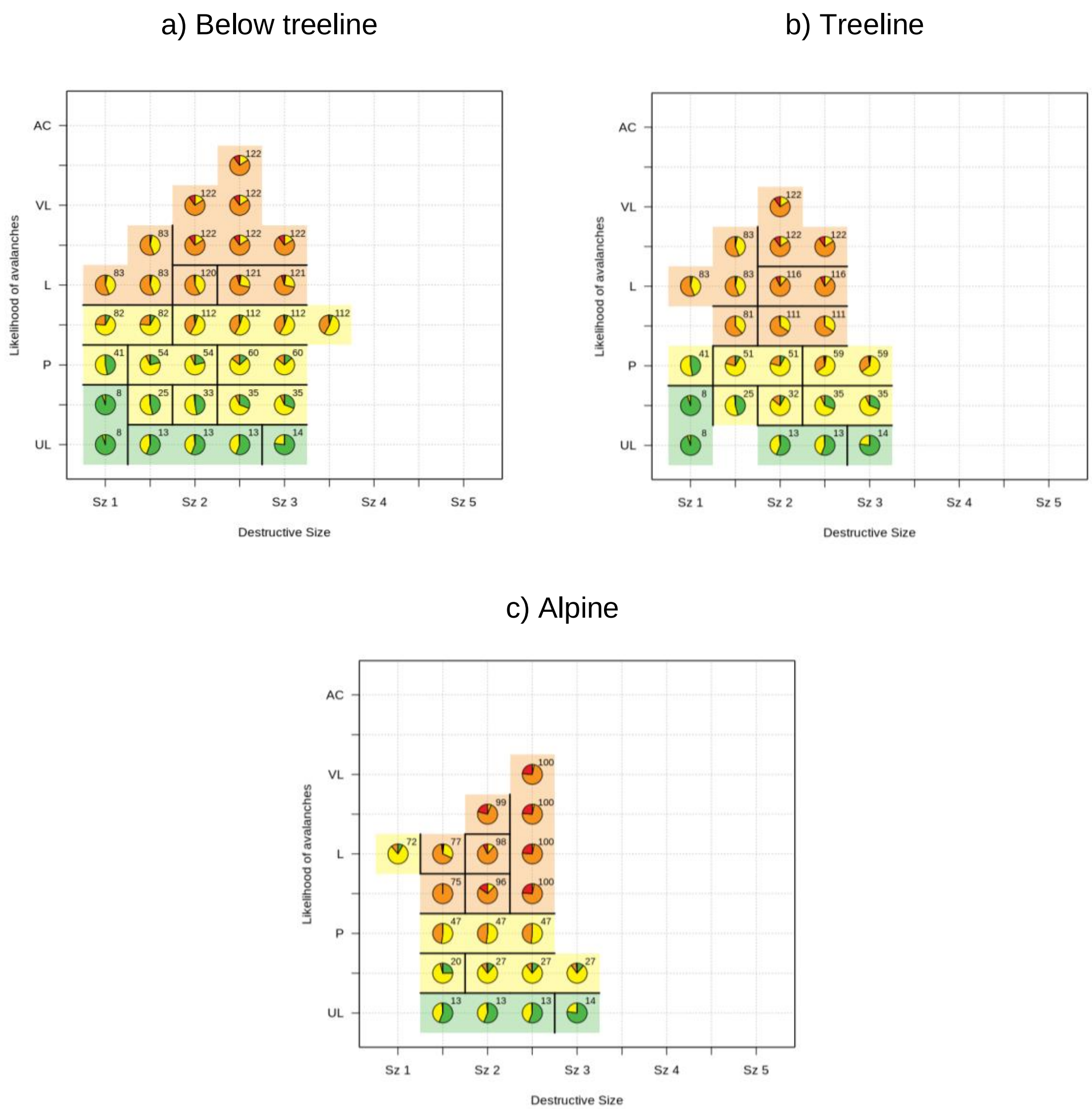



**Figure 4.10 Hazard assessment decision rules and danger rating distributions for Persistent slab avalanche problems at each elevation band according to observed typical likelihood of avalanches and typical destructive size. Same presenation as Figure 4.2.**

Similar to the patterns observed for *Storm slab avalanche problems*, mountain range, agency and aspect were responsible for few splits, which were located much farther down on the *Persistent slab avalanche problem* section of the decision tree (Figure 4.9). The hazard chart visualization of the effect of mountain range (Figure 4.11) confirmed that the impact of this parameter is minimal. The effect of agency and aspect were not further examined with hazard chart visualizations.

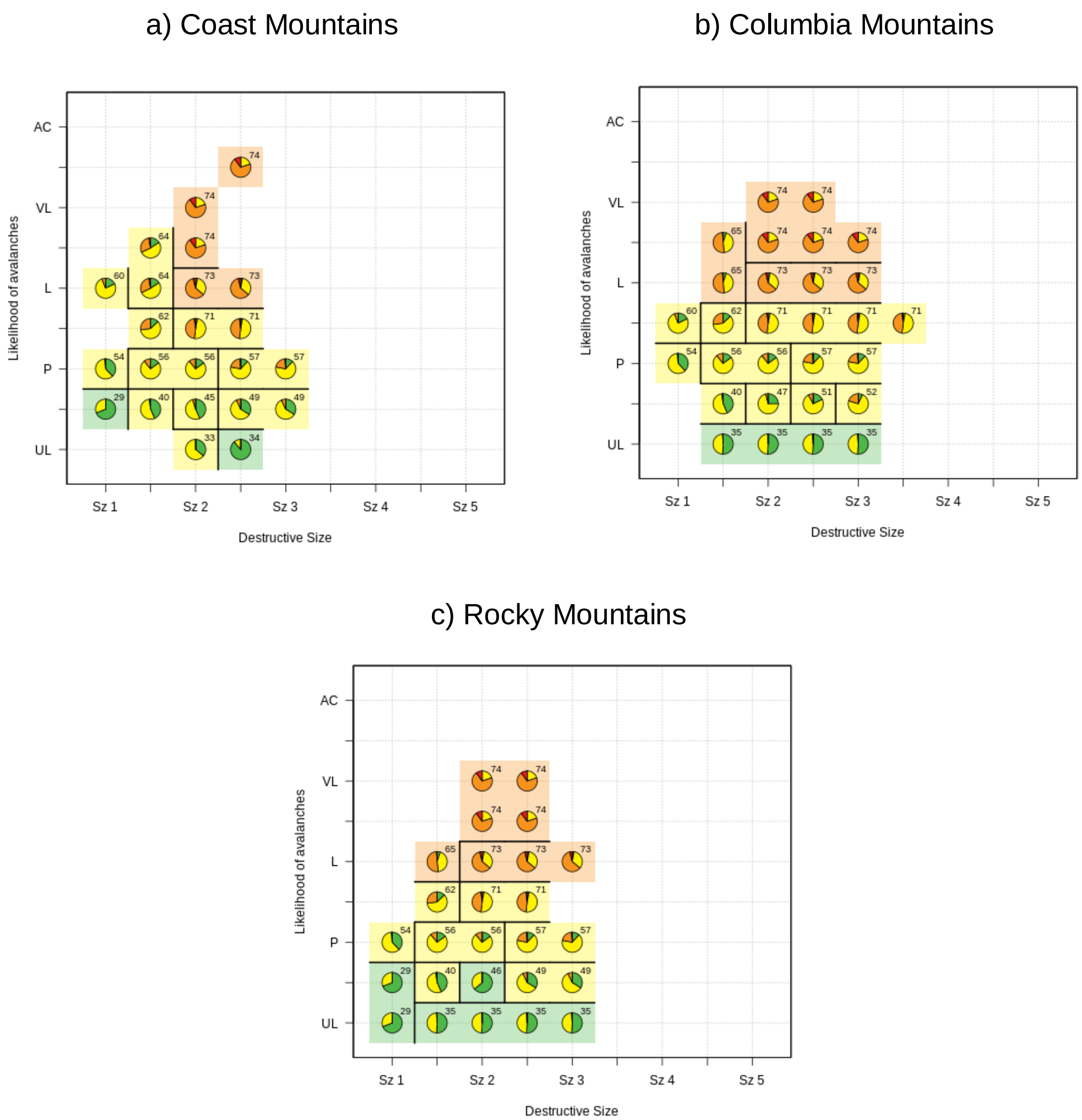



**Figure 4.11 Hazard assessment decision rules and danger rating distributions for Persistent slab avalanche problems in each mountain range according to observed typical likelihood of avalanches and typical destructive size. Same presentation as Figure 4.2.**

### *Wind slab avalanche problems*

With a total of 44 splitting rules resulting in 45 terminal nodes, the *Wind slab avalanche problem* portion of the Master CIT model included the most decision rules of any single avalanche problem type (Figure 4.12). Destructive size was responsible for most of the decision rules with a total of 13 (29%), followed by elevation band (11, 24%), likelihood (7, 16%), mountain range (5, 11%), agency (4, 9%) and aspect (3, 7%).

Substantial parts of the decision tree for *Wind slab avalanche problems* were shared with *Persistent slab avalanche problems*, and the danger rating assignments for these two avalanche problem types therefore exhibited many similarities. The top three levels of the tree were completely the same for these two avalanche problem types (Figures 4.9 and 4.12). Just like in the *Persistent slab avalanche problem tree*, likelihood of avalanches assessed at Possible was the main decision rule found in the *Wind slab avalanche problem* section followed by another likelihood split for likelihoods equal or smaller than Possible, and a split on destructive size for the other branch. Out of the 45 terminal nodes in the *Wind slab avalanche problem* tree, 19 (42%) were shared with the *Persistent slab avalanche problem* tree (Figure 4.9). Most of these shared terminal nodes occur in configurations with a) likelihoods of avalanches of Unlikely-Possible or lower and any destructive sizes, b) likelihoods of avalanche of Possible and destructive sizes of 1, and c) likelihoods of avalanche higher than Possible and destructive sizes of 1.5 or smaller in the alpine.

Although *Wind slab* and *Persistent slab avalanche problems* shared many of the splitting rules and terminal nodes, one of the main differences between the two avalanche problem types was that *Wind slab avalanche problem* assessments occupied a much smaller area on the hazard chart than *Persistent slab avalanche problems*. This resulted in fewer splitting rules being displayed on the hazard chart visualizations.

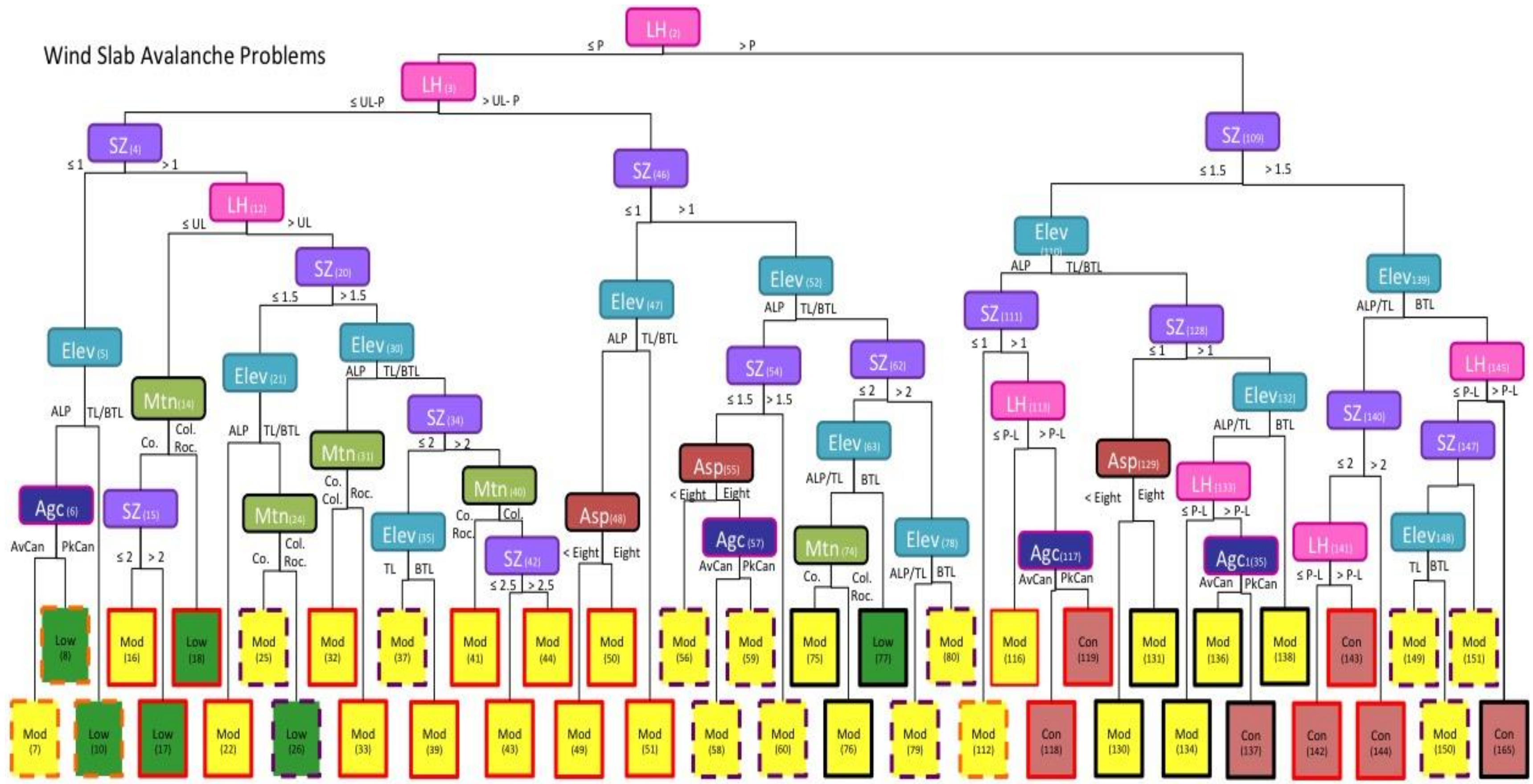
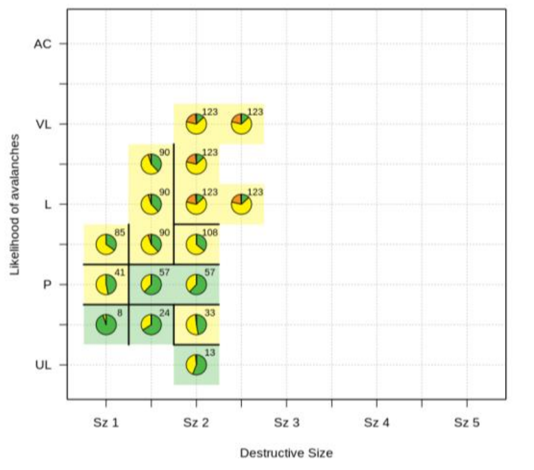


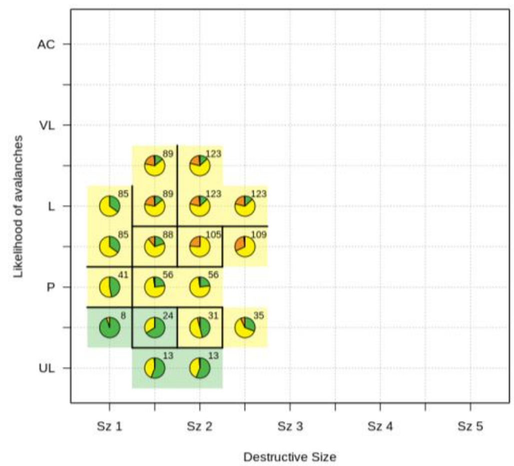

**Figure 4.12** **Wind slab avalanche problem section of the single avalanche problem CIT describing the decision rules and corresponding terminal nodes based on the most common danger rating assigned based on those rules. Red outlined terminal nodes are shared between Persistent slab, Deep persistent slab and Wind slab avalanche problems, purple dashed outlined terminal nodes are shared between Wind and Deep persistent slab problems, orange dashed outlined terminal nodes are shared between Persistent and Wind slab avalanche problems, and black outlined terminal nodes are unique to Wind slab avalanche problems.**

Similar to the *Persistent slab avalanche problem* tree section, splits based on elevation band were frequent in the *Wind slab avalanche problem* portion of the CIT model. Hence the same patterns of higher danger ratings for the same combinations of likelihood of avalanches and destructive size at higher elevations were apparent (Figure 4.13). In the case of *Wind slab avalanche problems*, alpine was the only elevation band where Considerable and High/Extreme contributed substantially to the distribution of danger ratings.

a) Below treeline




b) Treeline




c) Alpine

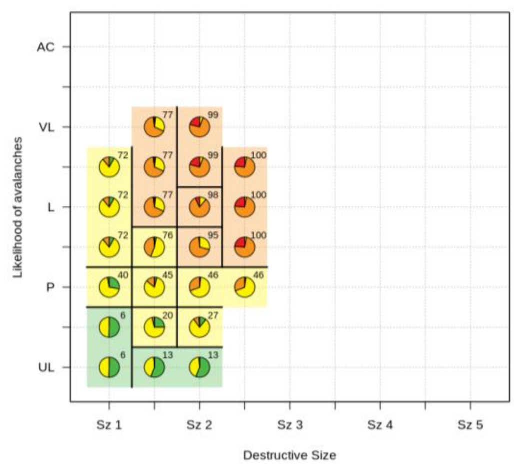
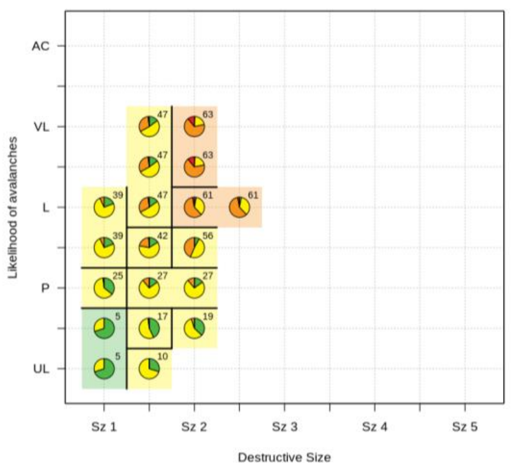


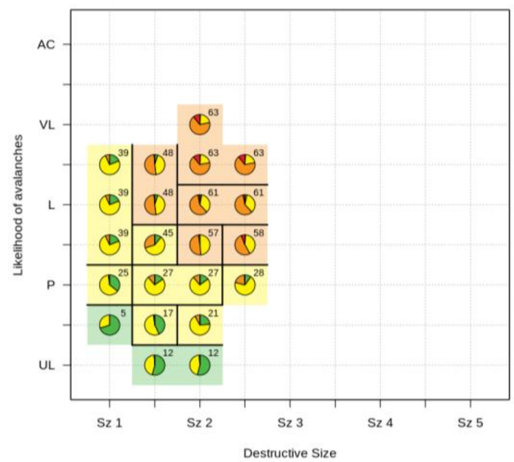

**Figure 4.13 Hazard assessment decision rules and danger rating distributions for Wind slab avalanche problems based on each elevation band according to observed typical likelihood of avalanches and typical destructive size. Same presentation as in Figure 4.2.**

Similar to *Persistent slab avalanche problem* assessments, mountain range, agency and aspect only played a minor role in the danger rating assessments for *Wind slab avalanche problems*. The hazard chart visualization of *Wind slab avalanche problems* for mountain range (Figure 4.14) clearly highlights that the most commonly assigned danger ratings were relatively similar for each mountain range.

a) Coast Mountains




b) Columbia Mountains




c) Rocky Mountains

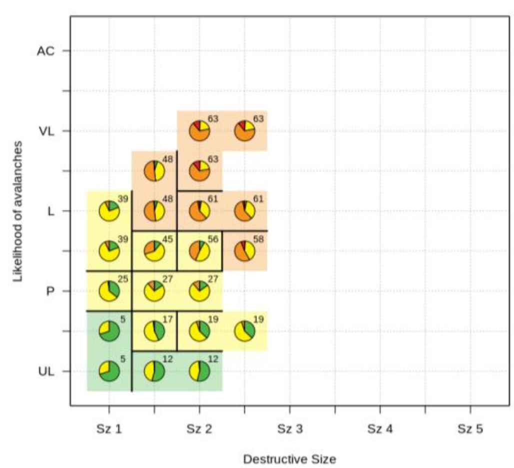



**Figure 4.14 Hazard assessment decision rules and danger rating distributions for Wind slab avalanche problems in each mountain range according to observed typical likelihood of avalanches and typical destructive size. Same presentation as Figure 4.2.**

Since the aspect and agency parameters only resulted in few splits in the *Wind slab avalanche problem* section of the Master CIT model and therefore only had limited effect on danger ratings, hazard chart visualizations were omitted as they did not provide further insight.

## 4.3. Analysis of hazard situations with multiple avalanche problems

### 4.3.1. Dataset overview

In total, my dataset included 54 different hazard situation types that contained multiple avalanche problems. Twenty of these hazard situation types consisted of two avalanche problems (Table 4.6) whereas 34 consist of three avalanche problems (Table 4.7). Overall, hazard situations with two and three avalanche problems accounted for 38% (16,386 assessments) and 11% (4,693 assessments) of the complete dataset respectively. The frequencies of most hazard situations with avalanche problem combinations were below 5% and many exhibited frequencies of 1% or less. The most common avalanche problem combinations within the dataset were *Persistent slab and wind slab problems* and *Persistent slab and storm slab problems*, which accounted for 41% of hazard situations with multiple problems and 21% of the entire dataset. Among the hazard situations with three avalanche problems, *Persistent, storm and wind slab problems* were the most prominent but only accounted for 4% of the hazard situations with multiple problems. My discussion of hazard situations with multiple avalanche problems will therefore only focus on *Persistent slab and wind slab problems* and *Persistent slab and storm slab problems.*

**Table 4.6 Frequency of hazard situations with two avalanche problems with the percentage of the dataset the combination contributed.**

| Avalanche problem combination | Number of assessments | |
|---|---|---|
| Persistent slab and wind slab problems | 4566 | 22% |
| Persistent slab and storm slab problems | 3994 | 19% |
| Deep persistent slab and wind slab problems | 1805 | 9% |
| Deep persistent and storm slab problems | 914 | 4% |
| Wind slab and cornice problems | 558 | 3% |
| Wind slab and dry loose avalanche problems | 536 | 3% |
| Persistent slab and wet loose avalanche problems | 506 | 2% |
| Wind slab and wet loose avalanche problems | 469 | 2% |
| Storm slab and wet loose avalanche problems | 344 | 2% |
| Storm slab and cornice problems | 329 | 2% |
| Deep persistent slab and persistent slab problems | 268 | 1% |
| Storm slab and dry loose avalanche problems | 250 | 1% |
| Cornice and wet loose avalanche problems | 192 | 1% |
| Persistent slab and dry loose avalanche problems | 141 | 1% |
| Wet slab and lose wet avalanche problems | 106 | 1% |
| Deep persistent slab and cornice avalanche problems | 78 | <1% |
| Deep persistent slab and dry loose avalanche problems | 64 | <1% |
| Persistent slab and cornice problems | 45 | <1% |
| Deep persistent slab and wet slab problems | 24 | <1% |
| Storm slab and wet slab problems | 17 | <1% |
| Total | 15206 | 74% |

In my dataset, the prevalence of *Persistent slab and wind slab problems* and *Persistent slab and storm slab problems* differed considerably with respect to elevation band and mountain range. While the *Persistent slab and wind slab problem* combination was more common in the alpine and treeline, the *Persistent slab and storm slab problem* hazard situation was found at similar frequencies at all elevation bands (Tables 4.7). The dataset for both hazard situations was skewed towards the Columbia Mountains (Tables 4.8), which reflects both the higher number of forecast regions in this mountain range and the higher frequency of these hazard situations in the transitional snow climate (Shandro & Haegeli, 2018). While *Persistent and wind slabs* were least common in the Coast Mountains, *Persistent and storm* slabs were least frequent in the Rocky Mountains.

**Table 4.7 Frequency of hazard situations with three avalanche problems with the percentage of the dataset the combination contributed.**

| Avalanche problem combinations | Number of assessments | |
|---|---|---|
| Persistent, storm and wind slab problems | 746 | 4% |
| Deep persistent, persistent and storm slab problems | 389 | 2% |
| Persistent slab, wind slab and cornice problems | 350 | 2% |
| Persistent slab, storm slab and cornice problems | 285 | 1% |
| Deep persistent slab, persistent slab and wind slab problems | 268 | 1% |
| Persistent slab, wind slabs and wet loose avalanche problems | 264 | 1% |
| Persistent slab, cornice and wet loose avalanche problems | 234 | 1% |
| Deep persistent slab, wind slab, and wet loose avalanche problems | 229 | 1% |
| Persistent slab, storm slab and wet loose avalanche problems | 215 | 1% |
| Wind slab, cornice and wet loose avalanche problems | 182 | 1% |
| Deep persistent slab, wind slab and cornice problems | 182 | 1% |
| Persistent slab, wind slab and dry loose avalanche problems | 177 | 1% |
| Deep persistent slab, storm slab and wind slab problems | 166 | 1% |
| Storm slabs, wind slabs and cornice problems | 118 | 1% |
| Deep persistent slabs, storm slabs and wet loose avalanche problems | 100 | <1% |
| Persistent slab, storm slab and dry loose avalanche problems | 99 | <1% |
| Storm slab, cornice, and wet loose avalanche problems | 98 | <1% |
| Deep persistent slab, storm slab and cornice problems | 95 | <1% |
| Deep persistent slab, cornice, and wet loose problems | 82 | <1% |
| Storm slab, wind slab and dry loose avalanche problems | 74 | <1% |
| Deep persistent slab, wind slab and dry loose problems | 63 | <1% |
| Wind slab, cornice and dry loose avalanche problems | 45 | <1% |
| Storm slab, cornice and dry loose avalanche problems | 42 | <1% |
| Deep persistent slab, storm slab and dry loose avalanche problems | 35 | <1% |
| Deep persistent slab, persistent slab and wet loose avalanche problems | 32 | <1% |
| Cornice, wet slab and wet loose avalanche problems | 28 | <1% |
| Deep persistent slab, wet slab and wet loose avalanche problems | 24 | <1% |
| Deep persistent slab, storm slab and wet slab problems | 24 | <1% |
| Deep persistent slab, persistent slab and cornice problems | 22 | <1% |
| Total | 5027 | 26% |

**Table 4.8 Avalanche problem combination frequency according to elevation band with percentage of assessments at each elevation band.**

| Avalanche problem combination | Below treeline | | Treeline | | Alpine | |
|---|---|---|---|---|---|---|
| Persistent slab and wind slab avalanche problems | 127 | 3% | 2302 | 50% | 2137 | 47% |
| Persistent and storm slab avalanche problems | 1052 | 26% | 1521 | 38% | 1421 | 36% |

**Table 4.9 Avalanche problem combination frequent according to mountain range with percentage of assessments within each mountain range**

| Avalanche problem combination | Coast Mountains | | Columbia Mountains | | Rocky Mountains | |
|---|---|---|---|---|---|---|
| Persistent slab and wind slab avalanche problems | 847 | 19% | 1937 | 42% | 1782 | 39% |
| Persistent and storm slab avalanche problems | 859 | 22% | 2693 | 68% | 442 | 11% |

## 4.3.2. Persistent slab and storm slab avalanche problem hazard situations

The hazard charts displaying the assessed combinations of typical likelihood of avalanches and destructive size for the individual and combined avalanche problem situations (Figure 4.15) showed that they occupy similar spaces. However, hazard situations with both avalanche problems present simultaneously exhibited fewer observations at size 1 compared to when the problems were present individually. Furthermore, the hazard situations where both avalanche problems were present simultaneously showed higher danger rating distributions for each likelihood and size combination. At many of the likelihood and destructive size combinations, the danger rating distribution was mainly split between Considerable and High/Extreme ratings.

### *General structure of classification tree*

The CIT model for *Persistent slab and storm slab avalanche problem* situations consisted of 40 decision rules that split the dataset into 41 terminal nodes (Figure 4.15). Performance indicators for this model showed the lowest hit rate, only predicting the correct danger rating 61% of the time. The multi-class AUC measure was 0.778.

Overall, the characteristics of the *Storm slab avalanche problem* dominated the avalanche hazard assessment for this type of hazard situation. *Storm slab* destructive size resulted in nine splits (22%) while *Storm slab* likelihood accounted for eight (20%). Elevation band split the dataset a total of seven times (17%). The likelihood of avalanches of the *Storm slab avalanche problem* was the most significant split separating the hazard situations at Likely, followed by a split of elevation band separating alpine assessments from those at treeline and below. *Storm slab avalanche problem* destructive size was responsible for most of the subsequent decision splits (9, 22%), while only few were based on the characteristics of the *Persistent slab avalanche*

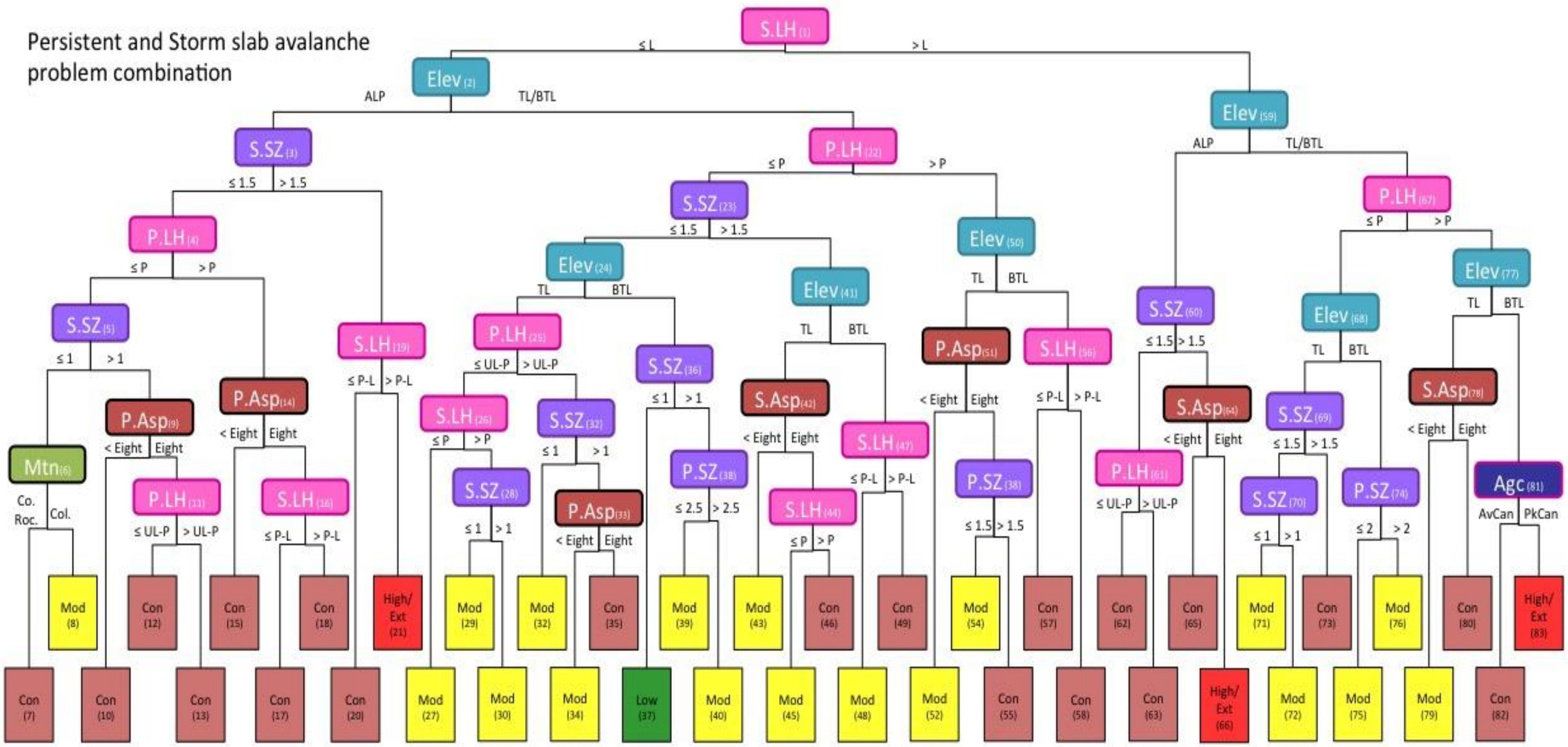



**Figure 4.15** **Persistent and Storm slab avalanche problem combination decision tree describing the decision rules and corresponding terminal nodes based on the most common danger rating assigned based on those rules. Nodes indicated with a *P* are characteristics of the Persistent slab avalanche problem while those indicated with an *S* are characteristics of the Storm slab avalanche problem.**

*problem* (12 splits, 29%). Among the splits that were based on *Persistent slab avalanche problem* characteristics, likelihood of avalanches was the most commonly included parameter with six splits (15%).

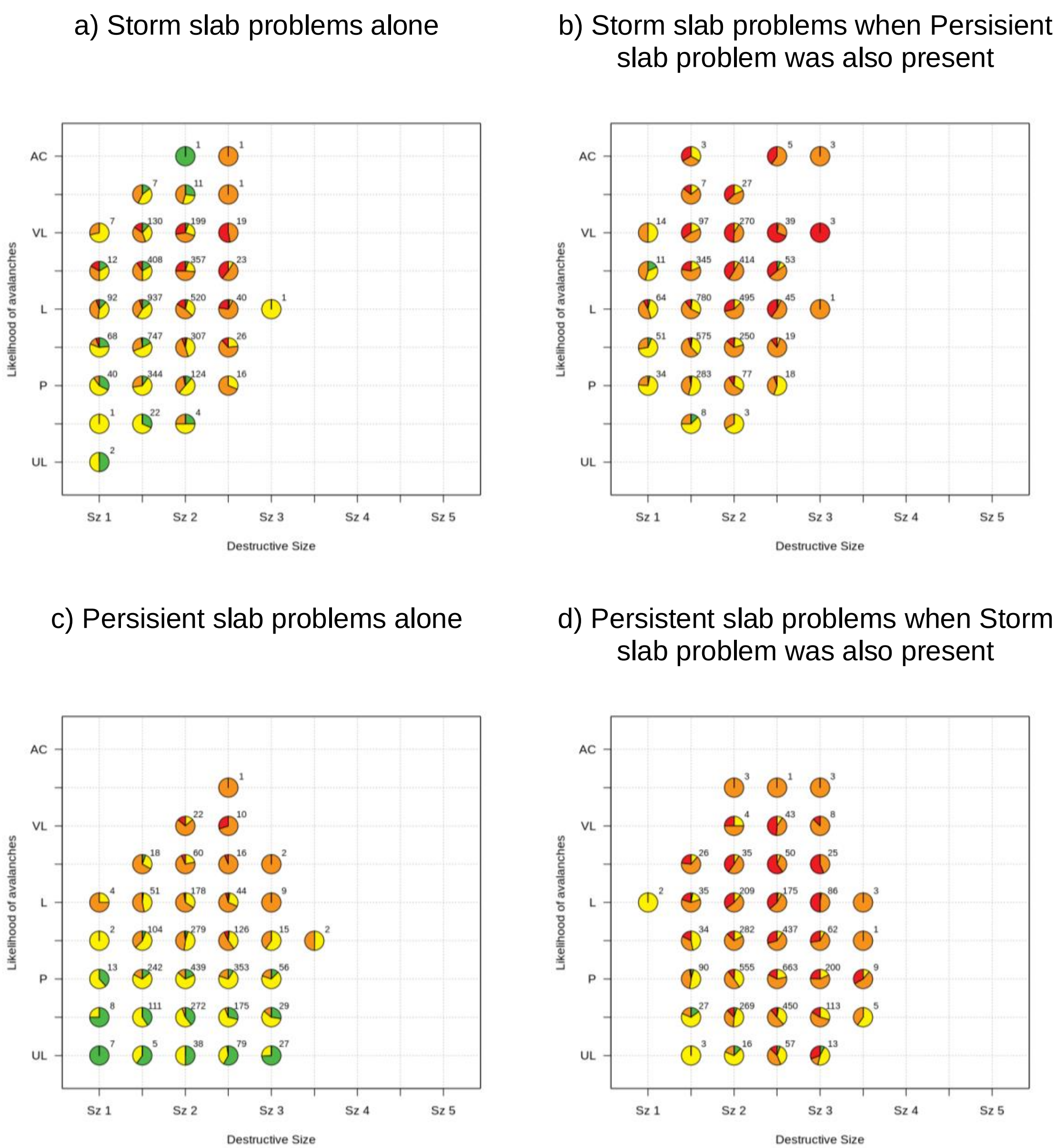



**Figure 4.16 Combinations of observed typical likelihood of avalanches and destructive sizes of Persistent slab and Storm slab avalanche problems contrasting hazard situations when the problems were present alone versus when they were both present at the same time. Same presentation as Figure 4.1.**

Of the less prominent parameters, the binary aspect parameter for *Storm slab avalanche problems* was responsible for three splits (7%) while *Persistent slab aspect* was responsible for four (10%), while agency only accounted for a single split in the final stage of a branch. The analysis found only one decision rule based on mountain range separating the Coast and Rocky Mountains from the Columbia Mountains.

### *Hazard chart visualizations*

Four series of hazard chart visualizations are shown to illustrate the interaction between concurrent *Persistent slab* and *Storm slab avalanche problems*. However, it is important to remember that these visualizations do not show the full complexity of the CIT model since they only include the likelihood of avalanches and destructive size terms of the two avalanche problems.

- *Storm slab avalanche problem* hazard charts with a *Persistent slab avalanche problem* at a likelihood of avalanches of Possible-Likely and various destructive sizes (Figure 4.17).
- *Storm slab avalanche problem* hazard charts with a *Persistent slab avalanche problem* at various likelihoods of avalanches and a destructive size of 2 (Figure 4.18).
- *Persistent slab avalanche problem* hazard charts with a *Storm slab avalanche problem* at a likelihood of avalanches of Possible-Likely and various destructive sizes (Figure 4.19).
- *Persistent slab avalanche problem* hazard charts with a *Storm slab avalanche problem* at various likelihoods of avalanches and a destructive size of 2 (Figure 4.20).

#### Storm slab avalanche problem hazard charts

The relative position of the coloured squares and the blue diamonds in the hazard chart indicated that when the *Persistent slab* and *Storm slab avalanche problems* are present together (Figures 4.17-20), the typical avalanches associated with the *Storm slab avalanche problem* are typically more likely than the avalanches of the *Persistent slab avalanche problem*. There is also a tendency that the *Persistent slab avalanche problem* involves larger avalanches, but the pattern is not as strong. These observations seem reasonable as the snowpack weakness responsible for the *Persistent slab avalanche problem* is typically buried deeper in the snowpack than the superficial *Storm slab avalanche problem*.

Overall, the *Storm slab avalanche problem* charts of the combined *Persistent slab and Storm slab avalanche problem* situations (Figures 4.17 and 4.18) highlighted the constant importance of the following splitting rules for the *Storm slab avalanche problem*:

a) Between destructive sizes of 1.5 and 2

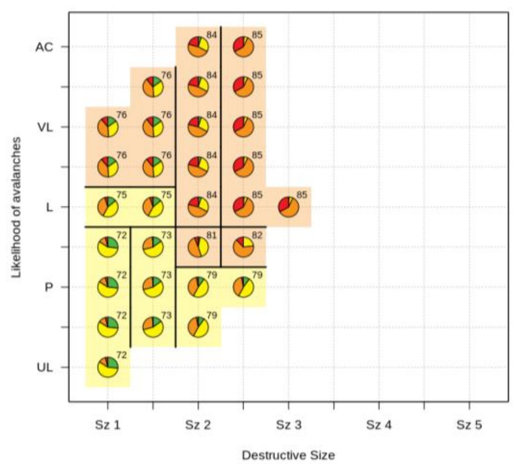
b) Between likelihoods of avalanches of Possible and Possible-Likely

c) Between likelihoods of avalanches of Possible-Likely and Likely

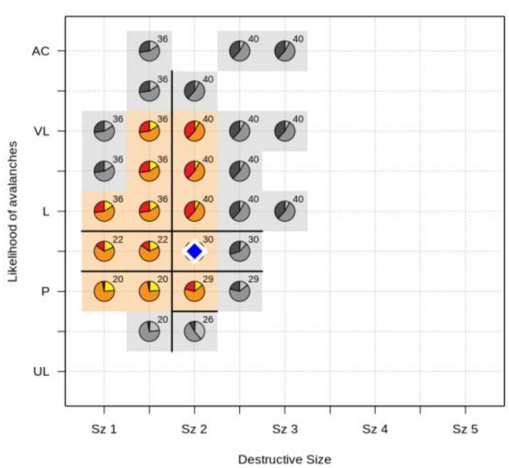
These three rules persisted in the *Storm slab avalanche problem* chart regardless of the characteristics of the *Persistent slab avalanche problem*. Furthermore, rules a) and b) were also present when the *Storm slab avalanche problem* exists in isolation (Figure 4.16, Panel a). Hence, these rules represent fundamental transitions in the assessment of hazard situations involving *Storm slab avalanche problems.*

While the locations of the transitions remained stationary, the danger rating distributions in the *Storm slab avalanche problem* hazard chart responded to changes in the likelihoods and destructive sizes of the *Persistent slab avalanche problem*. Comparisons of the first two panels in Figures 4.17 and 4.18 highlighted that adding even a small or unlikely *Persistent slab avalanche problem* (Panels b) increased the danger rating distributions relative to the pure *Storm slab avalanche problem* hazard situations (Panels a). The scenarios with increasing destructive size of the *Persistent slab avalanche problem* (Figure 4.17) showed a significant increase in danger rating distributions when the destructive size increased from 2 to 2.5. However, this change only affected *Storm slab avalanche problems* of likelihoods at Likely and higher and destructive sizes of 2 or larger.

a) Storm slab avalanche problem alone




b) with Persistent slab avalanche problem with P-L likelihood and size 1.5




c) with Persistent slab avalanche problem with P-L likelihood and size 2

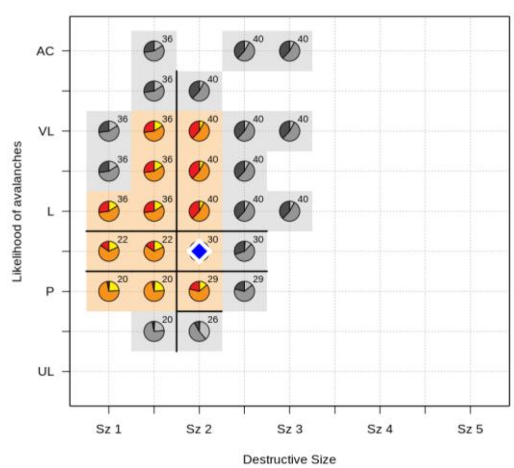



**Figure 4.17 Hazard chart for Storm slab avalanche problems along and in combination with a Persistent slab avalanche problem at a likelihood of avalanches of Possible-Likely and various destructive sizes. Same presentation as Figure 4.2.**

d) with Persistent slab avalanche problem with P-L likelihood and size 2.5

e) with Persistent slab avalanche problem with P-L likelihood and size 3

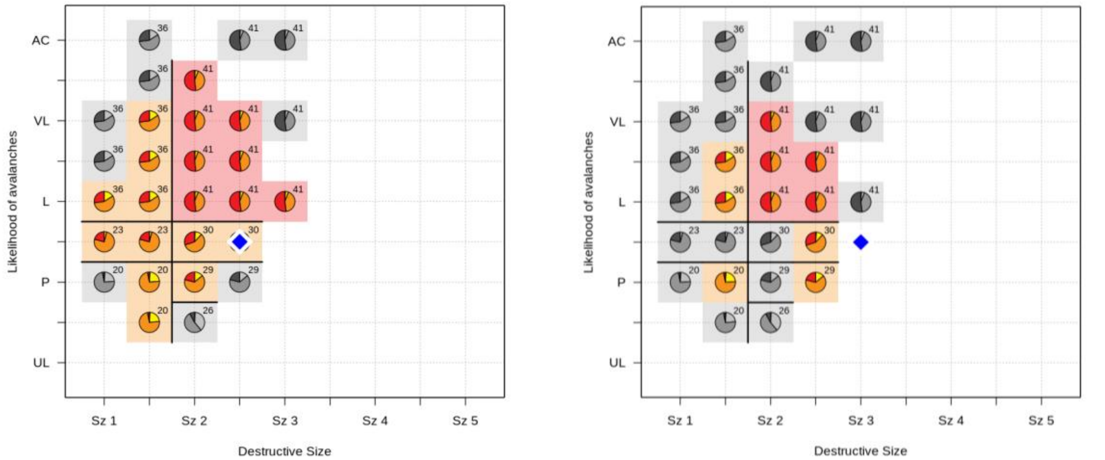



**Figure 4.17 Continued.**

The transitions with increasing likelihood of avalanches (Figure 4.18) were initially a bit more gradual with changes occurring at every step until the likelihood of avalanches for the *Persistent slab avalanche problem* reached Possible-Likely. However, additional increases in the likelihood of avalanches did not further increase the danger rating of the combined hazard situation. In addition, the available data points for these hazard situations became increasingly rare as shown by the decreasing number of coloured squares in the charts.

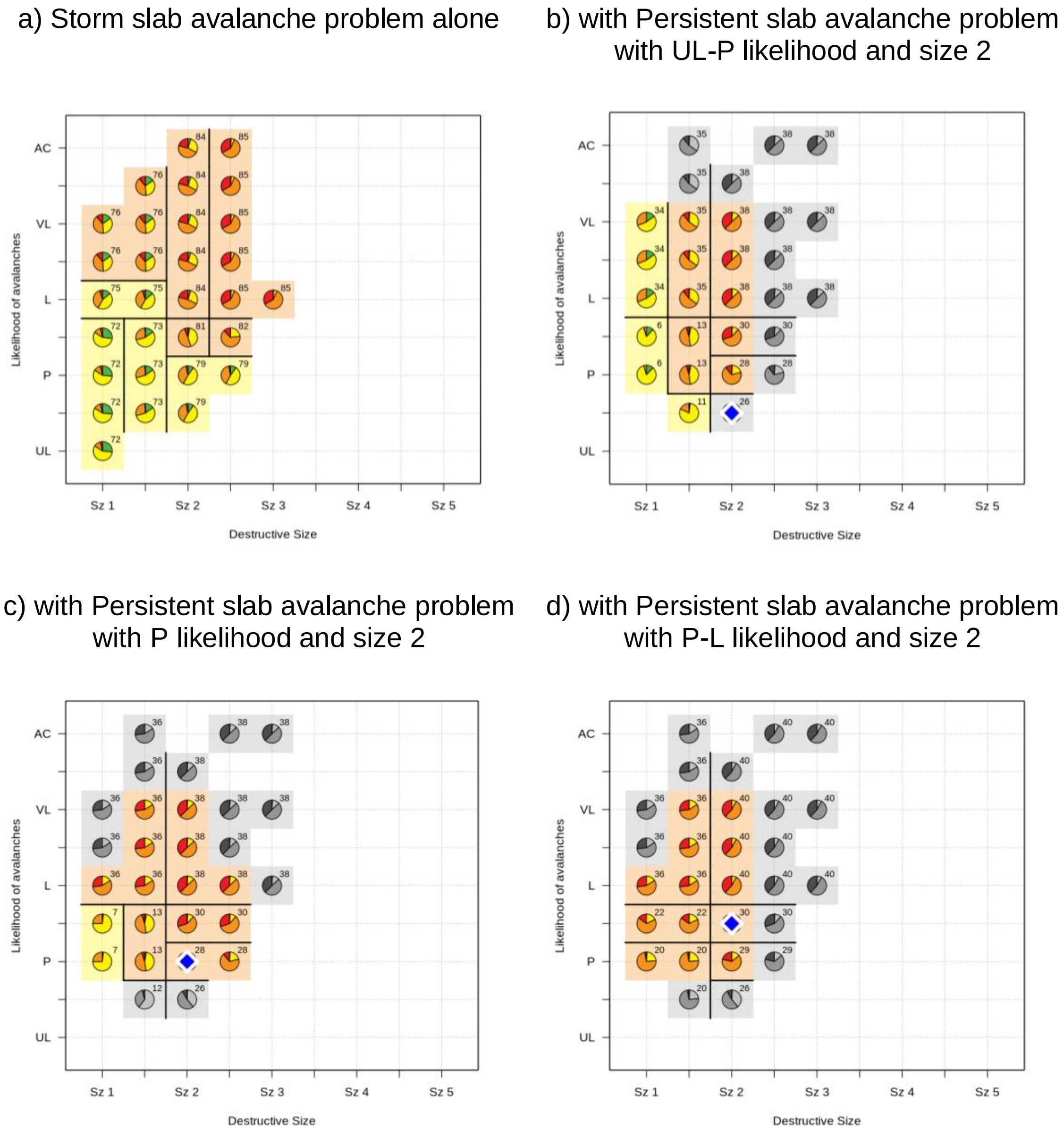



**Figure 4.18** **Hazard chart for Storm slab avalanche problem alone and in combination with a Persistent slab avalanche problem at various likelihoods of avalanches and a constant destructive size of 2. Same presentation as Figure 4.2.**

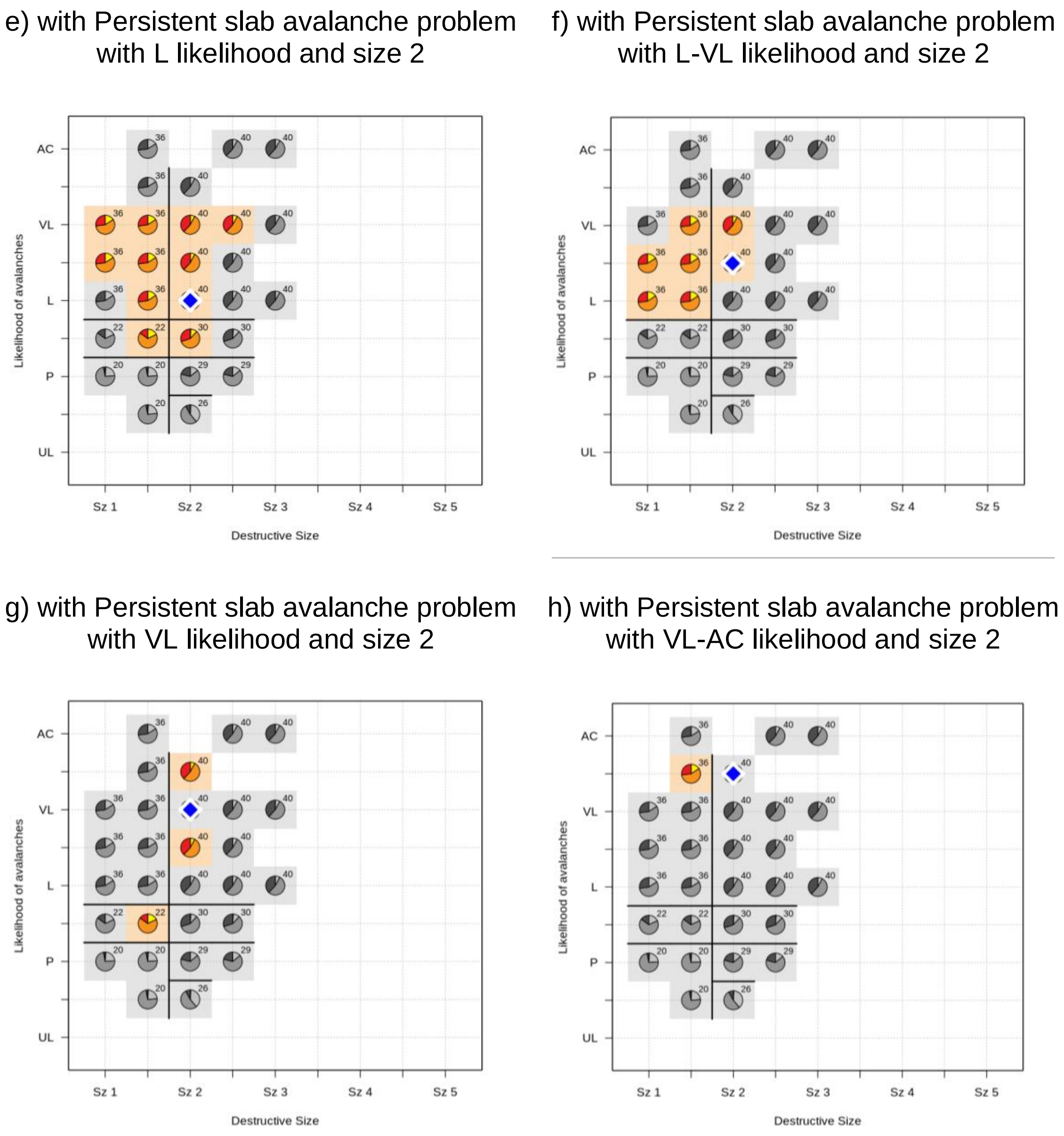



**Figure 4.18 Continued.**

**Persistent slab avalanche problem charts**

The *Persistent slab avalanche problem* hazard charts for the *Storm and persistent slab avalanche problem* combinations (Figure 4.19 and 4.20 tended to change a bit more dramatically than the *Storm slab avalanche problem* hazard charts. While the chart with a *Storm slab avalanche problem* of destructive size of 1.5 (Figure 4.19 Panel b) still showed a few splitting rules, they completely disappeared once the destructive size reaches 2 and the danger rating distribution became the same for the entire hazard chart (Figure 4.19 Panels c). Additional increases in the destructive size of the *Storm* *slab avalanche problem* had no further impact on the danger rating distribution for the combined hazard situation. This lack of decision rules in the *Persistent slab avalanche problem* space reflected the result of the CIT model that the danger rating assignment is dominated by the *Storm slab avalanche problem* and the *Persistent slab avalanche problem* is only of secondary importance.

a) Persistent slab avalanche problem alone

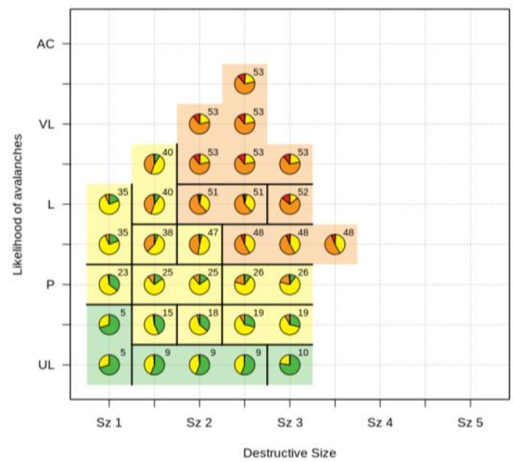



**Figure 4.19 Hazard chart for Persistent slab avalanche problem alone and in combination with a Storm slab avalanche problem at a likelihood of avalanches of Possible-Likely and various destructive sizes. Same presentation as Figure 4.2.**

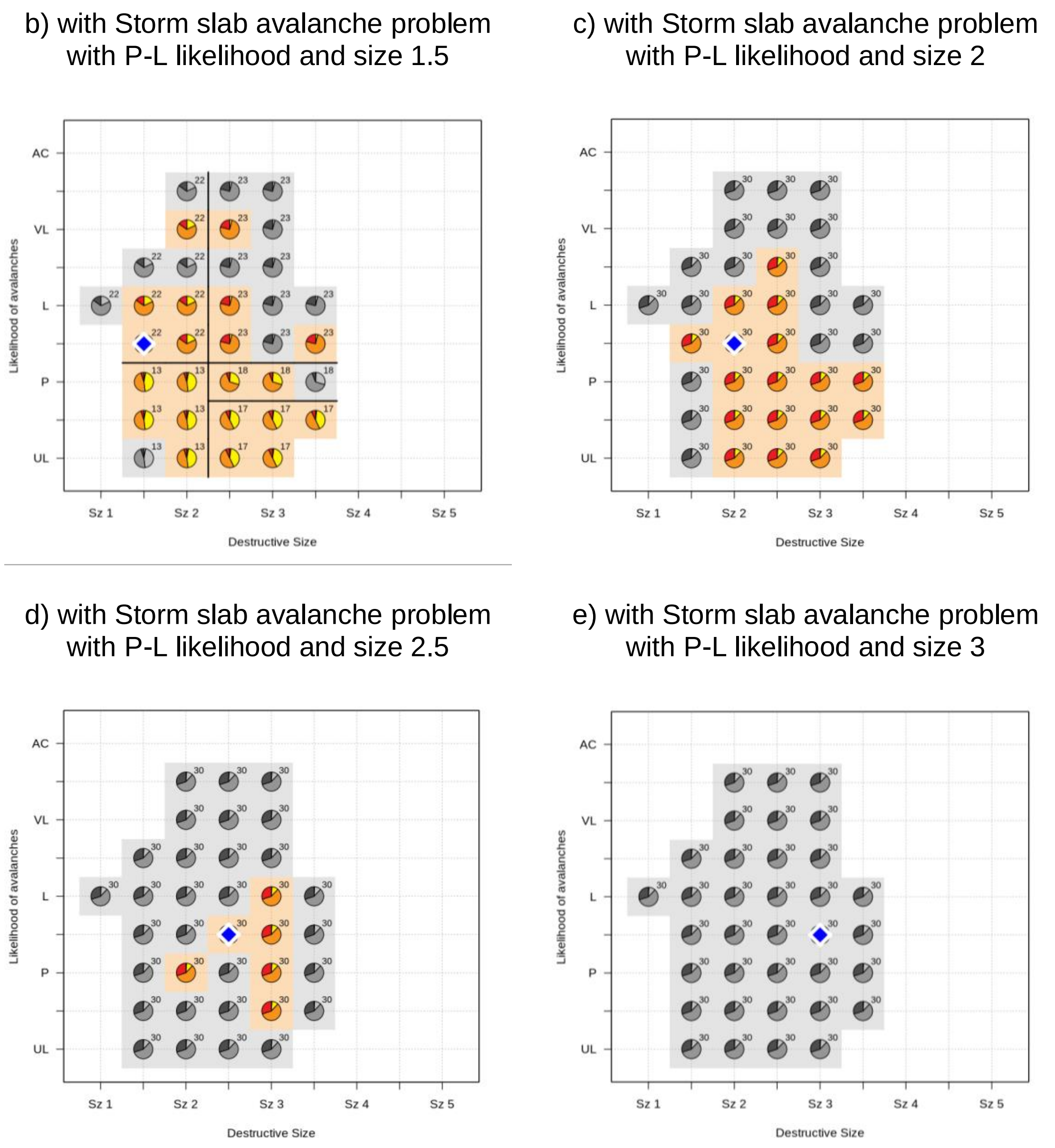



**Figure 4.19 Continued.**

The changes in the *Persistent slab avalanche problem* hazard chart in response to increases in the likelihood of avalanches of the Storm slab avalanche problem were a bit more variable (Figure 4.20), which showed that the *Storm slab avalanche problem* likelihood of avalanches was a more significant decision rule in the CIT model than its destructive size. As the *Storm slab avalanche problem* likelihood increased to Possible-Likely, the danger rating distributions on the hazard chart became progressively more severe (Figure 4.20, Panels b-d). No decision rules were found within these three hazard scenarios except when the *Storm slab avalanche problem* likelihood of avalanches was assessed at Possible (Figure 4.20Panel c). Once the likelihood of avalanches of the *Storm slab avalanche problem* exceeded Likely, the hazard charts reveal two splitting rules that divided the hazard space into three sectors for all of the higher likelihood values (Figure 4.20, Panels e-h). In all of these scenarios, the danger rating distributions included a substantial portion of High/Extreme ratings.

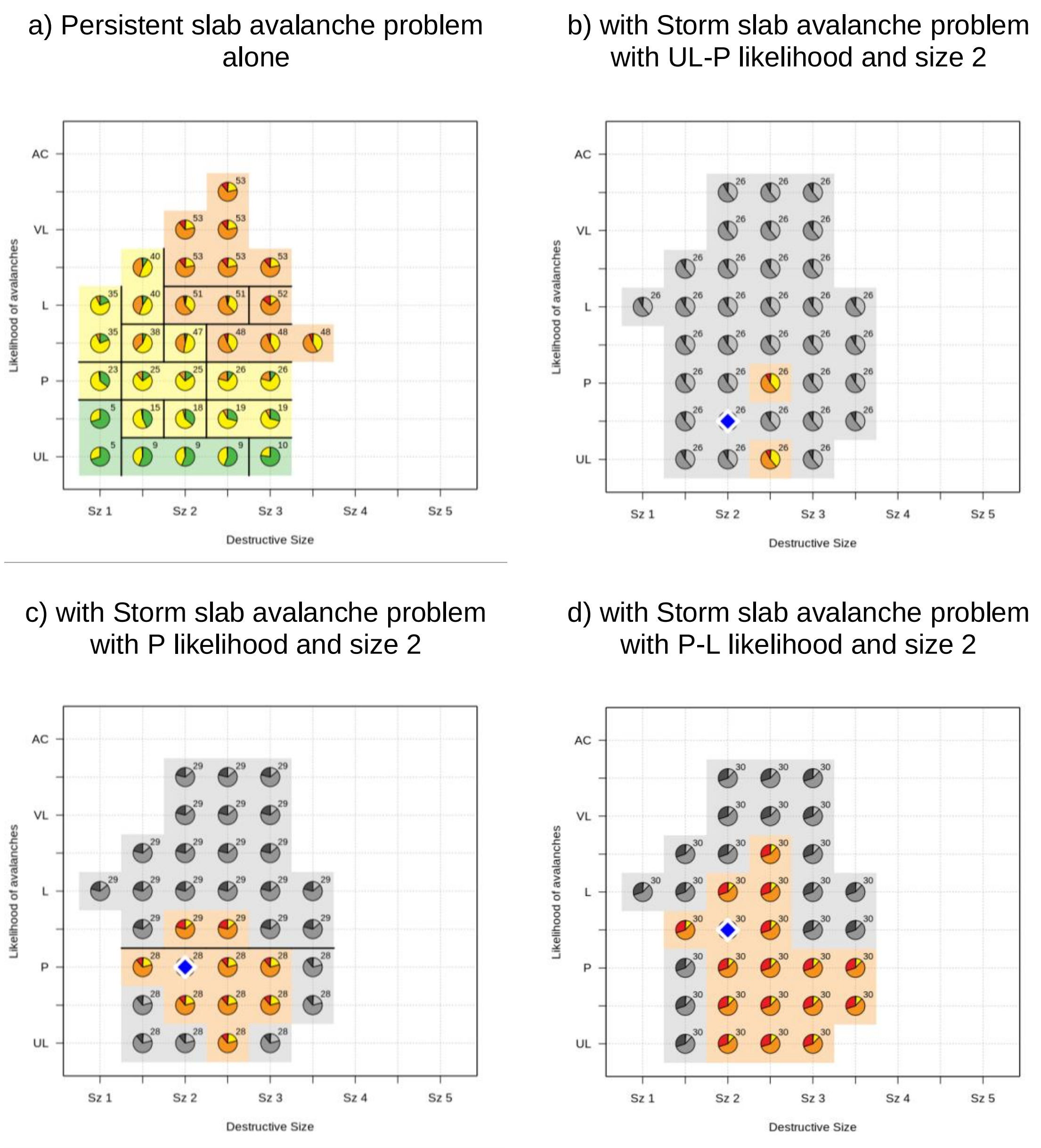



**Figure 4.20 Hazard chart for Persistent slab avalanche problem alone and in combination with a Persistent slab avalanche problem at various likelihoods of avalanches and a destructive size of 2. Same presenation as Figure 4.2**

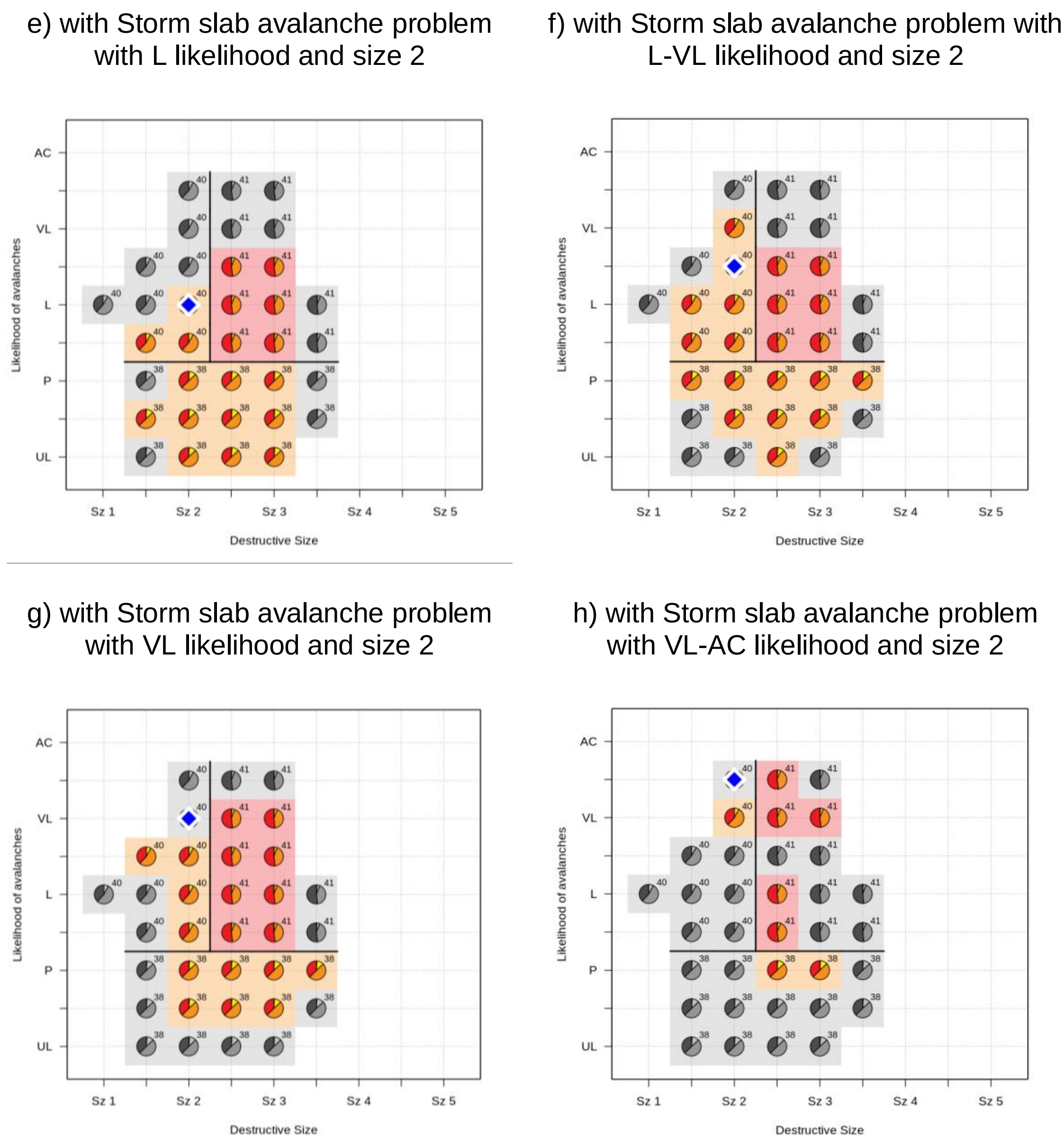



**Figure 4.20 Continued.**

### 4.3.3. Persistent slab and wind slab avalanche problem hazard situations

When *Persistent slab avalanche problems* were found in combination with *Wind slab avalanche problems*, the locations of the avalanche problem assessments on the hazard chart changed slightly (Figure 4.21). Both problems showed an increase in the extent of likelihood of avalanches at higher ends of the likelihood scale as well as more occurrences of higher destructive sizes. These differences were stronger among the

*Wind slab avalanche problem* assessments than the *Persistent slab avalanche problem* assessments.

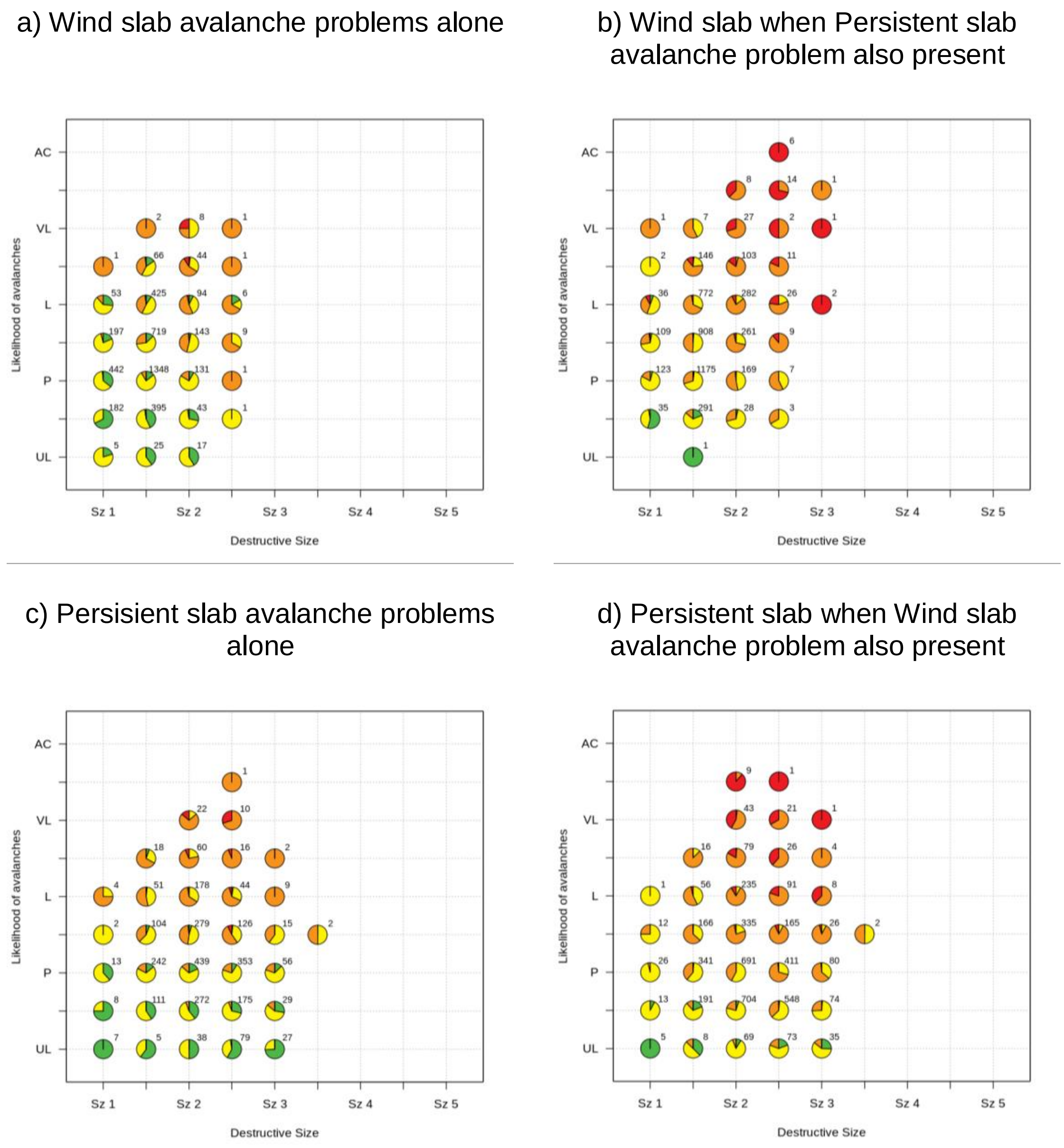



**Figure 4.21 Combinations of observed typical likelihood of avalanches and destructive sizes of Persistent slab and Wind slab avalanche problems contrasting hazard situations when the problems were present alone versus when they were both present at the same time. Same presentation as Figure 4.1.**

### *General structure of classification tree*

The CIT analysis of the *Persistent slab and wind slab avalanche problem* combination revealed a decision tree with 54 decision rules and 55 terminal nodes (Figure 4.22). This model performed the best out of all assessed trees with a hit rate of 75% and a multi-class AUC score of 0.821. In this decision tree, likelihood of avalanches of the *Persistent slab avalanche problem* made the first split. For likelihoods less than or equal to Possible, this first split was followed by a split on likelihood of avalanches of the *Wind slab avalanche problem*. For the other branch, *Persistent slab avalanche problems* with likelihoods greater than Possible, the first split was followed by another split of *Persistent slab avalanche problem* likelihood at Likely. In total, the likelihood of avalanches and destructive size parameters of both avalanche problems were responsible for similar numbers of splits in the CIT model, which highlights that both problems contributed equally to the avalanche danger rating assignments. While destructive size was the more influential parameter for the *Wind slab avalanche problem,* likelihood of avalanches was the more important parameter for the *Persistent slab avalanche problem*. Elevation band made a total of nine (16%) splits within the middle sections of the decision tree while the aspect parameter was used for the *Wind slab* and *Persistent slab avalanche problem* four (7%) and five (9%) times respectively. The agency that produced the assessment made only one (2%) split while the mountain range was not found to be a statistically significant contributor to the danger rating distributions.

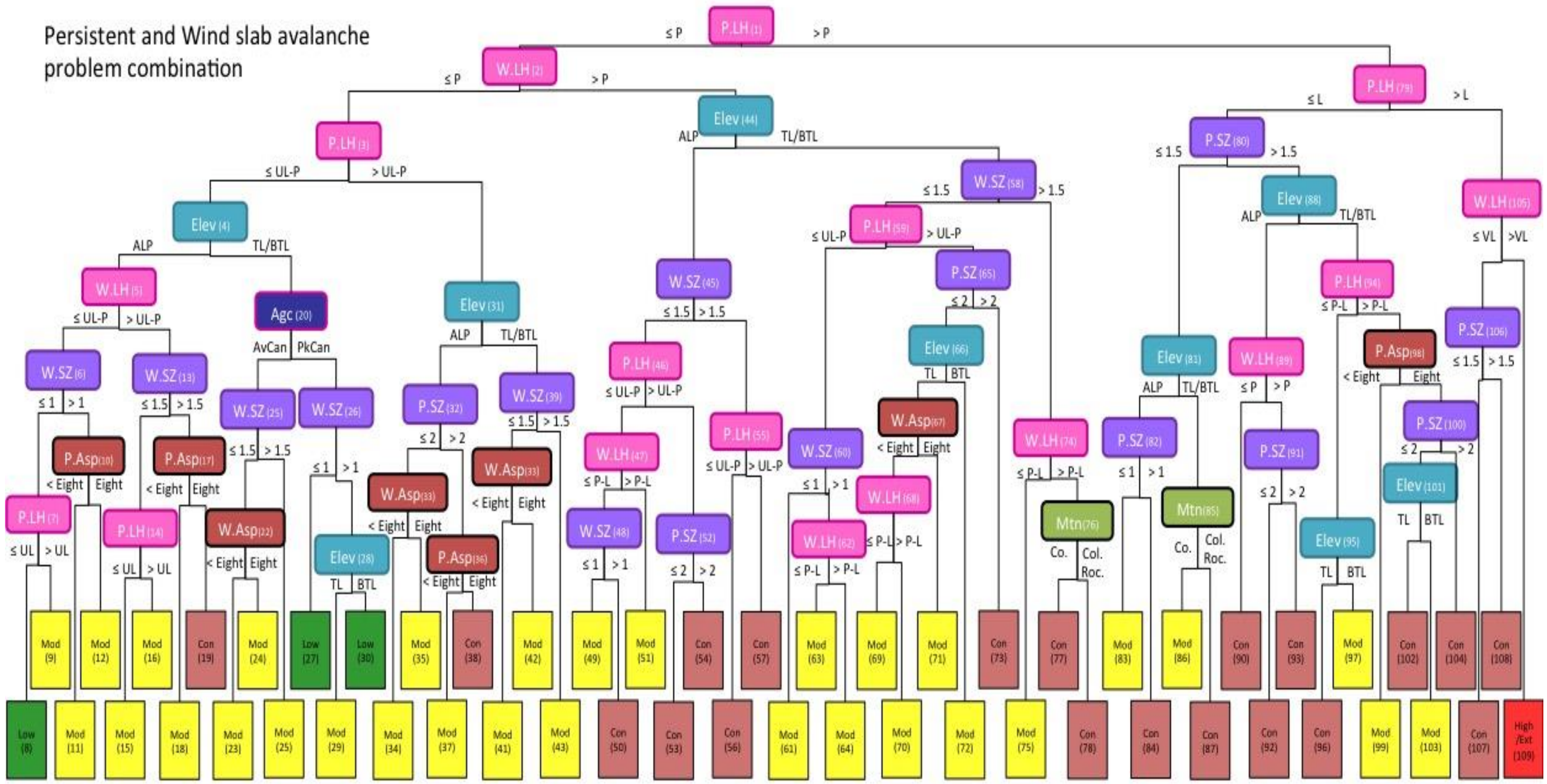



**Figure 4.22** **Persistent and Wind slab avalanche problem combination decision tree describing the decision rules and corresponding terminal nodes based on the most common danger rating assigned based on those rules. Nodes indicated with a *P* are characteristics of the Persistent slab problem while those indicated with a *W* are characteristic of the Wind slab avalanche problem.**

### *Hazard chart visualizations*

Similar to the discussion of the *Persistent slab and storm slab avalanche problem* combination, I am showing four series of hazard chart visualizations to illustrate the interactions between the two avalanche problems. The four chart series are:

- *Wind slab avalanche problem* hazard charts with a *Persistent slab avalanche problem* at a likelihood of avalanches of Possible-Likely and various destructive sizes (Figure 4.23).
- *Wind slab avalanche problem* hazard charts with a *Persistent slab avalanche problem* at various likelihoods of avalanches and a destructive size of 2 (Figure 4.24).
- *Persistent slab avalanche problem* hazard charts with a *Wind slab avalanche problem* at a likelihood of avalanches of Possible-Likely and various destructive sizes (Figure 4.25).
- *Persistent slab avalanche problem* hazard charts with a *Wind slab avalanche problem* at various likelihoods of avalanches and a destructive size of 2 (Figure 4.26).

**Wind slab avalanche problem hazard charts**

The relative position of the coloured squares and the blue diamonds in the hazard charts (Figures 4.23-26) indicated that when the *Persistent slab* and *Wind slab avalanche problems* are present together, the *Wind slab avalanche problem* typically involves smaller avalanches than the concurrent *Persistent slab avalanche problem* at a variety of likelihoods. This is reasonable, as the snowpack weakness responsible for the *Persistent slab avalanche problem* is typically buried deeper in the snowpack than the superficial *Wind slab avalanche problem*.

Comparing the hazard chart for single *Wind slab avalanche problems* with the hazard charts for *Persistent slab and wind slab avalanche problem* combinations (Figures 4.23 and 4.24) showed that adding a *Persistent slab* to a *Wind slab avalanche problem* increases the resulting danger ratings substantially. The effect of the destructive size is more sudden as even the addition of only a size 1.5 *Persistent slab avalanche problem* results in a substantial increase in the danger rating distributions (Figure 4.23)

Panel a and b). The effect of likelihood of avalanches, on the other side, is more gradual as the addition of a *Persistent slab avalanche problem* with a likelihood of avalanches of Unlikely-Possible and a destructive size of 2 only produced minor changes in the patterns of the hazard chart (Figure 4.23) Panel a and b).

When a *Persistent slab avalanche problem* is present, and its likelihood of avalanches is set to Possible-Likely, the decision rules in the *Wind slab avalanche problem* hazard chart disappear completely and the danger rating assessment becomes independent of the likelihood of avalanches and destructive size parameters (Figure 4.23). The avalanche danger rating distributions for the *Wind slab avalanche problem* increased gradually until the destructive size of the *Persistent slab avalanche problem* reaches size 2.5 (Panel d). Increasing the destructive size further to 3 (Panel e) did not change the danger rating distribution any further. In this progression, the proportion of Considerable danger ratings increased substantially, but the contribution of High/Extreme was low and did not change much.

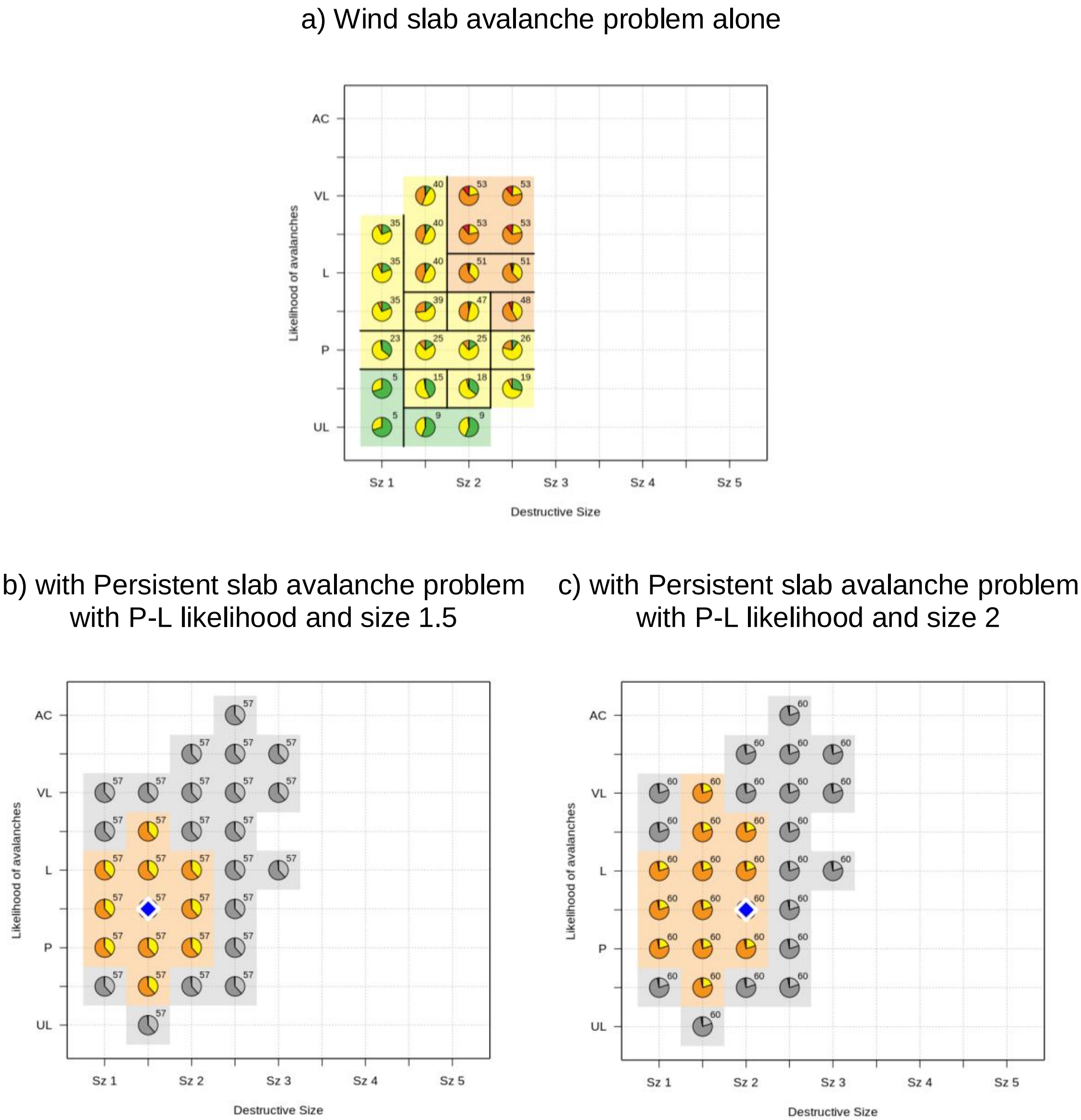



**Figure 4.23 Hazard charts for Wind slab avalanche problem alone and in combination with a Persistent slab avalanche problem at various destructive sizes and a likelihood of avalanches of Possible-Likely. Same presentation as Figure 4.2.**

d) with Persistent slab avalanche problem with P-L likelihood and size 2.5

e) with Persistent slab avalanche problem with P-L likelihood and size 3

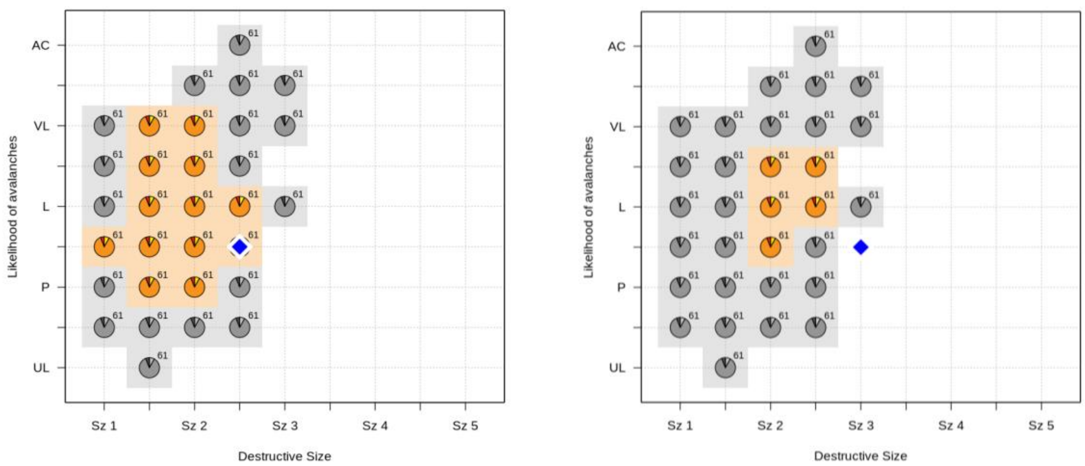



**Figure 4.23 Continued.**

Variations in the likelihood of avalanches for the *Persistent slab avalanche problem* at a destructive size of 2 had a more diverse effect on the *Wind slab avalanche problem* hazard chart than variations in its destructive size (Figure 4.24). At the lowest likelihood scenario of Unlikely-Possible, the decision rules and danger rating assessments were similar to when *Wind slab avalanche problems* were assessed on their own (Panel b). The main difference between the two scenarios was that none of the likelihood of avalanches and destructive size combinations in situations with two problems had Low as the most common danger rating. As the likelihood of the *Persistent slab avalanche problem* increased, the number of decision rules displayed in the *Wind slab avalanche problem* hazard chart decreased. When the likelihood of avalanches for the *Persistent slab avalanche problem* was Possible-Likely and Likely, there were no splits in the hazard chart (Panels d and e). Once the likelihood of avalanches of the *Persistent slab avalanche problem* reached Likely-Very Likely, a decision rule that separates *Wind slab avalanche problem* scenarios with likelihoods of Very Likely and lower from scenarios with higher likelihoods appeared (Panel f-h). While the danger rating distributions of the scenarios with lower likelihoods were dominated by Considerable ratings, the danger rating distributions of the scenarios with higher likelihoods of avalanches included more than 50% of High/Extreme ratings.

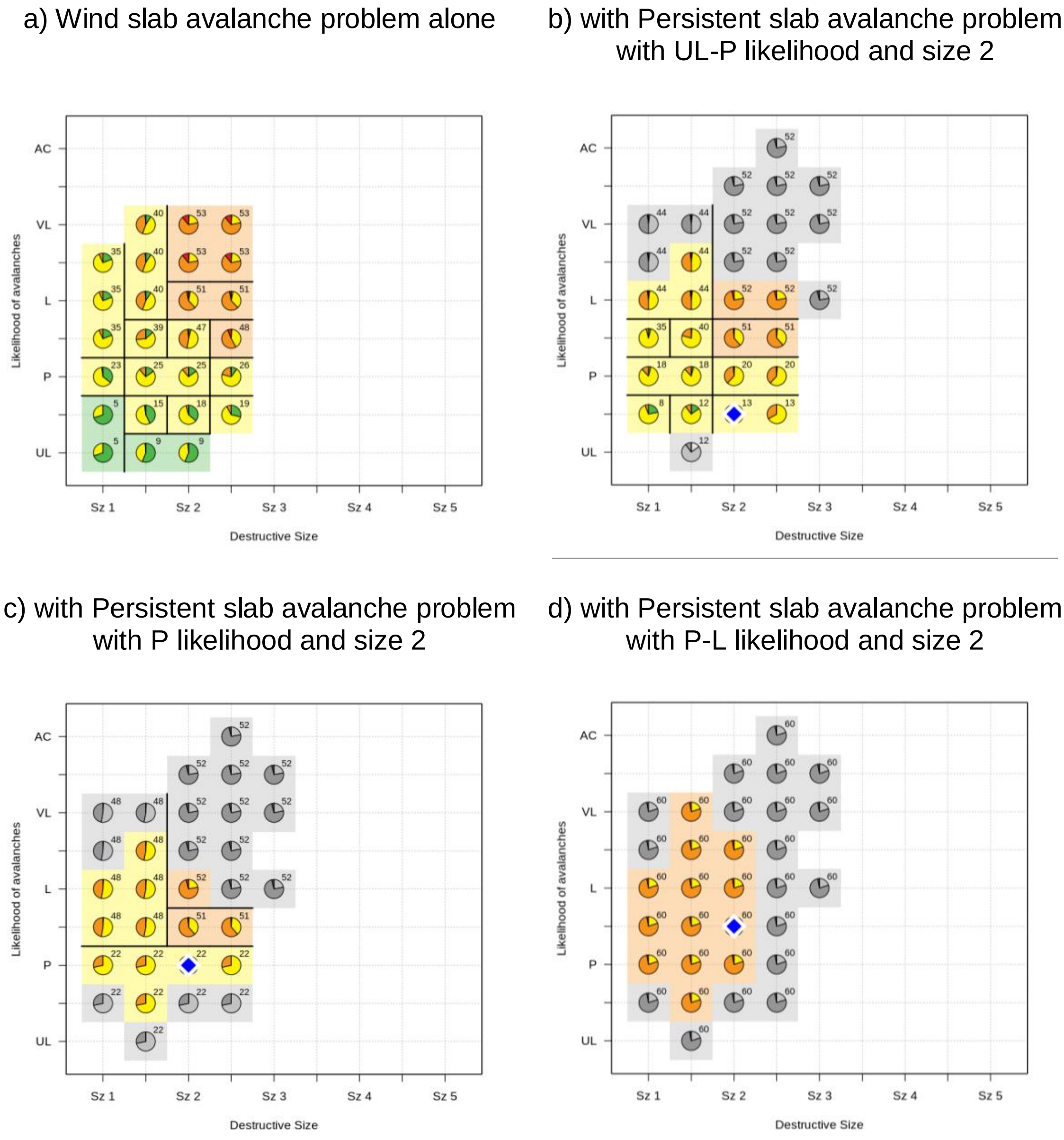
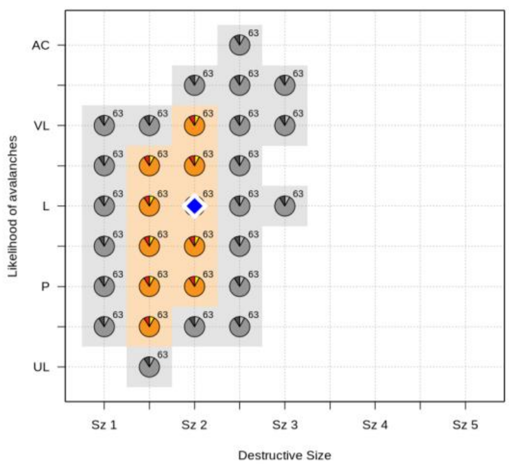
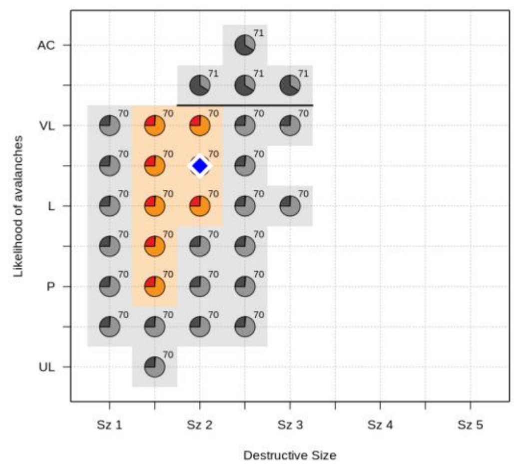



**Figure 4.24 Hazard charts for a Wind slab avalanche problem alone and in combination with a Persistent slab avalanche problem at various likelihoods of avalanches and a constant destructive size of 2. Same presentation as Figure 4.2.**

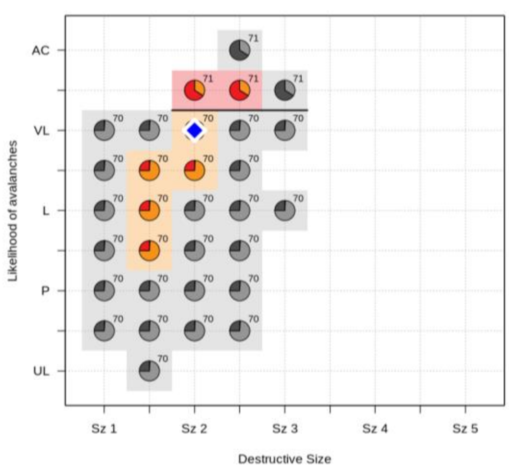
e) with Persistent slab avalanche problem with L likelihood and size 2




f) with Persistent slab avalanche problem with L-VL likelihood and size 2




g) with Persistent slab avalanche problem with VL likelihood and size 2




h) with Persistent slab avalanche problem with VL-AC likelihood and size 2

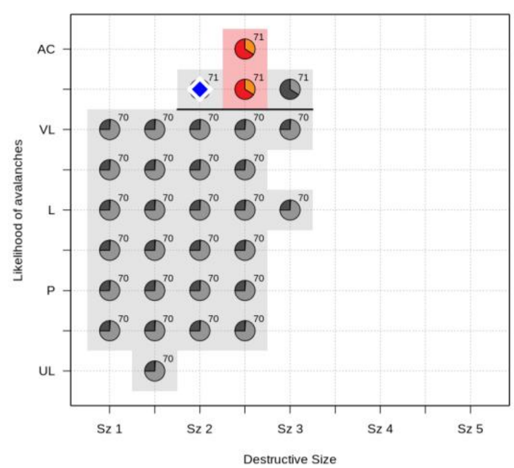



**Figure 4.24 Continued.**

**Persistent slab avalanche problem hazard charts**

An examination of the *Persistent slab avalanche problem* hazard charts with changes in the destructive sizes of a *Wind slab avalanche problem* (Figure 4.25 and 4.26) showed that the decision rules related to the Persistent slab avalanche problem persisted more as the characteristics of the *Winds slab avalanche problem* changed. Hence, adding a *Wind slab avalanche problem* initially (Figure 4.25 and 4.26, Panels b) only increased the danger rating distributions while the number and locations of many of the decision rules remained stationary. As the destructive size of the *Wind slab* *avalanche problem* increased to 2, the rules for *Persistent slab avalanche problems* with likelihoods smaller than Possible-Likely disappeared and the danger ratings increased in this area of the hazard chart. A further increase of the destructive size of the *Wind slab avalanche problem* did not cause any more changes in the hazard chart. However, the combination of a *Persistent slab avalanche problem* with a *Wind slab avalanche problem* of destructive size 2.5 or 3 (Panel d and e) were very rare.

a) Persistent slab avalanche problem alone

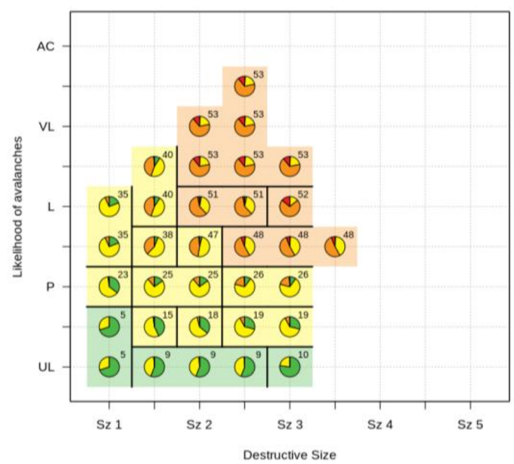
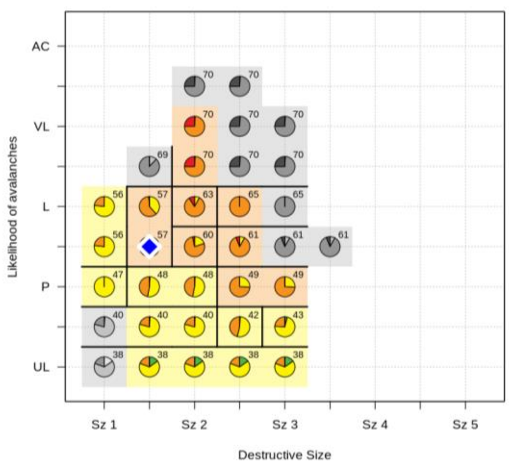
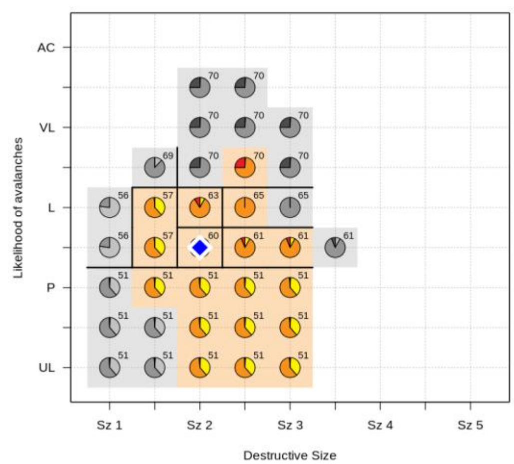



**Figure 4.25** **Hazard charts for Persistent slab avalanche problem alone and in combination with a Wind slab avalanche problem at various destructive sizes and a constant likelihood of avalanches at Possible-Likely. Same presentation as Figure 4.2.**

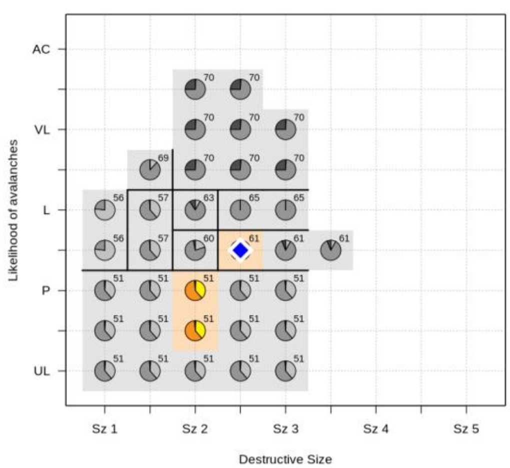
b) with Wind slab avalanche problem with P-L likelihood and size 1.5




c) with Wind slab avalanche problem with P-L likelihood and size 2




d) with Wind slab avalanche problem with P-L likelihood and size 2.5




e) with Wind slab avalanche problem with P-L likelihood and size 3

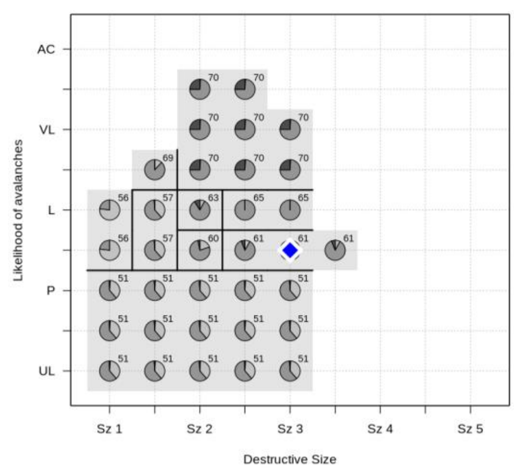



**Figure 4.25 Continued.**

The series of hazard charts with increasing likelihoods of avalanches for the *Wind slab avalanche problem* (Figure 4.26) revealed similar patterns. *Wind slab avalanche problems* with relatively low likelihoods of avalanches resulted in a decreasing number of splitting rules (Panels b-c) and once the likelihood reached Possible-Likely (Panel d), the same number of splitting rules appeared at the same locations as in Figure 4.25. The danger rating distributions remained the same until the likelihood value of the *Wind slab avalanche problem* reached Very Likely-Almost Certain (Panel h), when more than 50% of the assessments for *Persistent slab avalanche problems* with likelihoods higher than Likely had High/Extreme danger ratings.

The persistence of the likelihood of avalanche splitting in these hazard charts (Figures 4.25 and 4.26) is consistent with some of the most important decision splits in the CIT model and clearly highlights that the likelihood transitions from Possible to Possible-Likely, Likely and Likely-Very Likely, play important roles as how avalanche forecasters assess *Wind slab avalanche problem* hazard situations when *Persistent slab avalanche problems* are present. While some of these splitting rules for *Persistent slab avalanche problems* were also found in the *Persistent slab and storm slab avalanche problem* hazard chart visualizations (Figures 4.19 and 4.20) they were not quite as prominent for that combination. This might indicate that during times with both *Storm slab* and *Persistent slab avalanche problems*, the characteristics of the *Storm slab avalanche problem* are more important, whereas the characteristics of the *Persistent slab avalanche problem* are more important when it co-occurs with a *Wind slab avalanche problem*.

a) Persistent slab avalanche problem alone

b) with Wind slab avalanche problem with UL-P likelihood and size 2

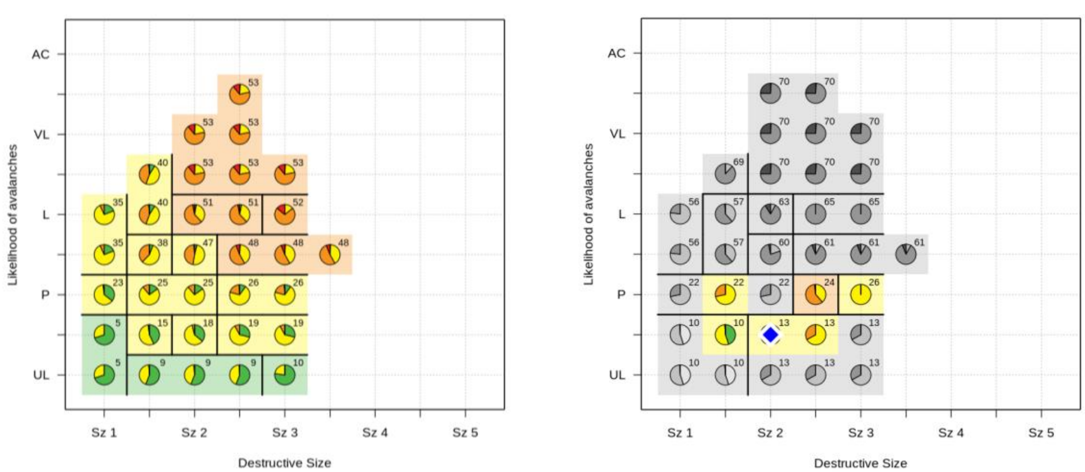
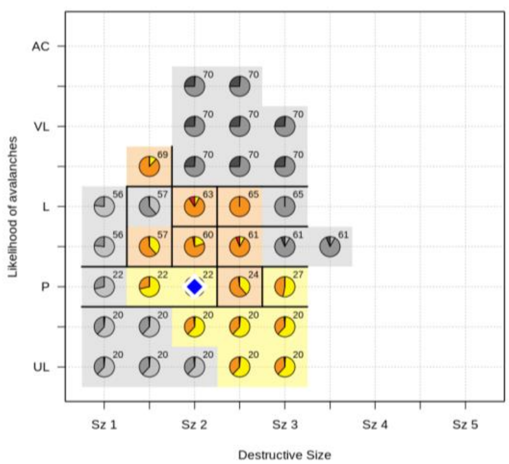
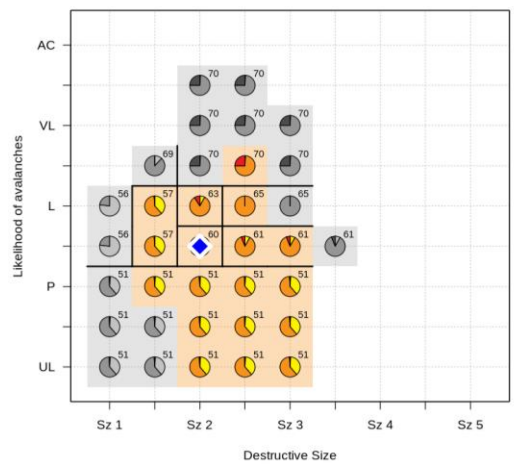



**Figure 4.26** **Hazard charts for Persistent slab avalanche problem alone and in combination with a Wind slab avalanche problem at various likelihoods of avalanches and a constant destructive size of 2. Same presentation as Figure 4.2.**

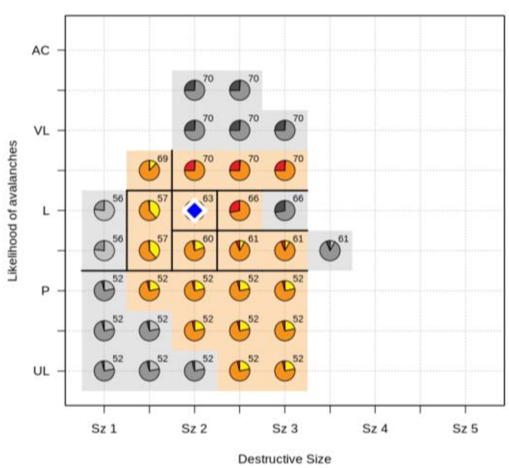
c) with Wind slab avalanche problem with
P likelihood and size 2




d) with Wind slab avalanche problem with
P-L likelihood and size 2




e) with Wind slab avalanche problem with
L likelihood and size 2




f) with Wind slab avalanche problem with
L-VL likelihood and size 2

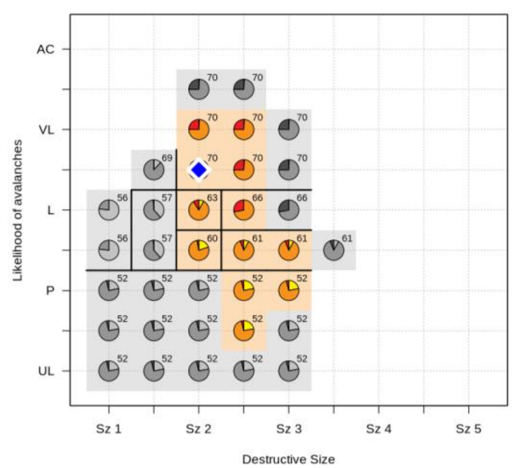
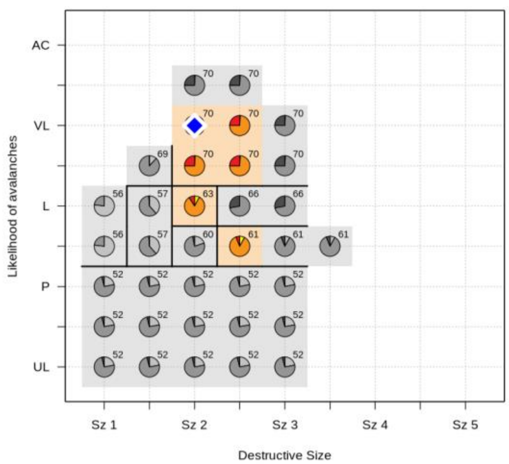



**Figure 4.26 Continued.**

g) with Wind slab avalanche problem with VL likelihood and size 2




h) with Wind slab avalanche problem with VL-AC likelihood and size 2

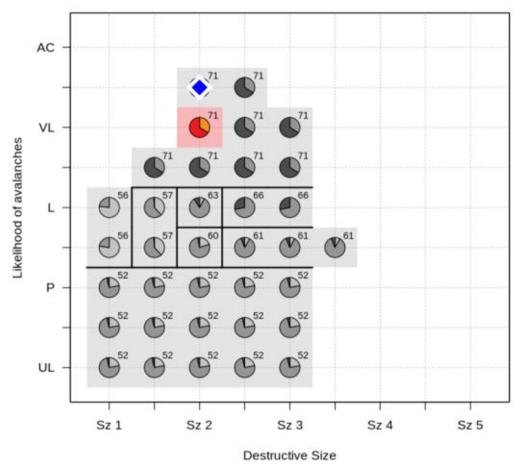



**Figure 4.26 Continued.**

# Chapter 5. Discussion

The purpose of my research was to explore the relationship between parameters of the CMAH and assess their influence on avalanche danger rating assignments. In the following section I reflect on the analysis in the context of the research questions based on the findings of the CIT models.

## 5.1. General patterns of decision rules based on the core components of the CMAH

As expected, my analysis of single avalanche problem hazard situations confirmed that the typical likelihood of avalanches and destructive size parameters of the CMAH are key attributes influencing danger rating assignments. The CIT model identified many statistically significant splits related to these two parameters. The hazard chart visualizations of the assessments revealed that while forecasters used the full likelihood scale for expressing the typical likelihood of avalanches, the maximum value used for typical destructive size was 3.5 on the scale from 1 to 5.

One of the main findings of the single avalanche problem CIT model is that avalanche forecasters do not assess all avalanche problem types the same, and that danger ratings of different avalanche problem types are influenced differently by changes in the likelihood of avalanches and destructive size parameters. Most notably, the first splitting rule in the single avalanche problem CIT model separated *Storm slab avalanche problems* from all other problem types. Single *Storm slab avalanche problems* exhibited significantly higher danger ratings than other single avalanche problem types, and destructive size affected the level of the avalanche danger rating more than likelihood of avalanches. The importance of the main decision rule being based on destructive size of 1.5 separating regions of Moderate from Considerable danger ratings is nicely illustrated by both the decision tree and the hazard chart visualization. This can likely be explained by the fact that according to the definitions in the avalanche size classification (Canadian Avalanche Association, 2014) avalanches of size 2 or larger can kill people, while smaller avalanches are generally not big enough to be harmful to people. In contrast, the danger rating distributions of *Deep persistent slab avalanche problems* were more strongly determined by the likelihood of avalanches parameter, and for *Persistent slab* and *Wind slab avalanche problems*, it was a more even combination of the likelihood of avalanches and destructive size parameters.

My analysis further revealed that the splitting rules for likelihood of avalanches and destructive size of avalanche problem combinations differ from the rules when avalanche problems are assessed individually. However, the observed differences are context dependent. For example, in *Persistent and storm slab avalanche problem* combinations, *Storm slab avalanche problems* were found to influence the resulting danger rating more than the concurrent *Persistent slab avalanche problem*. While the danger rating distributions changed in response to the severity of the two avalanche problems, the locations of some of the *Storm slab avalanche problem* splitting rules within the combination were relatively unaffected. In contrast, the number of decision rules for the *Persistent slab avalanche problem* in the combination was fewer than when the problem was assessed on its own. In the case of *Persistent and wind slab avalanche problem* combinations, it was the *Persistent slab avalanche problem* that had a stronger influence on the avalanche danger rating than the *Wind slab avalanche problem*. The number of *Wind slab avalanche problem* decision rules decreased when coupled with a *Persistent slab avalanche problem.*

Some of the avalanche problem-specific splitting rules for likelihood of avalanches and destructive size exhibit substantial persistence. This means that the location of the splitting rule on the hazard chart stays the same for a specific avalanche problem regardless of whether the problem is assessed by itself or in combination with another problem. For example, the transition in likelihood of avalanches from Possible to Possible-Likely seems to be a fundamental rule for assessing *Persistent slab avalanche problems* regardless of whether it is present by itself or in combination with other avalanche problems. Similarly, the change from destructive size 1.5 to 2 emerged as a fundamental transition for *Storm slab avalanche problems* due to the potentially lethal consequences of avalanches of size 2 or larger. Hence, my results indicate that avalanche forecasters might have fundamental, avalanche problem specific thresholds for likelihood of avalanches and destructive size when assigning avalanche danger ratings within the CMAH framework.

## 5.2. Influence of additional parameters on the avalanche danger rating

The CMAH outlines key parameters that forecasters consider when evaluating avalanche hazard. In addition to likelihood of avalanches and destructive size, my analysis also examined the potential effect of elevation band, mountain range, and whether or not the problem was present on all aspects on avalanche danger ratings. Through this analysis, I found that all these parameters have a statistically significant effect on danger rating distributions. However, closer analyses of the CIT models and hazard chart visualizations revealed that some parameters influence the danger rating more than others.

At the beginning of the assessment process in *AvalX*, public avalanche forecasters are asked to describe the location of where an avalanche problem is present in terms of elevation band and aspect. The subsequent hazard assessment of the avalanche problem then focuses on the conditions within the specified location. At the end of the process, elevation specific danger ratings are specified based on these assessments. My analysis found that avalanche problems with the exact same characteristics are assessed more severely at higher elevation bands. In other words, a *Storm slab avalanche problem* with the same typical values for likelihood of avalanches and destructive size get a higher danger rating in the alpine than at treeline. While the prevalence of avalanche problem types differs among elevation bands (Shandro & Haegeli, 2018) and differences in the conditions can lead to avalanche problems of different severity, there are no indications in the definitions of avalanche problem types and the descriptions of relevant risk mitigation strategies (Statham et al., 2018; Haegeli, Atkins & Klassen, 2010) that indicate that elevation should have a direct effect on avalanche danger ratings. This means that avalanche forecasters might have a bias towards assigning higher danger ratings at higher elevations.

Since avalanche danger ratings of an elevation band need to represent the hazard condition of all aspects (i.e., cardinal directions), it seems reasonable that an avalanche problem that is only present on one aspect sector might result in a lower danger rating than when the same problem is present on all aspects. However, my analysis revealed that aspect only plays a minor role in avalanche danger rating assessments. The only avalanche problem type where I found significant splitting rules associated with aspect was *Wet loose avalanche problems*, where problems that were present on all aspects resulted in higher danger ratings than when they were present on fewer aspects. Surprisingly, no aspect splits emerged for *Wind slab avalanche problems*, the only other avalanche problem types that frequently occur on limited aspects. While this result might seem counterintuitive initially, a reasonable interpretation is that danger ratings generally represent the worst-case condition in a given elevation band. In other words, avalanche forecasters choose danger ratings to warn recreationists about to the worst conditions. If warranted, they might provide additional information in the text part of the avalanche bulletin to inform more advanced users that conditions are more favourable on specific aspects.

Agency and mountain range, the final two parameters included in my analyses, did not result with many splits in the various CIT models. This means that I did not find systematic differences in the way that avalanche forecasters from Avalanche Canada and Parks Canada assess avalanche hazard situations examined in my study. This is comforting as several recent studies (e.g., Lazar et al., 2016; Statham, Holezi & Shandro, 2018; Techel et al., 2018) found substantial differences in avalanche hazard assessments between agencies. Furthermore, my results indicate that avalanche hazard situations were assessed independently of the mountain range and snow climate they were located in. In other words, a *Storm slab avalanche problem* of a specific nature generally received the same danger rating regardless of whether it was in the Coast Mountains or Rocky Mountains.

## 5.3. Model performance

The hit rates of the CIT models developed in this study ranged from 61% to 75%, whereas the multi-class AUC were between 0.778 and 0.821 (Table 5.1).

**Table 5.1 Performance indicators for CIT models**

| Decision Tree Model | Hit Rate | Multi-Class AUC |
|---|---|---|
| Single avalanche problem | 63% | 0.805 |
| Persistent slab and Storm slab problem combination | 61% | 0.778 |
| Persistent slab and Wind slab problem combination | 75% | 0.821 |

The CIT models developed in this study perform considerably worse than the models developed by Schirmer, Lehning and Schweizer (2010) and Bellaire and Jamieson (2013). A possible reason for this difference is the fact that these studies used different types of datasets. Schirmer, Lehning and Schweizer (2010) and Bellaire and Jamieson (2013) used datasets with physical weather and snowpack data measured at point locations and linked them to validated danger ratings. In contrast, the data for my study relied entirely on human judgment data. While I originally hypothesized that the involvement of human forecasters might address some of the challenges in the models linking weather and snowpack observations to avalanche hazard, the results of my analysis show that forecaster involvement might introduce a different type of variability.

Avalanche forecaster was not included in my CIT models as a parameter as the objective of my analysis was to capture forecaster expertise in general. However, McClung (2002) mentioned human bias as an issue in avalanche forecasting with factors such as risk propensity and perception affecting how a forecaster produces an avalanche forecast or assigns an avalanche danger rating. Future research on the link between the CMAH and avalanche danger ratings should therefore examine the effect of forecaster variability on avalanche danger rating assignments in more detail.

With a hit rate of 75%, the POLR model developed by Haegeli, Falk and Klassen (2012) also performed considerably better than the CIT models presented in this study. There are several possible reasons for this difference. First, the two studies used different datasets. Haegeli, Falk and Klassen (2012) only had a dataset of two winter seasons from Avalanche Canada, whereas the present study included eight seasons from both Avalanche Canada and Parks Canada. Second, my models only used the typical likelihood and size parameters, whereas the POLR model used the maximum as well as the typical values to represent the avalanche problem. This allowed for a potentially more comprehensive representation of avalanche problems in the model, while the use of the typical values within my model only captured part of the avalanche hazard. However, my model comparison did not reveal any substantial performance differences between CIT models with different likelihood of avalanches and destructive size representation. Another possible reason for the observed difference in performance is that Haegeli, Falk and Klassen (2012) produced a single model that included information from all concurrent avalanche problems and did not create separate models for different combinations of avalanche problems. Furthermore, the analysis of Haegeli, Falk and Klassen (2012) included contribution as an additional variable that describes the importance of problems for the danger rating assignment. This variable was not available for the dataset used in the present study.

## 5.4. Operational insights and potential for decision aid development for avalanche forecasting

The results of this study provide useful insights into how the CMAH has been applied in hazard assessments for public avalanche bulletins by avalanche forecasters. One of the objectives of the introduction of the CMAH was to standardize the workflow, streamline the bulletin production process, and make avalanche bulletins more consistent (Statham, Haegeli et al., 2018). While my analyses were able to identify meaningful relationships between the danger ratings and the components of the CMAH, my models indicate that there is substantial variability in the present danger rating dataset that cannot be accounted for by the components of the CMAH. This is evident by the relatively low performance indicators of the models and the broad distributions of danger ratings displayed in the pie charts on the hazard chart visualizations. This means that avalanche forecasters assign a wide range of danger ratings to hazard situations that are the same with respect to avalanche problem type, typical likelihood of avalanches, typical destructive size, elevation band, aspect, mountain range and agency. While it is possible that additional hazard factors not included in the CMAH are partially responsible for the observed unexplained variability, the most likely source is inconsistency between and within avalanche forecasters. This result confirms concerns around avalanche bulletin consistencies that have been raised by other recent studies including Lazar et al. (2016), Techel et al. (2018), and Statham, Holezi and Shandro (2018). This means that the lack of an explicit link between the avalanche danger scale and the CMAH is a substantial stumbling block for producing consistent avalanche danger ratings.

While forecaster training is one way to address this inconsistency, decision aids that automatically combine the CMAH attributes that a forecaster enters into *AvalX* and produce a danger rating or distribution of danger ratings have great promise to improve avalanche bulletin consistency (Statham, Holeczi, & Shandro, 2018). While forecasters might be resistant to completely delegate the danger rating assignment to a computer program, the output of a decision aid could offer a useful starting point or independent reference for a human forecaster, especially during tricky hazard situations. Since the relationship between avalanche problems and danger ratings is multidimensional and complex, a data-driven design approach is preferred over an expert opinion driven approach (Statham, Haegeli et al., 2018). Examining the potential of the existing hazard assessment dataset for the design of meaningful decision aids was therefore one of the primary motivations for the present study. While my analysis was able to identify key patterns in avalanche hazard assessments, the remaining unexplained variability seems too large to directly derive a meaningful decision tool from my research. A decision tool developed from the existing dataset might only reinforce and perpetuate the existing biases and inconsistencies. However, the present research represents the first quantitative insight into the complex relationship between avalanche problems and the avalanche danger scale. The models and visualizations presented in this study can provide avalanche forecasters with new ways for exploring their past hazard assessments in a comprehensive way and starting a meaningful, evidence-based discussion about what danger ratings should be associated with different types of conditions. Examples of critical questions that forecasters might need to discuss include *'Does it make sense that each avalanche problem type has different rules for assigning danger ratings?'* or *'Should the overall danger rating be heightened with an increase in elevation band?'*. The resulting guidelines could then be implemented in a decision aid directly in *AvalX*. So, instead of having a purely data-driven approach to the design of this decision aid, the decision aid would be based on data-informed expert opinion.

## 5.5. Limitations

While the present analysis offers meaningful first insights into the relationship between the components of the CMAH and the avalanche danger scale, several limitations need to be considered when interpreting the results. For instance, meaningful CIT models could only be created for avalanche problems and problem combinations with a sufficiently large dataset. Overall, the models used to derive the main results—a) Master CIT model for single avalanche problems, b) CIT model for *Persistent slab and storm slab avalanche problem*, and c) *CIT model for Persistent slab and wind slab avalanche problem*—only represent 65% of the available hazard assessments with one or more avalanche problems. However, most of the avalanche problem situations that were not included in the analysis are relatively rare and do not have big enough datasets (i.e., less than 300 data points) to provide meaningful statistically significant insights. It is therefore inherently difficult to provide a truly comprehensive picture of the existing decision rules. While this issue could be addressed by developing an even bigger dataset, the additional information gain might only be incremental and of limited operational value.

Perhaps the biggest limitation in my analysis approach was the reduction of the avalanche problem hazard assessments to only the typical values of likelihood of avalanches and destructive size. The original value triplets (minimum, typical and maximum) for these parameters are an important component of the CMAH as they allow forecasters to represent uncertainty in the hazard assessment. By simplifying this aspect of the hazard characterization to just one parameter, information was lost that could potentially be responsible for some of the observed unexplained variability. While including the full value triplets in the CIT analysis could result in different splitting rules and might allow a finer grained interpretation of the connection of the CMAH to the danger rating scale, the resulting decision trees would likely become extremely difficult to describe and interpret. The applied objective of this research project and the desire to provide avalanche forecasters at Avalanche Canada and Parks Canada with interpretable results seemed valid reasons for justifying this simplification.

# Chapter 6. Conclusion

The purpose of this research was to explore the relationship between hazard assessments produced according to the conceptual model of avalanche hazard (CMAH; Statham et al. 2018) and the North American Public Avalanche Danger Scale (Statham et al., 2010). Using a dataset of 42,589 avalanche hazard assessments included in public avalanche bulletins produced by Avalanche Canada and Parks Canada from 2012 to 2018, I employed conditional inference trees (CIT; Hothorn, Hornik & Zeileis, 2006) to examine how the CMAH parameters used to describe the location and nature of avalanche problems—forecasting agency, mountain range, avalanche problem type, elevation band, aspect, likelihood of avalanches and destructive size—relate to avalanche danger ratings. I chose decision trees for the analysis because of their ability to model complex non-linear relationships and simultaneously produce tangible and easy to interpret insight into the underlying decision rules. Furthermore, I selected the CIT over the traditional CART methodology (Breiman et al., 1998) because of its grounding in statistical significance testing, which produces unbiased splits and trees that do not require pruning.

I first used hazard assessments with only one avalanche problem to derive a single CIT model for all avalanche problem types. The model included the typical values of likelihood of avalanches and destructive size representing the core components of the CMAH as well as elevation band, mountain range, forecast agency and a binary representation of aspect. I then extracted the splitting rules from the CIT model and plotted the results for specific scenarios onto hazard charts for a more tangible and easy to understand visualization. I subsequently built separate CIT models for two of the most frequent avalanche problem combinations—*Persistent and storm slab avalanche problems* and *Persistent and wind slab avalanche problem* combinations—to assess how having multiple avalanche problems present simultaneously affects the decision rules.

Results of the CIT analyses revealed both expected and surprising patterns. Likelihood of avalanches and destructive size, the two key contributors to avalanche hazard, influenced avalanche danger as expected. Avalanche danger ratings generally increased with increasing likelihood of avalanches and destructive size, and higher danger ratings were more prevalent in scenarios in the top right corner of the hazard chart, whereas lower ratings were assigned most commonly towards the bottom left corner. A more surprising result was that avalanche danger ratings depend on avalanche problem type and location in the terrain. Avalanche problem type was the first and therefore statistically most significant split in the CIT model for single avalanche problems. First, the model separated *Storm slab avalanche problems* from all other avalanche problem types. Further down on the tree, *Wet loose avalanche problems* and *Dry loose avalanche problems* were separated from *Deep persistent slab avalanche problems*, *Persistent slab avalanche problems* and *Wind slab avalanche problems*. This was surprising as it highlights that identical combinations of likelihood of avalanches and destructive size were not assessed the same for every avalanche problem type. Furthermore, I found that the danger ratings for different avalanche problem types were more sensitive to changes in either typical likelihood of avalanches or typical destructive size. While destructive size was the more influential contributor for *Storm slab avalanche problems*, likelihood of avalanches was more dominant for *Deep persistent slab avalanche problems*, *Persistent slab avalanche problems* and *Wind slab avalanche problems*. Another surprising result of my analysis of single avalanche problem situations was that elevation band emerged as a key parameter affecting avalanche danger ratings. Identical combinations of likelihood of avalanches and destructive size were consistently assessed more serious in the alpine than at treeline or below. In comparison, forecasting agency, aspect and mountain range seemed to have little effect on danger ratings.

My analysis of multiple avalanche problem situations offered additional insight on how decision rules change when additional avalanche problems are present. As expected, my findings show that avalanche danger ratings were generally higher when multiple avalanche problems are present. While likelihood of avalanches and destructive size remained the main drivers for the avalanche danger rating, the number and locations of splitting rules changed. I also found that one avalanche problem type typically influenced the danger rating assignment considerably more than the other. For *Persistent and storm slab avalanche problem combinations*, for example, the *Storm slab avalanche problem* influenced the danger rating assignment more than the *Persistent slab avalanche problem*.

Despite the CIT models extracting meaningful relationships, the relatively low performance measures of the models highlighted a substantial amount of variability in the dataset that cannot be explained with the CMAH. While some of this variability is likely due to simplifications in the model specification (e.g., only using typical values for likelihood of avalanches and destructive size) and hazard related factors not captured in the CMAH, inconsistencies between individual forecasters is another likely source. This interpretation is consistent with other recent research that has highlighted inconsistencies in avalanche hazard assessments (e.g. Lazar et al. 2016; Statham, Holezi & Shandro 2018; Techel et al. 2018). This means that the introduction of the CMAH only partially succeeded in making avalanche bulletins more consistent. While the framework has added structure to the forecasting process and facilitates more consistent documentation, the lack of an explicit link between the components of the CMAH and the North American Avalanche Danger Scale leaves the system vulnerable to forecaster interpretation and human bias.

While my results do not seem to provide sufficient insight for the direct development of an operational decision aid to address this issue, the derived models do create new opportunities for avalanche forecasters to critically review their forecasting practices. The identified decision rules can be used to illustrate how the CMAH has been used in the past and to explicitly highlight inconsistencies or challenges. This was not possible prior to the introduction of the CMAH framework. A more explicit examination of differences among forecasters might offer additional opportunities that allow individual forecasters to better understand their approach to the hazard assessment process and shine light on potential sources of inconsistencies or bias. Overall, this will improve the understanding of the connection between avalanche problems and avalanche danger ratings to create a platform for an informed discussion about what ratings should be associated with what conditions. These rules can eventually be incorporated into a formal decision aid to improve consistency in avalanche danger ratings in the long-term.

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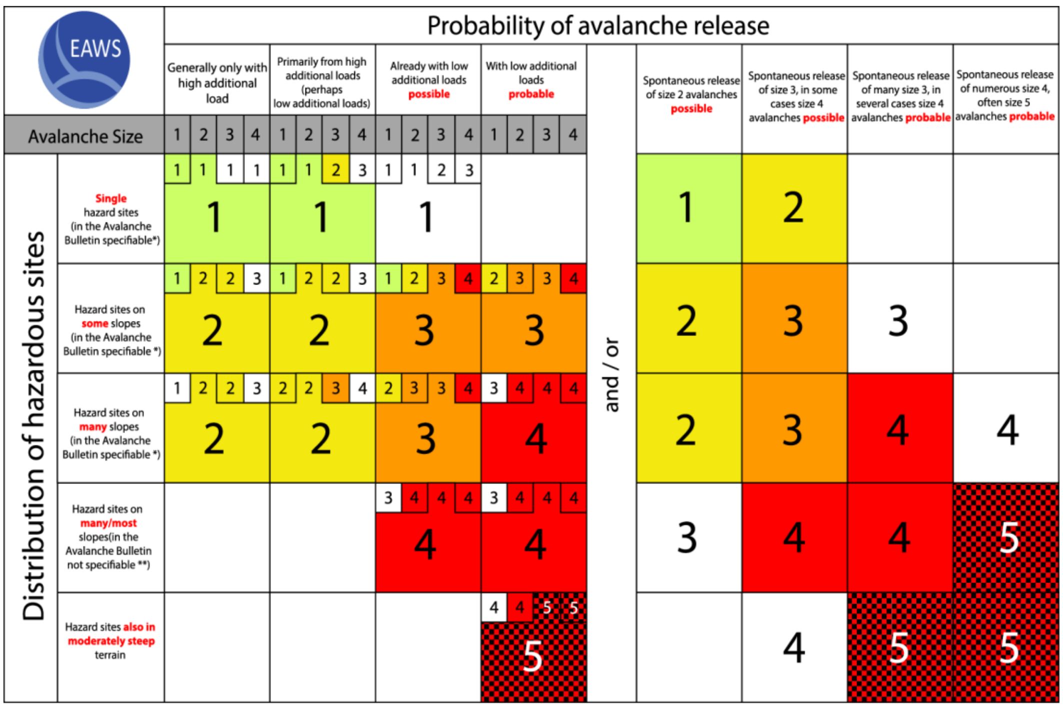
# Appendix A.

# Bavarian Matrix




* specifiable with respect to altitude, exposition and/or relief

** The hazard sites are too numerous or too diffusely distributed to be specifiable with respect to altitude, exposition and/or relief

**Figure A1: The Bavarian Matrix used for assigning avalanche danger ratings in Europe based on the distribution of hazardous sites and the probability of avalanche release.**

## Appendix B.

## Single Avalanche Problem Decision Trees

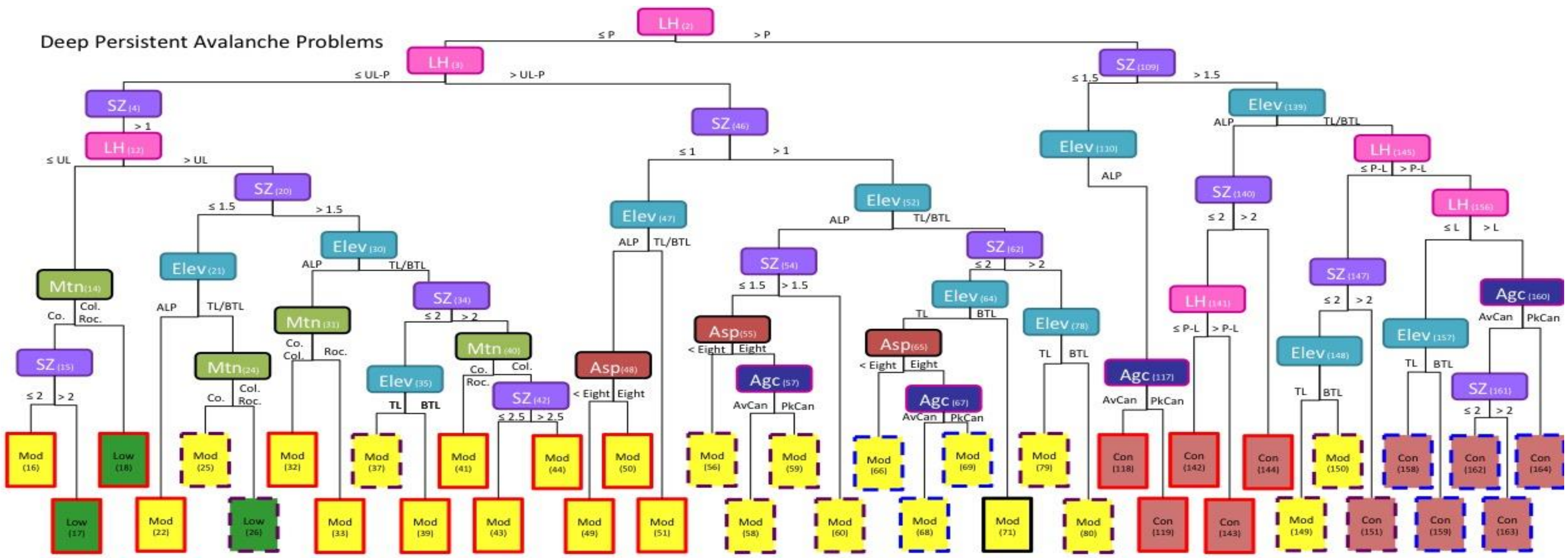


Figure B1: Deep persistent slab avalanche problem section of the single avalanche problem CIT mode describing the decision rules and corresponding terminal nodes based on the most common danger ratings assigned based on those rules. Red outlined terminal nodes are shared between Persistent slab, Deep persistent slab and Wind slab avalanche problems, blue dashed outlined terminal nodes are shared Persistent and Deep persistent slab problems, and purple dashed outlined terminal nodes are shared between Wind and Deep Persistent slab problems while black outlined terminal nodes are unique to Deep persistent slab avalanche problems.

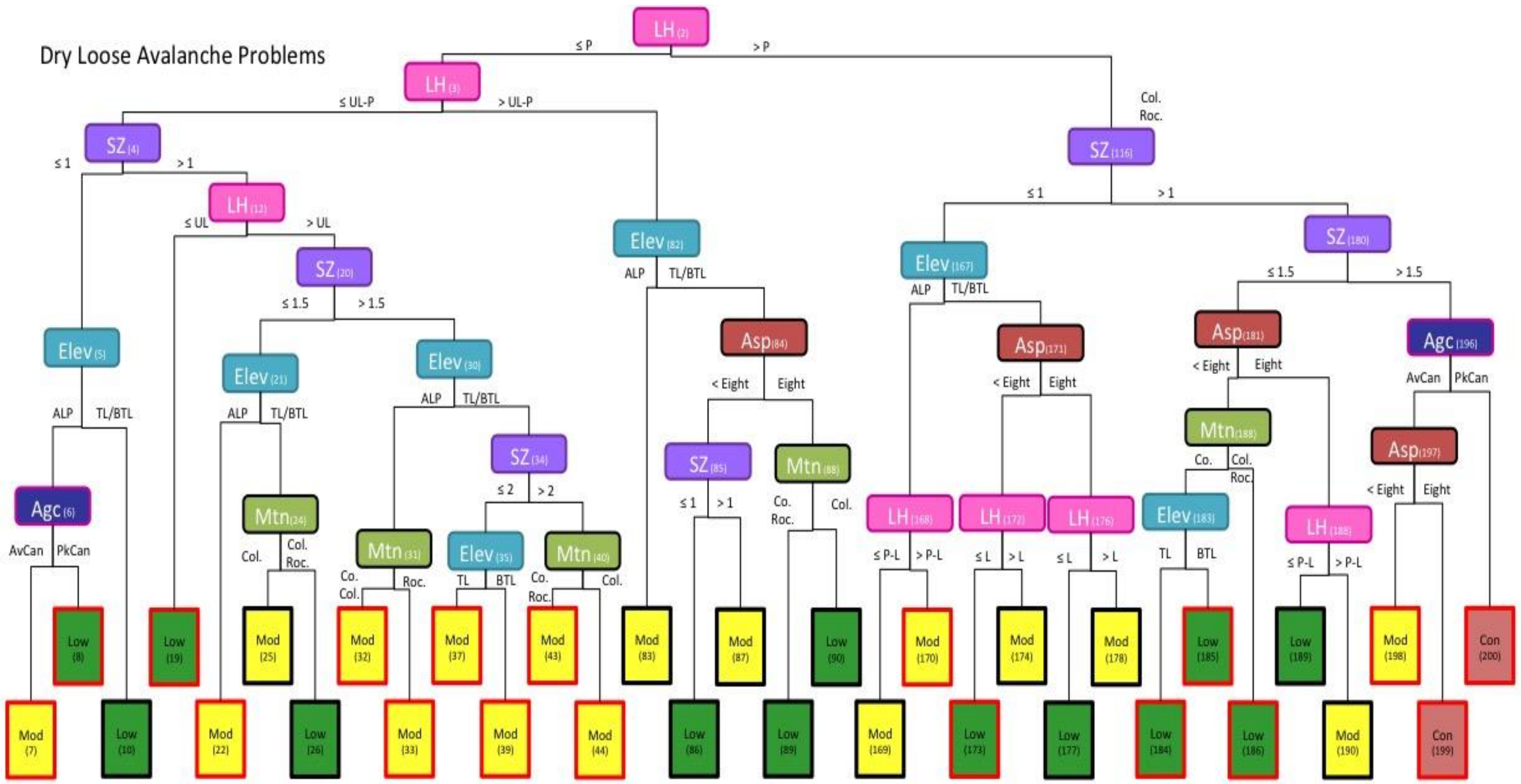



**Figure B2:** Dry loose avalanche problem section of the single avalanche problem CIT model describing the decision rules and corresponding terminal nodes based on the most common danger rating assigned based on those rules. Red outlined termianl nodes are shared between Dry loose and Wet loose avalanche problems while black outlined termianl nodes are unique to Dry loose avalanche problems.

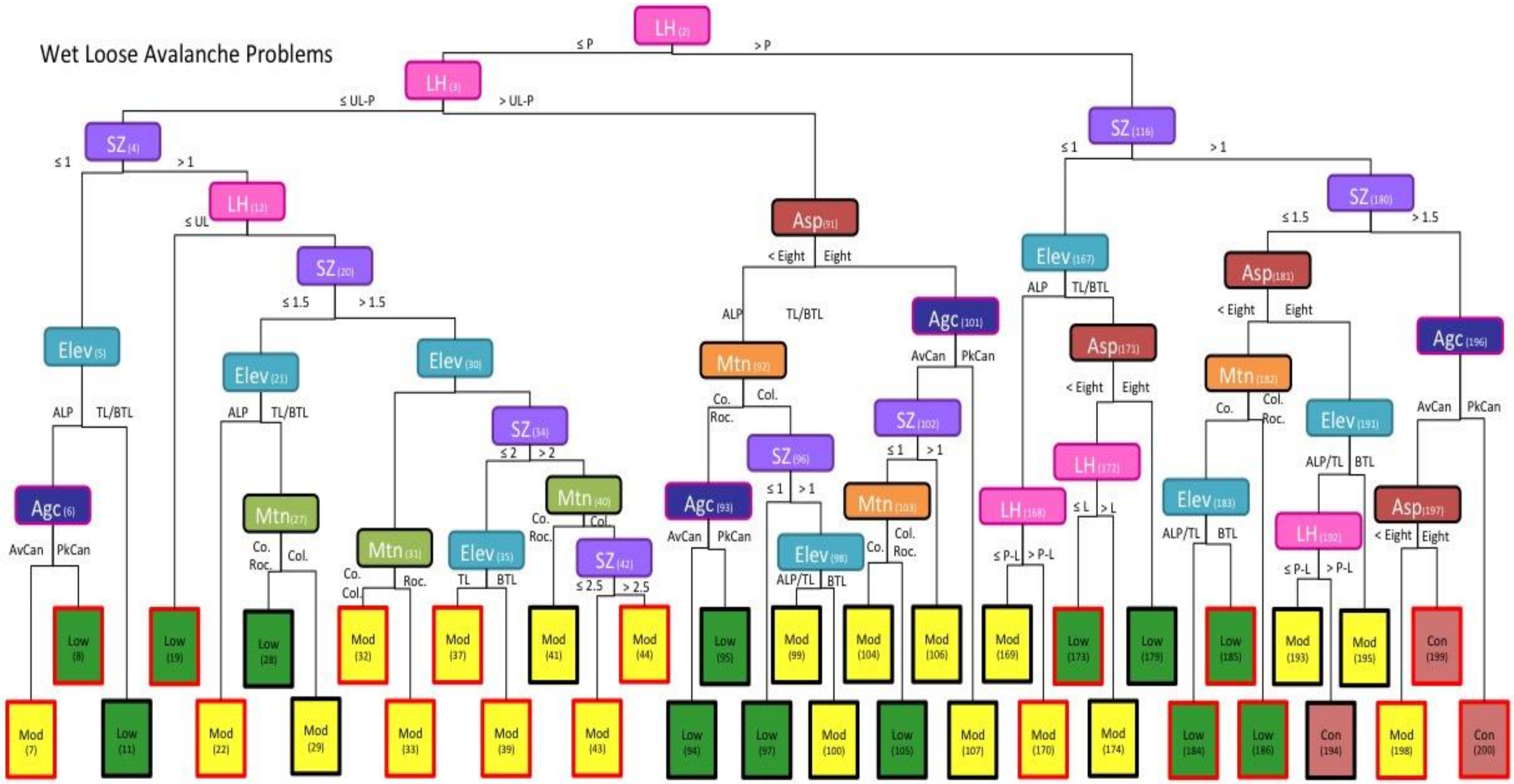



**Figure B3:** Wet loose avalanche problem section of the single avalanche problem CIT model describing the decision rules and corresponding terminal nodes based on the most common danger rating assigned based on those rules. Red outlined termianl nodes are shared between Wet loose and Dry loose avalanche problems while black outlined termianl nodes are unique to Wet loose avalanche problems.