50 SHADES OF BLUE: RISK GRADIENTS WITHIN AVALANCHE HAZARD ZONES

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ABSTRACT: Avalanche hazard zone maps for occupied structures in North America and Europe are typically based on a combination of avalanche frequency and impact pressure, and land-use decisions are often based solely on the hazard zoning. However, there is an emerging recognition by practitioners that because (by definition) avalanche magnitude and frequency can vary widely within each hazard zone, overly restrictive land-use decisions or mitigation prescriptions are possible when regulation follows the zoning. As the vulnerability of structures and people depend strongly on impact pressure, we would expect the risk to vary widely across the hazard zones, and on that basis, it is unlikely that optimal land-use and mitigation regulation can span a hazard zone uniformly. In this paper, we explore the limitations of hazard zone maps through a case study by comparing a hazard zone map to a risk index map. We discuss possible applications of risk index maps to land-use regulation in place of or alongside hazard zone maps. To do this, we borrow concepts and techniques developed for other rapid slope geohazards such as landslides. Our results in this case study show that, for the most part, similar land-use decisions would have been made with either approach, but there are some meaningful differences. The risk index maps identify where land-use planning decisions may be overly conservative if based on hazard criteria alone. An exploration of the risk gradients within the hazard zones can be a valuable tool for practitioners and land-use regulators to manage avalanche risk in an efficient and optimal way.

KEYWORDS: Risk, hazard, zoning, mapping, land use.

1. INTRODUCTION

Avalanche hazard zone maps for occupied structures in North America and Europe are often based on a combination of avalanche frequency and impact pressure. In Canada, three zones representing high (Red), moderate (Blue), and low (White) hazard are typically used (CAA, 2016). Important land-use decisions are made by regulators, such as prohibiting or allowing development (with or without conditions) based on which hazard zone a property is in. While the hazard zoning approach is implicitly risk-based since impact pressure relates to consequence, it does not explicitly estimate the potential for damage to structures or chance of death in each zone, nor does it cumulate losses from multiple scenarios, and as such there is no direct estimation of risk.

Risk-based or risk-informed approaches to land-use regulation and decision-making have the advantage of allowing the user to compare risk from avalanches to risks from other geohazards and unrelated hazards (e.g. traffic collisions). Such an approach also aids in cost-benefit analysis of measures to reduce the risk, as well as presenting a more comprehensive summation of all the ways that a specific consequence could arise.

The motivation for this paper is an emerging recognition by practitioners that because (by definition) avalanche magnitude and frequency can vary widely within each hazard zone, overly restrictive land use decisions or mitigation prescriptions are possible when regulation follows the zoning. This is evident within the Canadian Blue Zone, where impact pressures are between 29 kPa and 1 kPa and avalanche frequency is between 1:30 years and 1:300 years. As the vulnerability of structures and people depend strongly on impact pressure, we would expect the risk to vary widely across the hazard zone, and on that basis, it is unlikely that optimal land-use and mitigation regulation can span a hazard zone uniformly.

We explore these limitations of hazard zone maps by developing corresponding risk index maps and making comparisons between the two, with a discussion of possible applications of risk index maps to land-use regulation in place of, or along with hazard zone maps. To do this, we borrow concepts and techniques developed for landslide hazard and risk mapping.

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2. BACKGROUND

2.1 *Hazard Zone Maps*

Avalanche hazard zone maps in Canada follow a frequency and magnitude classification system, where magnitude is expressed as impact pressure (CAA, 2016; Figure 1).

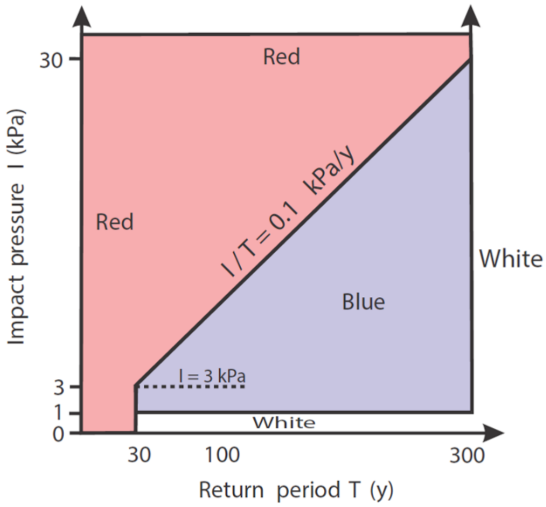

Figure 1: Hazard zones for occupied structures in Canada. (CAA, 2016).

In theory, this system uses a "highest hazard" approach, where many frequency-magnitude (F-M) pairs (or return period - impact pressure pairs) are evaluated at any location on the map, and the zone is based on the highest rated credible pair. LeSueur et al. (2024) describe this as one of several approaches to landslide hazard mapping.

In practice, however, often the largest magnitude event (i.e. 300-year event for avalanche hazard zone mapping) is assumed to control the hazard in the runout zone and forms the basis for the hazard map (McClung, 2005). This is known as "hazard intensity" mapping, where intensity (magnitude) is mapped for a fixed return period (LeSueur et al., 2024). This is done because avalanche hazard assessments in Canada are almost always data-sparse (as opposed to some European nations that may have a long record of avalanche occurrences), so it can be difficult to differentiate between 30- and 100-year, or 100- and 300-year return period scenarios (McClung, 2005; Jamieson and Campbell, 2018).

McClung (2005) used principles of risk to compare hazard zone definitions for Switzerland, Austria, and Canada. The focus was on zone boundaries and providing the mathematical framework to make the comparison in risk terms. He notes that the hazard zones are implicitly risk-based, as avalanche probability and vulnerability of structures would scale with return period and impact pressure, both of which define the hazard zones. Thus, there is an implicit vulnerability and risk tolerance using these hazard classification systems. Other studies have made the case for regional risk assessment as an important land-use planning tool (e.g. Ortner et al, 2023), and directly as a zoning tool (Arnalds et al., 2004).

2.2 *Risk Index Maps*

The purpose of a risk index map is to show how the probability of some loss could vary from place to place. For this paper, risk is expressed as the probability of death of an individual inside a non-reinforced single-family dwelling due to impact by avalanche. The probability of loss is hypothetical for areas where there are no elements at risk, and thus it is a 'risk index' rather than a true estimate of risk. This allows risk index maps to be used for land-use planning where new development may be proposed.

Risk index maps may be developed using a single F-M pair; however, it is preferable to estimate risk from several hazard scenarios and present the sum or total risk.

Strouth and McDougall (2022) have advocated for the use of 'micromorts' as the fundamental unit for communicating life safety risk. One micromort is equal to a probability of death of 1 x 10^{-6} (i.e. one-in-a-million). Estimating risk in micromorts makes interpreting the values and variations more natural, without reducing the precision of the risk estimate. Since avalanche frequency is expressed in years, the risk maps we present in this paper use the unit of micromort per year.

3. METHODS

In this paper we present a worked example of the development of a hazard zone map and a corresponding risk index map. The worked example is hypothetical but is based on a real location with realistic inputs.

We modelled four avalanche F-M scenarios, expressed by return periods of 10-, 30-, 100- and 300-years, using RAMMS (Christen et al., 2010). We did not reinterpret the model results, and only dense flow was considered for simplicity. In practice, the powder component and additional data (e.g. additional models, field evidence) would be considered in determining the hazard zones. Comparison of the hazard zone and risk index maps can be achieved without consideration of these factors. Because these maps only represent model outputs to compare the two methods, we emphasize that they would not be considered sufficient to serve as maps used to make land-use decisions.

We developed the hazard zone map using the "highest hazard" method (i.e. considering each of the four F-M scenarios) and the Canadian zoning system (CAA, 2016) (Figure 2a).

To develop the risk index map, we compute risk index (in micromorts per year) across the map for each of the four F-M scenarios. The probability of loss for each raster cell is estimated using a vulnerability function from Arnalds et al. (2004) for wood-frame residences assuming an individual was always home (i.e. temporal exposure is 1). The vulnerability is dependent on avalanche velocity, which is derived from the RAMMS output at each cell for each scenario. We ignore the encounter probability calculation as McClung (2005) argued for, as this sort of risk analysis is essentially an expected value calculation, in which case the average return period is the appropriate parameter. These simplifications reduce the risk calculation for each scenario to the product of annual frequency and vulnerability factor at each raster cell. Finally, the incremental risk calculated for each scenario is summed at each raster cell to produce the risk index map.

We categorized the output to a four-level risk classification (Table 1) so the risk map can be more easily compared with the hazard map. A risk of 100 micromorts per year (or an annual probability of death of 1 x 10^{-4}, or one-in-ten thousand) is a common risk-tolerance threshold for landslides adopted by some Canadian jurisdictions (e.g. District of North Vancouver, Town of Canmore). A risk below 1 micromort per year is often considered acceptable without mitigation (Strouth and McDougall, 2022).

Table 1. Risk classification system.

Risk Class	Risk Index (Micromorts /Year)	Comparable Annual Risk of Fatality (after Strouth and McDougall, 2022)
Very High	> 1,000	40^{th} year of life in USA (2,000)
High	100-1,000	Traffic collision (100)
Moderate	10-100	General anesthesia, per instance (10)
Low	< 10	Drowning in bathtub (1)

4. RESULTS

Figure 2 shows the a) hazard zone map, and b) risk index map for the lower track and runout zone of the hypothetical avalanche path we analyzed. The Red, Blue, and White hazard zones are symbolized following the CAA (2016) hazard classification scheme, and the risk classes correspond to Table 1. The raster layer that forms the basis for the hazard zone and risk index maps has a 3 m by 3 m resolution (approximately 36,000 cells).

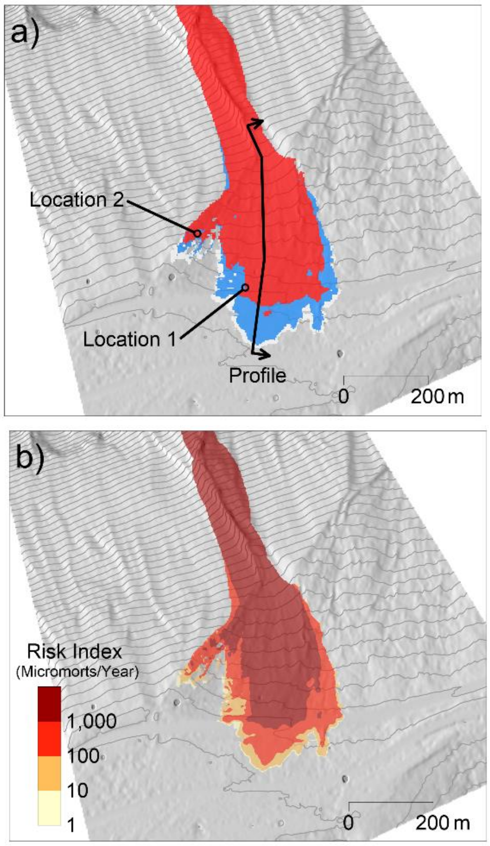

Figure 2. a) Hazard zone map and b) risk index map for the hypothetical avalanche path. See Figure 3 and 4 for details

Both mapping methods identify the same total hazard extents as they are derived from the same RAMMS outputs; however, the land-use implications may differ depending on the type of map used, hazard or risk zone definition and related land-use policies.

A comparison of the hazard zone map to the risk index map illustrates unique cases to consider in the CAA (2016) hazard classification scheme. Figure 2a shows a reference profile through the runout zone along with two reference locations (Location 1 and 2).

4.1 High Frequency, Low Risk

Locations 1 and 2 are both located near the Red/Blue Zone boundary. According to the CAA (2016) classification criteria, Location 1 is within the Blue Zone, while Location 2 is within the Red Zone, as shown in Figure 3. However, based on the risk index calculations, Location 1 is approximately twice as risky as Location 2 (800 vs. 400 micromorts per year).

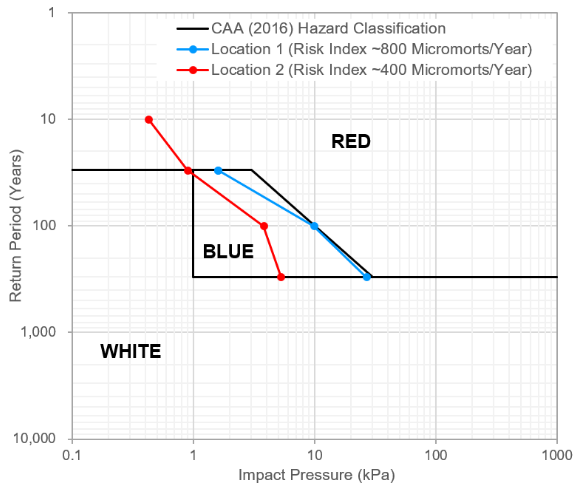

Figure 3: Hazard curves for Locations 1 and 2 (Figure 2a) plotted in a log-log F-M space along with the CAA (2016) zoning definitions. Each node of the hazard curves corresponds to an individual hazard scenario (10-, 30-, 100-, and 300-year).

Location 2 is classified in the Red Zone because it is within the runout of the 10-year avalanche scenario, even though the F-M relationships of the longer return period scenarios are within the Blue Zone definitions (Figure 3). Location 1 is downslope of the 10-year runout and does not meet the Red Zone criteria for the 30-, 100-, and 300-year scenarios; however, the impact pressures from these longer return period events are larger than from those same events at Location 2 (Figure 3). Therefore, the risk is higher at Location 1.

This highlights the fact that that the Red Zone hazard space defined by return periods less than 30-years, regardless of impact pressure, could be considered conservative when impact pressures are very low (e.g. < 3 kPa) and may include locations that are less risky than other locations that meet Blue Zone criteria.

This situation is partially addressed in the Swiss hazard zoning system, which allows areas subject to powder flow impacts with return periods of less than 30 years and impact pressures less than 3 kPa to be designated as Blue Zone; however, dense flow impacts with return periods less than 30 years remain in the Red Zone regardless of impact pressure (Switzerland, 1984). This highlights the implicit intolerance in the hazard zone definitions to high frequency (return period <30 years) avalanches. While it is logical to avoid construction in areas with frequent avalanche activity since avalanches with low impact pressures can be hazardous to people outside of buildings, this particular zoning criteria does not consider impact pressure, and therefore includes areas of relatively low risk in the Red Zone.

4.2 Highest Hazard vs. Hazard Intensity

Incremental and total risk along the profile in Figure 2a is shown in Figure 4. Frequent avalanche scenarios control the risk in the upper areas of the profile, while the long-return period events (30-, 100-, and 300-year) control the risk in the lower profile. Rapid flow deceleration of the long-return period scenarios in the lower runout zone causes a rapid decrease in risk towards the end of the profile. The 300-year avalanche becomes the highest risk scenario near the Red/Blue Zone boundary. This suggests that for locations far into the runout zone, a single magnitude hazard intensity approach (i.e. considering only the 300-year event) may be sufficient, as described by McClung (2005). However, for assessing hazard and risk higher in the runout zone, such as in the Red and upper Blue Zone, it shows that a single magnitude approach could underestimate hazard and risk.

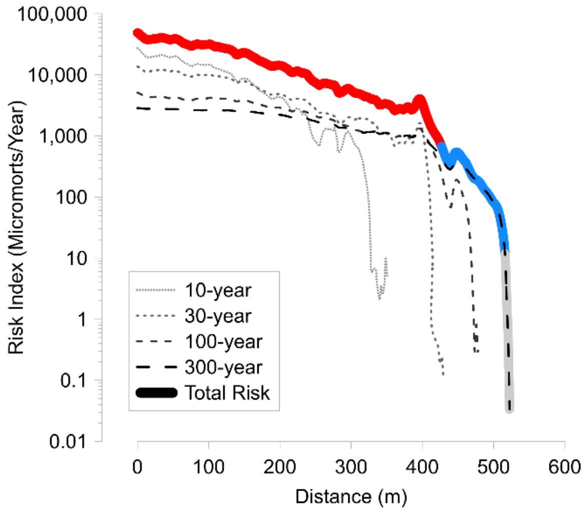

Figure 1: Incremental and total risk along profile shown in Figure 2a. Incremental risk is the risk contributed by the 10-, 30-, 100-, and 300-year return periods while total risk is the sum of all risks. The total risk line is coloured by the CAA (2016) hazard classification along the profile.

4.3 Risk Variability in the Hazard Zones

The CAA (2016) zone definition for the Blue Zone ranges in impact pressure from 29 kPa to 1 kPa. In this example, that relates to a variation in risk of two orders of magnitude (~1000 to ~10 micromorts per year) over a short horizontal distance of ~100 m (Figure 4).

By comparing the CAA (2016) hazard classification for each grid cell to the computed risk index (Figure 5), we see that the inter-quartile ranges of the risk index are aligned with the hazard zones. However, there is a wide range of risk values represented in each hazard zone across the model domain. Including outliers, the Red Zone includes grid cells with risk index values between approximately 1 and 100,000 micromorts per year, which spans tolerable to intolerable risk. The Blue Zone has a tighter distribution, but still spans two orders of magnitude in risk index.

Because risk varies by orders of magnitude across the Blue Zone, managing avalanche risk on either end of the zone may require mitigation efforts that also vary by orders of magnitude. This suggests that uniform land-use policy across the Blue Zone may inconsistently manage avalanche risk, with the potential for being under conservative at the Red/Blue Zone boundary and over conservative at the Blue/White Zone boundary.

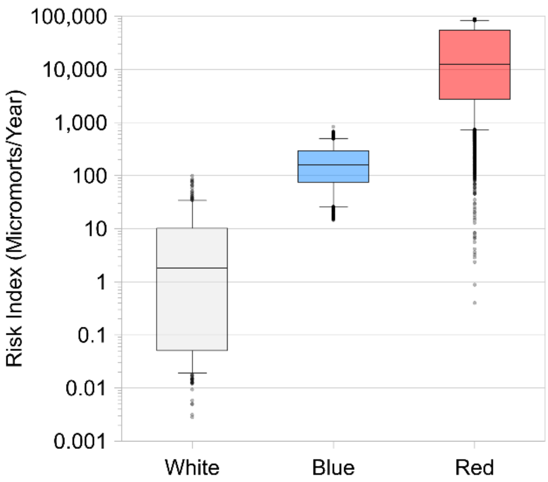

Figure 5: Box-and-whisker plot of the risk index distribution for each of the White (n = 931), Blue (n = 2,896), and Red (n = 31, 972) Zones across the model domain. Boxes represent the inter-quartile range, bisected by a line representing the median value; whiskers reach the 5th and 95th percentiles, and outliers are indicated by points.

4.4 Hazard Zones and Risk Tolerance Thresholds

When overlaying incremental risk isolines from a 300-year avalanche on the CAA (2016) hazard classification, 100 micromorts per year (a common tolerable risk threshold as long as it is mitigated to a level as low as reasonably practicable) runs through the middle of the Blue Zone (Figure 6). Furthermore, if using just the 300-year return period scenario as a hazard zoning tool, the Blue Zone spans a risk of 14 to 433 micromorts (Figure 6). While these risk index values only represent incremental risk contributed from one F-M scenario (300-year in this case) and are sensitive to other assumptions (e.g. vulnerability function), this again points to the possibility that uniform land-use policy across the Blue Zone may be inefficient for managing avalanche risk.

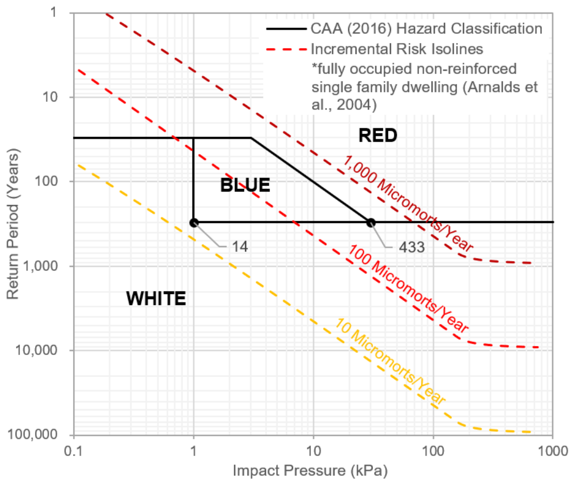

Figure 6: Risk isolines for a 300-year avalanche scenario plotted on the CAA (2016) hazard classification. Incremental risk isolines show the risk from a single avalanche scenario and is calculated by setting a constant risk level and computing the associated scenario pairs. We have labelled the incremental risk level at the Red/Blue and Blue/White Zone boundaries for the 300-year avalanche scenario for reference.

5. DISCUSSION

Broadly speaking, the hazard zone and risk index maps are similar, and the inter-quartile ranges of the risk index are aligned with the hazard zones (Figure 5). However, this case study shows that risk index estimates vary by several orders of magnitude across the hazard zones. This suggests that while in many cases we could expect the hazard zone map to be sufficient for land-use decisions, there are some meaningful differences.

The risk profile varies along the avalanche flow path and is governed by the higher frequency scenarios in the upper part of the runout zone, transitioning to the lower frequency/higher magnitude scenarios further along the path (Figure 4). This illustrates the importance of considering scenarios of multiple magnitudes (i.e. F-M pairs) to accurately quantify hazard and risk. However, in our example, the 300-year event became the highest hazard near the Red/Blue Zone boundary. This suggests that a hazard intensity mapping approach might be sufficient when producing zone maps according to CAA (2016).

Considering the hazard curves in Figure 3, it seems that the hazard zoning scheme may not consistently zone locations by risk. In such cases, the risk index may provide useful information for land-use planning. For example, in the case of high frequency-low magnitude events (< 30 years and < 3 kPa), the risk index suggests that these locations may be a better fit in the Blue Zone.

Also, the Blue Zone appears to span a common risk tolerance threshold for other slope geohazards (100 micromorts per year), which suggests that development may not be tolerable in the upper area of the Blue Zone, while it may be quite tolerable in the lower Blue Zone.

Our exploration of the hazard and risk maps has demonstrated that risk index maps illuminate specific scenarios where the current zoning methods span orders of magnitude of risk or results in classifications with inconsistent risk. Risk allows us to combine the scenarios in a meaningful way and understand the locations where the highest losses overtime from all scenarios, are expected. Given that most hazard assessments in practice are conducted using computer models which output raster map products, the extra effort to produce a risk index map is minimal, especially compared to the potential upside of viewing the problem from the risk perspective.

However, some disadvantages are that risk-based approaches require additional parameters to be estimated which may contribute additional uncertainty to the analysis, and development and communication of risk tolerance criteria can be challenging.

It is not entirely clear how a regulator might make use of a risk index map until risk-based tolerance criteria for avalanches are developed. However, regulators will benefit from the same insights and, perhaps most importantly, how risk tolerance criteria and thresholds in use for other geohazards such as landslides relate to the typical avalanche hazard criteria.

6. CONCLUSION AND FURTHER WORK

Our original motivation for this work was a sense that there were '50 shades of blue' in the Canadian avalanche hazard zoning scheme, and that better land-use decisions could be made by analyzing the zones at a more granular level. We approached this analysis using risk, since this best relates to the objectives of regulators (i.e. public safety).

Our analysis shows that for this hypothetical case, the Red and Blue Zones are well-centered on risk index values that are broadly related to common risk tolerance thresholds, but also that there can be high variability in risk across the zone, and significant overlap in risk index between the zones.

This work applies previous studies that incorporate risk into land-use maps for landslides (Strouth and McDougall, 2022) and using vulnerability functions for avalanches (Arnalds et al. 2004). Further work is required to determine if such conclusions apply at other sites. Some thoughts for further work needed to improve the quality of risk index maps include:

- Continued research for the development of fragility/vulnerability curves for avalanche impacts to a variety of structures, which could consider additional parameters such as flow depth.
- Comparison of the risk index method to the hazard zoning method considering additional data (e.g. powder avalanche flow, using additional models, interpretation of field evidence).
- Case studies comparing the risk index method to existing hazard zone maps.
- Drafting of best-practices guidelines for conducting risk calculations as part of hazard assessments for land-use, which could include the form of impact pressure or velocity raster outputs of modelling software like RAMMS.
- For future updates to the Canadian hazard zonation scheme, include discussion of the variability of hazard and risk in the Blue Zone with guidance on how a consistent risk target may be achieved (e.g. site-specific risk assessments).

As McClung (2005) points out, the Canadian hazard zone definitions can be re-cast into risk terms, albeit with some assumptions around probabilities and vulnerability. Nonetheless, a deeper exploration of the risk gradients within the hazard zones is a useful tool for practitioners and land-use regulators to manage avalanche risk in an efficient and optimal way.

7. ACKNOWLEDGEMENT

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