Can we quantitatively assess the snow avalanche risk to backcountry workers?

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ABSTRACT
This paper outlines methods for analyzing snow avalanche risk to workers in start zones and in runout zones. For runout zones, quantitative methods based on the Canadian landslide guidelines are useful but do not consider the daily avalanche hazard. For start zones, a quantitative method is outlined that includes the daily avalanche hazard but omits terrain characteristics. These quantitative methods are compared to a qualitative method for runout and start zones that includes the daily avalanche hazard and a proven terrain classification.

RESUME
Cet article décrit les méthodes d'analyse du risque d'avalanche de neige pour les travailleurs dans les zones de déclenchement et dans les zones de dépôt. Pour les zones de dépôt, les méthodes quantitatives fondées sur les lignes directrices canadiennes sur les glissements de terrain sont utiles, mais ne tiennent pas compte du risque d'avalanche quotidien. Pour les zones de départ, une méthode quantitative est décrite qui inclut le risque d'avalanche quotidien mais omet les caractéristiques du terrain. Ces méthodes quantitatives sont comparées à une méthode qualitative pour les zones de déclenchement et de dépôt qui comprend le danger d'avalanche quotidien et une classification de terrain éprouvée.

1 INTRODUCTION

The ISO 31000 Risk Management Guidelines (Canadian Standards Association 2010) identifies risk assessment as the stage of risk management that precedes mitigation. Further, risk assessment consists of three stages: risk identification, risk analysis, and risk evaluation in which the results of analysis are compared to criteria to determine if a risk is acceptable or tolerable. This paper is about the risk analysis *methods* and not about the criteria to which the results of risk analysis can be compared. Applications of ISO 31000 to snow avalanche risk management (which includes risk assessment and hence risk analysis) are covered in Canadian Avalanche Association (2016).

This paper summarizes quantitative and qualitative risk analysis methods for backcountry workers during three types of exposure to snow avalanche terrain

- working at temporary worksites in avalanche runout zones (Section 2.1)
- traversing avalanche runout zones on a trail, road or fixed route (Section 2.2)
- travelling through avalanche start zones (Sections 3 and 4)

Some advantages of quantitative risk analyses (Jamieson and Conlan in press) include:

- Better comparisons with risk due to other hazards or activities.
- Can be used in evaluating whether a risk is acceptable due to established criteria (e.g. Finlay and Fell (1997) proposed 1 death per 10,000 worker-years as acceptable).
- Assumptions more likely to be stated clearly.

Some advantages of qualitative risk analyses (Jamieson and Conlan in press) include:

- Require few or no data.
- Easier, faster, less complex, and typically less costly.
- Expertise with probability and risk calculations not required..

In addition, factors that cannot be quantified but thought to be important can be included in a qualitative analysis. Specifically, the qualitative risk matrix in Gould and Campbell (2014) includes the daily avalanche hazard in the assessment for workers in avalanche terrain. For higher levels of the avalanche hazard and more severe avalanche terrain, workers are required to have higher levels of training or on-site guidance by a qualified person. Thus, their method both assesses and mitigates the avalanche risk to workers. This method is presented in Section 2 for comparisons with quantitative methods.

The quantitative methods in this paper are based on the Canadian landslide guidelines (Porter and Morgenstern 2013, Bobrowsky and Couture 2014). The risk of death for an individual exposed to a mass movement R_{ind} is calculated as

$$R_{Ind} = P_H \, P_{S:H} \, P_{T:S} \, V_{D:T} \qquad [1]$$

where P_H is the probability of the mass-movement hazard, in this case, the snow avalanche; $P_{S:H}$ is the probability that the avalanche reaches a specified location given that the avalanche occurs; $P_{T:S}$ is the temporal exposure, i.e. the probability that the individual is at the specified location when the avalanche reaches it; and $V_{D:T}$ is the vulnerability of the individual, i.e. the probability of death of the individual, given the impact. Eq. 1 is easily modified for situations in which multiple people are exposed (Porter and Morgenstern 2013, Jamieson and Gauthier in press).

Since many small snow avalanches are neither consistently observed nor recorded, the product $P_H\, P_{S:H}$ for avalanches large enough to threaten people or infrastructure is often easier to calculate than the component terms, P_H and $P_{S:H}$.

Each of the terms in Eq. 1 are random variables. In this paper and many analyses, calculations are based on the expected values (averages). Assuming the terms on the right side of Eq. 1 are independent, the expected value of risk is the product of the expected values of the terms. (See Jamieson and Gauthier (in press) for a Monte Carlo analysis of snow avalanche risk in which random variations in temporal exposure and vulnerability are simulated.)

Qualitative and quantitative analytical methods for workers in avalanche runout zones are outlined in Section 2, followed by methods for workers in start zones in Section 3.

2 WORKERS IN SNOW AVALANCHE RUNOUT ZONES

For workers in runout zones, Section 2.1 summarizes methods for workers at temporary worksites, including quantitative methods that require the hours of exposure be countable. Section 2 summarizes analytical methods for workers traversing runout zones along an established route.

2.1 Workers at temporary worksites in avalanche runout zones

Examples of temporary winter worksites in runout zones include surveying and harvesting infested timber.

Based on the exposure time of workers at temporary worksites in runout zones, the quantitative risk can be assessed based on Eq. 1. However, adjusting $P_H\, P_{S:H}$ for short-term variations in weather and snowpack (e.g. a local daily hazard rating) is currently impractical.

Fortunately, qualitative methods – many of which consider the daily avalanche hazard – exist (see Canadian Avalanche Association 2016, Section 9.5). For example, in Table 1, Gould and Campbell (2014) proposed a qualitative method for managing the exposure and hence risk of workers that includes a five-level local hazard rating (e.g. Statham et al. 2018) and three classes of avalanche terrain from Campbell and Gould (2013). Class 1 terrain includes avalanche runout zones where the return period for potentially injurious or fatal avalanches exceeds 10 years. Isolated small start zones incapable of producing injurious or fatal avalanches are also included in Class 1 Terrain.

2.2 Workers traversing one or more runout zones along a route, trail or road

For quantitative analysis according to Eq. 1, $P_{T:S}$ is the exposure time (Rheinberger et al. 2009) where avalanches with the specified return period are expected to reach. Eq. 1 applies to workers on foot or in vehicles since the vulnerability $V_{D:T}$ for both situations have been published (e.g. Jamieson and Gauthier in press). The product $P_H\, P_{S:H}$ (or its components P_H and $P_{S:H}$) need to be calculated separately for each runout zone traversed by the workers. (The long-term averages of these terms may be easier to calculate for snow avalanches than for landslides, since snow avalanches are much more frequent.) However, $P_H\, P_{S:H}$ varies strongly in the short term due to changes in weather and snowpack properties, which can be represented by levels of the daily local avalanche hazard (typically 5 levels) as determined by an avalanche forecaster. However, it is difficult or impractical to quantify $P_H\, P_{S:H}$ for the daily local avalanche hazard.

Semi-quantitative analytical methods, while not the focus of this paper, also exist. The AHI risk index (Schaerer, 1989) is based on non-probabilistic indices analogous to the terms $P_H\, P_{S:H}$, $P_{T:S}$ and $V_{D:T}$ on the right side of Eq. 1. Each of the components of the AHI risk index can take on values greater than one, and hence is not a probability. However, the resulting AHI index, is monotonically related to risk. It has been applied to people on trails that cross snow avalanche runout zones by Owens and Fitzharris (1989). However, as for the quantitative method outlined in the previous paragraph, it is difficult or impractical to include the daily avalanche hazard in the AHI risk index.

Table 1. Example of backcountry field trip planning matrix for non-avalanche workers (Gould and Campbell 2014).

Hazard rating (e.g. Statham et al. 2018)	Backcountry travel work requirements		
4, 5	Work plan approval	On-site guidance	On-site guidance
2, 3	Safety equipment, rescue training	Work plan approval	On-site guidance
1	Safety equipment, rescue training	Safety equipment, rescue training	Work plan approval
	Class 1	Class 2	Class 3
	Terrain exposure class (Campbell and Gould 2013).		

3 A QUANTITATIVE METHOD FOR WORKERS TRAVELLING IN AVALANCHE START ZONES

This section illustrates a quantitative method for assessing the avalanche risk to workers travelling through avalanche start zones. It is based on Jamieson et al. (2009) and has been applied to at least one work place, i.e. the ASARC avalanche research program at the University of Calgary from 2000 to 2014 (www.ucalgary.ca/asarc). Although terrain characteristics, including start zone area and slope angle, have an important effect on human-triggering (e.g. Munter 1991, p. 119, Haegeli 2010; McClung 2013, 2014), these factors are not considered in the following method.

When people are involved in avalanches in the backcountry, the individual, or someone in their travel group, usually triggers the avalanche that carries the individual downslope. Tremper (2008, p. 15) reports that over 90% of avalanche victims are killed in an avalanche triggered by the victim or one of the victim's backcountry companions. Hence, temporal exposure $P_{T:S}$ is not independent of the probability of the avalanche reaching the victim's location $P_H\ P_{S:H}$. Consequently, the expected values of the random variables cannot be multiplied as in Eq. 1.

This analysis for people in avalanche start zones follows Jamieson et al. (2009), who ignored the probability of being caught in a natural (spontaneous) avalanche or in an avalanche triggered by a travel companion. The resulting assumption that the individual is caught in a self-triggered avalanche is best suited to small groups and especially when only one person is travelling in the start zone at a time. Under this large assumption, $P_H\ P_{S:H}\ P_{T:S}$ in Eq. 1 is replaced by $P_{IMP,1}$, which is the probability of an individual being impacted while travelling in a single avalanche start zone. The probability of an individual being impacted, i.e. caught by an avalanche in a single start zone $P_{IMP,1}$ is the product of triggering probability P_{Trig} (which strongly depends on avalanche likelihood or hazard) and the conditional probability of being caught in the avalanche $P_{Caught|Trig}$.

For a single exposure to an avalanche start zone, the risk of death based on Eqs. 1 and 2, and the stated assumptions is

$$R_1 = P_{IMP,1}\ V_{D:T} \qquad [3]$$

Each person travelling up, down or across a start zone can be considered a Bernoulli (binomial) trial. The probability of a person not being caught in n exposures to a start zone is

$$P_{IMP,n} = (P_{IMP,1})^0\ (1-P_{IMP,1})^n \qquad [4]$$

The probability of a person getting caught at least once in n exposures is the encounter probability

$$En = 1 - (1 - P_{IMP,1})^n \qquad [5]$$

(e.g. McClung 1999). As noted in Jamieson and Conlan (in press), $n\ P_{IMP,1}$ is the first non-zero term in the McLaurin expansion of Eq. 5 so for small $n\ P_{IMP,1}$, roughly less than 0.03, the encounter probability can be approximated by $n\ P_{IMP,1}$.

If the exposures are independent, it does not matter if one individual is exposed n times (individual risk) or multiple people are exposed a total of n times (collective risk), although the latter situation is more relevant to teams of workers in the backcountry. Combining Equations 2, 3 and 5, the risk of at least one death in n independent exposures is

$$R_n = 1 - (1-P_{IMP,1})^n\ V_{D:T} \approx n\ P_{Trig}\ P_{Caught|Trig}\ V_{D:T} \qquad [6]$$

Based on human-triggered avalanches in Switzerland, Schweizer and Lütschg (2001) estimated that the probability of an individual being caught in an avalanche triggered by the individual $P_{Caught|Trig}$ averaged 0.4, although this likely varies with the snowpack conditions as well as the skill and experience of the individual (Jamieson and Jones 2016).

After adjusting for non-reporting of non-fatal avalanche involvements, Jamieson and Jones (2015) estimated the average probability of death to an individual $V_{D:T}$ for the reported distribution of potentially fatal avalanches that catch (impact) people in the backcountry to be 0.03.

The probability of an individual triggering a potentially fatal avalanche in a start zone P_{Trig} depends on the regional avalanche hazard or danger rating (Jamieson 2009, Techel et al. 2015). (In North America, the term *avalanche danger* is used for public communication to recreationists whereas *avalanche hazard* is used internally within avalanche forecasting operations (Statham et al. 2018). These two 5-level ratings systems are very similar.) Focusing on the effect of avalanche hazard (or danger) on triggering of potentially fatal avalanches, Jamieson (2009) used an expert survey in which respondents assumed the individual was travelling up, down or across the middle of the start zone and not using skilled route selection. While ignoring the effect of terrain and skilled route selection may be reasonable for Low (Level 1 of 5) and, perhaps, Moderate (Level 2) avalanche danger, many backcountry recreationists and some backcountry workers use skilled route selection for Considerable (Level 3 of 5) or higher levels of avalanche hazard. Based on the expert survey Figure 1 shows the triggering probability increases roughly by an order of magnitude with each level of avalanche hazard.

4 RISK ASSESSMENT FOR WORKERS EXPOSED TO MULTIPLE AVALANCHE START ZONES

4.1 Risk analysis for 400 exposures to start zones

Application of the method in Section 3 to a backcountry work site requires strong and therefore limiting assumptions. Notably, it assumes only one person travels up, down or across a start zone at a time, and that natural avalanche occurrence impacting people in avalanche start zones is negligible. However, since human triggering is much more likely than natural avalanches in start zones, the assumption of unskilled route selection means that risk tends to be overestimated, which contributes to conservative assessments.

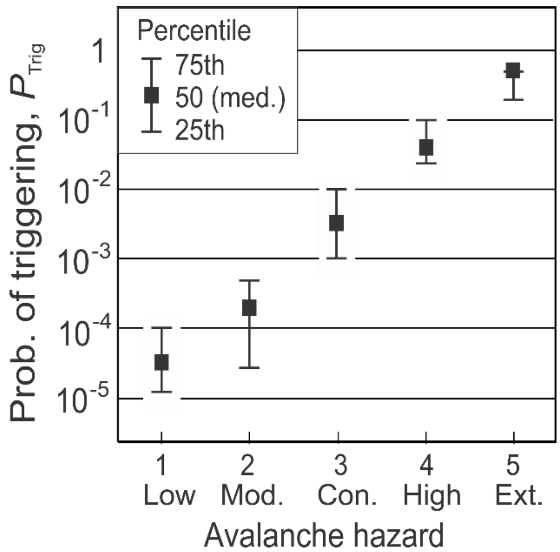

Figure 1. The probability of an individual triggering a potentially fatal slab avalanches in a single exposure to an avalanche start zone (after Jamieson 2009)

As an example of applying the method in Section 3, consider a team of backcountry workers expected to travel through 400 start zones during a winter – one worker at a time – but without skilled route selection. The annual collective risk of a death can be calculated with Eq. 6. Using P_{Trig} from Jamieson (2009), $P_{Caught|Trig}$ from Schweizer and Lütschg (2001) and Vulnerability $V_{D:T}$ from Jamieson and Jones (2015), Figure 2 shows the risk of a death for four scenarios, each with 400 exposures at different levels of avalanche hazard. The linear approximation in Eq. 6 allows the risk due to exposures at different levels of hazard to be added, e.g. 200 at Moderate hazard and 200 at Considerable hazard. The figure shows a substantial increase in risk with exposure due to Level 3 (Considerable) avalanche hazard. Also, the figure shows the uncertainty due to the interquartile range of survey responses on triggering probability (Jamieson 2009), which is not the only source of uncertainty.

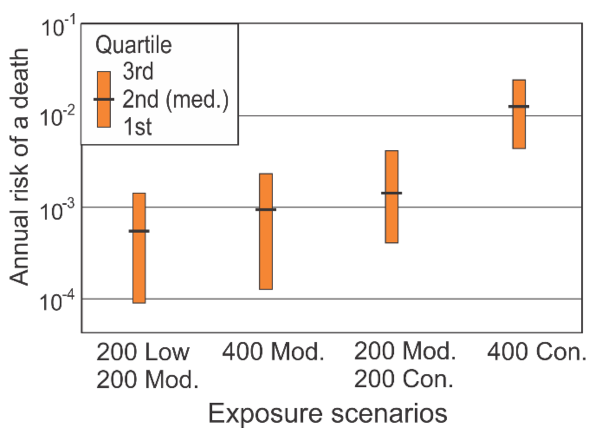

Figure 2. Annual risk of death to workers or recreationists for four scenarios involving 400 exposures with combinations of Low (Level 1), Moderate (Mod., Level 2) and/or Considerable (Con., Level 3) avalanche hazard. The bar shows the interquartile range based on the survey of triggering probability, which is only part of the uncertainty.

This analysis focusses on the avalanche hazard, which is a strong factor; However, it omits other relevant factors that often influence expert route selection such as local slope angle (McClung 2014), aspect and elevation (Grimsdottir and McClung 2006), convolutions in terrain and vegetation (Thumlert and Haegeli 2017). McClung (2013) reported that the risk of death was greatest for local slab depth (measured perpendicular to the slope) between 0.6 and 1 m; however, the distribution of slab depth over a forecast region is considered when the avalanche hazard is rated. Although relevant, these local factors cannot readily be applied as quantitative modifiers of the components of Eq. 6.

4.2 Risk evaluation and mitigation for a team of backcountry workers

For an operation in which workers travel in avalanche terrain during winter, there is no published level of tolerable collective risk. However, many risk owners seek to minimize the risk to workers, and the ALARP principle requires that risk be reduced as much as reasonably practical. The avalanche risk to the backcountry workers (e.g. Fig. 2) could be reduced by mitigation measures such as

- reducing or avoiding exposure to avalanche start zones when the avalanche hazard is at or above a threshold such as Level 3 (Jamieson and Jones 2016),
- reducing or avoiding exposure to avalanche start zones for higher levels of terrain severity during higher levels of avalanche hazard as indicated by decision support tools such as the Avaluator™ (Haegeli 2010) (which was developed for recreationists),
- hiring trip leaders trained in expert route selection,
- training the backcountry workers in skilled route selection and avalanche rescue (Jamieson and Jones 2016),
- vulnerability reduction methods such as avalanche flotation devices (also called balloon packs or avalanche airbags) (Haegeli et al. 2014), or
- a combination of these mitigation measures, which may be formalized in an avalanche risk control plan (avalanche safety plan).

Except for avalanche flotation devices, which reduce vulnerability by about 10% (Haegeli et al. 2014), the measures in the list above have not yet been quantified, which limits their inclusion in quantitative risk analyses.

Table 2. Analytical methods for workers exposed to snow avalanche terrain

Worker exposure to snow avalanche terrain	Inclusion of daily avalanche hazard	
	No	Yes
Up, down or across start zones	Not available. Not recommended	Quantitative but terrain simplified (Sections 3 and 4 of this paper) Qualitative (Gould and Campbell 2014)
Temporary work in runout zones	Quantitative [a] (e.g. Porter and Morgenstern 2013)	Qualitative (Gould and Campbell 2014)
Traverse runout zones	Quantitative [a] (e.g. Rheinberger et al. 2009). Semi-quantitative (e.g. Owens and Fitzharris, 1989)	Qualitative (Gould and Campbell 2014)

[a] analytical method exists but application to assessing avalanche risk workers not published or known to author.

4.3 Risk assessment and mitigation for an individual worker

Recognizing the large assumptions in this analysis, the methods allow the avalanche risk to be calculated for an individual worker. Because Eq. 6 is approximately linear, the risk can be scaled from the scenarios shown in Figure 2. For example, for a worker who is expected to travel up, down or across 40 start zones in a winter when the avalanche danger is Moderate, the average annual risk would be roughly 10^{-4}, which is in the tolerable range for involuntary human activity summarized by Finlay and Fell (1997). However, the ALARP (As Low As Reasonably Practical) principle requires that the risk be reduced until the cost of further risk reduction would be grossly disproportionate to any benefits gained (e.g. Porter and Morgenstern 2013, Canadian Avalanche Association 2016, p. 40). Specifically, a cost-benefit analysis should be presented to show that all cost-effective and practical mitigation measures are implemented. Hence, even for 40 exposures per winter, the mitigation measures in the list above should be implemented whenever practical.

5 CONCLUSIONS

This paper focused on the question: Can we quantitatively assess the snow avalanche risk to backcountry workers? As shown in Table 2, the answer is *yes* for three different types of exposure (countable exposures to start zones, countable traverses of runout zones, and countable worker hours in runout zones). However, the quantitative methods have disadvantages. The two quantitative methods for runout zones in the middle column of Table 2 do not consider the short-term variations in the avalanche hazard. While the quantitative analytical method for start zones (Sections 3 and 4) includes short-term hazard variations, it assumes only one worker at a time in a start zone. The spatially variations of terrain and snowpack within avalanche start zones are ignored, but partly compensated by assuming unskilled route selection, which tends to overestimate risk and hence contributes to conservative assessments.

Qualitative analytical methods have their advantages. The method by Gould and Campbell (2014) summarized in Table 1 includes the daily avalanche hazard, includes multiple terrain factors using an accepted terrain classification, and has been used operationally for worksites.

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