HOW MANY START-ZONES CAPABLE OF PRODUCING AN AVALANCHE LARGE ENOUGH TO BURY OR KILL A SKIER DO HELI-SKI GUIDES ENCOUNTER IN A DAY?

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ABSTRACT: Snow avalanches are the greatest risk threatening commercial heli-skiing groups. Guides manage the risk from avalanches by selecting terrain with a low likelihood of avalanching given their evaluation of the avalanche hazard. To do so guides make critical risk management decisions each time they encounter a slope capable of producing an avalanche. This study explores the exposure of guides to start zones capable of producing avalanches of size 2 or greater. A fuzzy logic model of potential avalanche release areas was implemented employing slope gradient, ground roughness, exposure to prevailing winds and forest stem density data. A data set of 100 documented avalanche location polygons were used to validate the model and derive threshold criterion necessary to identify potential release areas. Lead guides at Canadian Mountain Holidays Galena Lodge were equipped with GPS units over the course of the 2015 to 2018 winter seasons, creating a dataset of 6500 tracked heli-skiing descents. The linear geometries of the tracks were combined with a vector model of potential avalanche release areas through an overlay analysis to quantify exposure of guides to avalanche start zones. The results of this analysis show that guides were exposed to potential avalanche release areas capable of producing a size 2 avalanche in 27.5% of the terrain they skied and chose to enter such terrain on average 19.4 times per day.

KEYWORDS: GPS tracking, release areas modeling, terrain selection.

1. INTRODUCTION

Heliskiing guides minimize the potential for accidentally triggering avalanches through exposure management. The most attractive terrain for skiing is often capable of producing avalanches and guides need to balance avoiding avalanche prone slopes while providing an enjoyable skiing. The risk is managed by first assessing the nature, severity and spatial distribution of the local hazard, then selecting terrain that minimizes the exposure (Haegeli and Atkins, 2010). Heliskiing guides may make numerous such terrain choices per run. However, no study to date has attempted to estimate the number of such decisions guides make or to quantify their cumulative exposure.

The aim of this study is twofold:

- To estimate the frequency that guides at CMH Galena are exposed avalanche start zones capable of producing avalanches of size 2 or larger;
- To explore if the frequency of their exposure varies with respect to changing avalanche hazard.

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2. BACKGROUND

The techniques for the use of GPS tracking devices in exploring the terrain preferences of professional ski guides are now well established (Hendrikx and Johnson, 2016; Thumlert and Haegeli, 2018). Previous studies in this field have decoupled the various terrain parameters under consideration (slope, aspect, convexity, forest density etc.) to examine their relationship with terrain usage. This approach requires that the combined effects of these attributes be modeled through weighted linear combinations which can result in sharp, unrealistic, and arbitrary transitions or breaks in the modeled effect. An alternative and hitherto unexploited approach can be found in modern spatial avalanche release area models. Primarily developed to supply the initial conditions for avalanche dynamics simulations, these models pose an interesting opportunity as a terrain metric for the study of guides terrain usage.

Several spatial models of avalanche release areas that require limited input parameters and are appropriate for regional scale analysis or in areas with limited historical records have been proposed (Barbolini et al., 2011; Bühler et al., 2013; Pistocchi and Notarnicola, 2013; Veitinger et al., 2016). The literature of natural hazards modelling generally considers fuzzy logic modelling approaches as superior over binary classifications and weighted linear combinations. Fuzzy logic approaches are well suited to handling uncertainty in contexts such as the modeling of avalanche release where the underlying physical processes are not fully understood.

3. METHODS

The methodology employed in this study is based on the rationale that a fuzzy logic model of potential avalanche release areas can be generated from data sources freely available in Canada and trained using a limited dataset of prior avalanche events. This model can be combined with the linear geometries of GPS tracks of guided heli-skiing descents through a spatial overlay analysis to explore patterns in exposure of heli-skiing guides to terrain capable of producing avalanches of size 2 or greater.

3.1 Study site

This study focuses on the terrain usage patterns of guides at Canadian Mountain Holidays (CMH) Galena in the Selkirk Mountains of British Columbia, Canada. The skiing tenure at CMH Galena extends over 1,150 km^2 and is comprised of 296 established runs. Each run has predefined helicopter landing and pick up locations. However, there are multiple options for descent routes that guides may choose between these fixed points. CMH guides use a systematic framework to evaluate avalanche hazard and choose appropriate terrain as part of their overall risk management process. This process is an operational fixture of all CMH operations and is described in more detail in Haegeli and Atkins (2016).

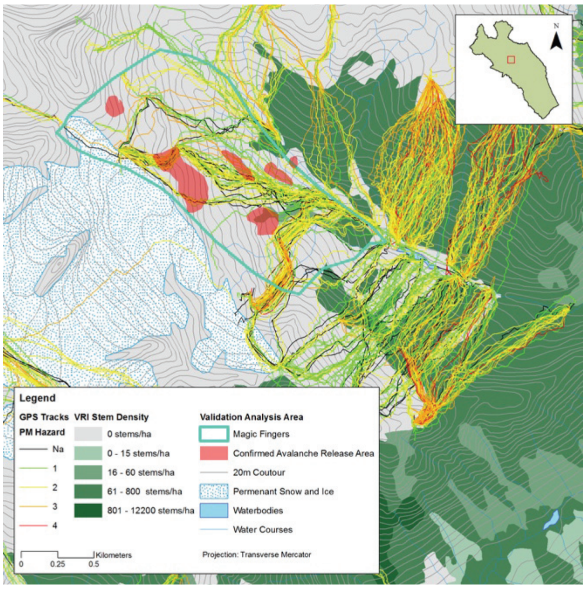

Figure 1: sample study data

3.2 Data sources

All the terrain data used in this study is freely available. A coverage mosaic of raster digital elevation data was acquired from the Canadian Digital Elevation Model with a resolution of 0.75 arc seconds (roughly 18 m). Although previous studies have found higher resolution elevation data to provide better model accuracy, this comes at the detriment of increased computational cost, an importation consideration in regional scale studies. Forest cover data, measured in live and dead stems per hectare, was obtained from the British Columbia Vegetation Resources Inventory (VRI).

A survey of senior guides at CMH Galena provided a vector data set of 100 prior avalanche release areas to be used for model training and validation. Fourteen ski runs were selected that represented a broad range of terrain types present in the tenure. The boundaries of avalanche start zones from prior size 2 or greater avalanche occurrences within these regions were manually discretized as polygons class features from satellite imagery using Google Earth.

We used GPS tracks of lead guides' terrain choices at CMH Galena from the 2015/16 and 2016/17 winter seasons. The custom-designed passive GPS trackers were set to record positional data every four seconds which resulted in an average distance between observation points of 20 m while skiing. The technological specification of this system are described in Haegeli and Atkins (2016). The *SarpGPSTools* R package (Haegeli et al., in prep) was used to process the GPS files and store the extracted tracks as linear geometries in a postgreSQL database. The tracks were broken down into 14,395 segments based on their intersection with alpine (> 2250 m), tree line (1850-2250 m), and below tree line (< 1850 m) elevation bands. The guiding teams evening avalanche hazard assessment (i.e., nowcast) for each elevation band was attached as an attribute the track segments. To ensure the dataset only included 'successful' terrain choices, tracks recorded on days with skier accidently triggered avalanche incidents of size 2 or larger would have been excluded from the dataset. However, no such incidents occurred during the study period.

3.3 Potential release area model

The potential release area (PRA) model (Figure 2) employed in this study is implemented in R and builds on the approach developed by Veitinger et al. (2016). Our model is based on four parameters: slope, wind shelter, terrain roughness, and forest density.

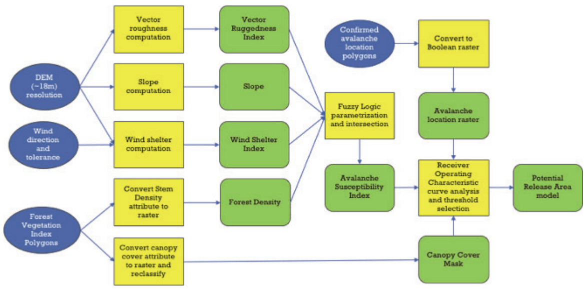

Figure 2: PRA model algorithm

Cauchy functions (Eq. 1) are used to model the membership of the four geomorphological parameters.

$$\mu(x) = \frac{1}{1 + \left(\frac{x - c}{a}\right)^{2b}} \tag{1}$$

The model employs a fuzzy logic intersection operation to combine the four parameters into a continuous PRA class membership function. This approach allows for the partial compensation of parameters. When the membership values for all parameters are high the operator behaves like the arithmetic mean. However, when the membership value for one or more of the values is the operator behaves like the classic union.

Slope gradient and aspect are calculated from the digital elevation model (DEM). Slopes between 25° and 55° degrees are considered as potential release areas. The degree of membership is modeled by a Cauchy function (Fig. 2) that approximates the distribution of slope angle in human triggered avalanche accidents (Schweizer and Lütschg, 2001). The mean slope angle for human triggered avalanches is 39°. Slopes with gradients of less than 30 ° and greater than 50 ° are assigned lower membership values since human triggered avalanches become less likely.

The wind shelter index (Winstral et al., 2002) is used to model the upwind influence of terrain on snow distribution for a specified prevailing wind direction and directional tolerance. The index is a proxy for snow accumulation on the lee side of topographic obstacles. Wind shelter index varies between -1.5 and 1.5 in complex alpine terrain with negative values retuned for wind exposed features. The degree of membership is modeled by a Cauchy membership function (Fig. 2) that assigns higher membership values to lee slopes lower values to windward terrain.

Terrain roughness is used to model breaks in morphology that may limit the propagation of avalanche release. The vector dispersion method (Sappington et al., 2007) is used to calculated surface roughness from the slope gradient and aspect. The degree of membership is modeled by a Cauchy function proposed by Veitinger et al. (2013) that assigns high membership values for even and smooth terrain, with lower values in increasingly rough terrain (Fig. 2). Terrain's susceptibility to avalanches strongly decreases for roughness values between 0 and 0.001. Between 0.01 and 0.02, avalanches are unlikely but possible. Above 0.02, avalanches are not expected.

The density of tree stems per hectare is used to model effects that increasing forest density has on inhibiting avalanche release both through the mechanical anchoring to the slope and disruption continuous week layers in the snowpack. The degree of membership is modeled by a Cauchy function (Fig. 2) that approximates the empirical relationship between forest density and avalanche occurrences proposed by Viglietti et al. (2010) and is supported by expert interpretation. Higher membership values are assigned to open terrain or sparsely forested glades with a density 15 stems/ha or less. The preventative effect of forest cover increases between 60 stems/ha and 350 stems/ha. Densities below 450 stems/ha are assigned low membership values as avalanches are unlikely.

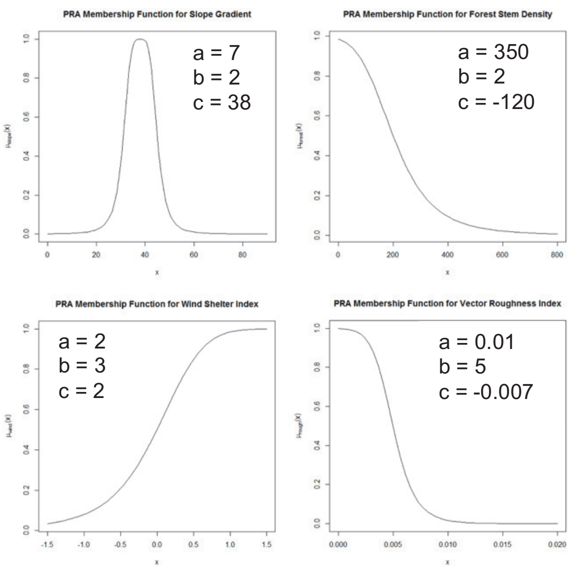

Figure 3: Cauchy membership functions for model parameters

3.4 Validation of PRA model

A Receiver Operating Characteristic (ROC) curve can be used to illustrates the diagnostic ability of a binary classifier system as its discrimination threshold is varied. True and false positive rates are calculated for the model over a range of thresholds using the rasterized locations of prior avalanche occurrences as a validation dataset. The area under the ROC curve is then used to evaluate and compare the performance of model independent of threshold selection. This value lies between 0.5 to 1 where 0.5 denotes the performance of a random guess and 1 denotes a perfect classifier. Interpreting ROC values is context dependent, but values from 0.7 to 0.8 are considered acceptable for studies of natural hazards.

The area under the ROC curve score (AUROC) for the PRA model tested against the raster representations of prior avalanche start zones was 0.72. An implementation of Veitinger et al.'s (2016) approach using the same data resulted in an AUROC score of 0.67.

A threshold must then be selected to transform the continuous PRA class membership into a binary classification scheme. Several approaches are advocated in the literature depending on the structure and completeness of the training data. The Max Youden Index (MYI) represents the point on the ROC curve farthest from line of equality *(x=y).* Selecting this index as a classification threshold provides the largest improvement in model specificity over a random guess. However, a weakness of the approach is MYI tends to recommend an overly conservative classifier when incomplete validation datasets are employed.

We applied the MYI threshold of 0.06 to transforms the continuous PRA class membership into a binary classification scheme of potential release areas that best matched the characteristics of the training data set. Employing this threshold criterion resulted in a classifier with a 0.81 true positive rate and a 0.30 false positive rate (Fig. 4).

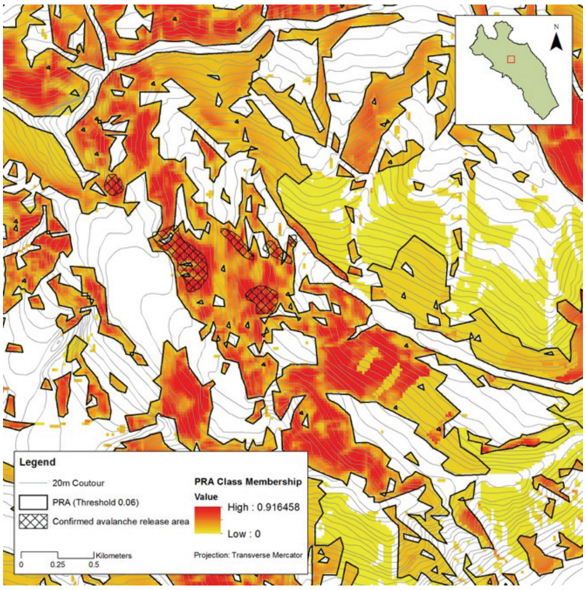

Figure 4: sample PRA model output

3.5 Quantification of GPS track exposure

We employed a spatial intersection analysis of the linear geometries of the GPS tracks and the binary potential release area classification scheme to explore the exposure of guides potential release areas. We first converted the potential release area raster to a polygon feature class. We then calculated vector geometry for each potential release area feature and removed instances with an area of less than 2500 m^2 (i.e., 50 m by 50 m). The geometric intersection of the PRA polygon feature class with the GPS tracks polyline feature class was then analyzed respect to their frequency per run, percentage of total distance traveled and distribution by hazard ratings.

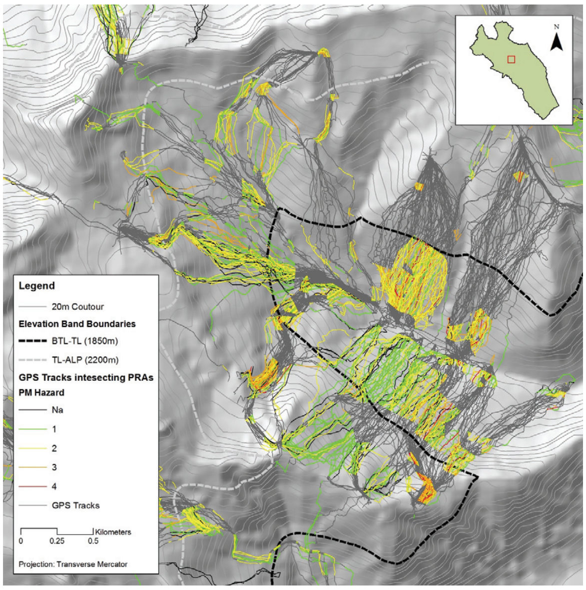

Figure 5: sample of GPS tracks intersecting PRA regions

4. RESULTS AND DISCUSSION

The 6641 GPS tracks intersected the modeled potential release areas 16077 times an encounter frequency 2.42 times per run (Figure 5). On days where more than 3 runs were skied the guides skied an average of 8.2 runs. Thus, guides chose to enter terrain capable of producing a size 2 avalanche at an average rate of 19.4 times per day. Alternatively of the 11989km ski descents tracked 3301km of these (27.5%) were in terrain capable of producing avalanches size 2 or greater.

Analyzing these intersections down by hazard rating (Figure 6) indicated a trend that guides expose themselves to fewer potential release areas as the hazard increases as expected. Interestingly, this trend appears to be to stronger in alpine terrain than at tree-line as was not evident at bellow tree-line elevations.

The addition of the fuzzy forest density parameter to the model captured the variability in the preventative effects that forest cover on avalanche release. This is an improvement over previous avalanche release areas models that have either used forested cover as a masking layer or treated open and forested terrain as equivalents. Even though the parametrization of the Cauchy membership function drew on an empirical relationship between forest cover and avalanche occurrences, it is largely based on the expert judgement of experienced guides. Further quantitative analysis on the relationship between forest density and avalanche formation is required.

The study also demonstrates the potential of avalanche release area models for use in to exploring the terrain preferences guides. Quantifying the exposure of guides to potential avalanche release areas can serve as a proxy for the magnitude of the risk management tasks of heliskiing guides. This can provide a useful operational tool for self-check-ins, the transfer of institutional knowledge with a guiding team, or for external auditing.

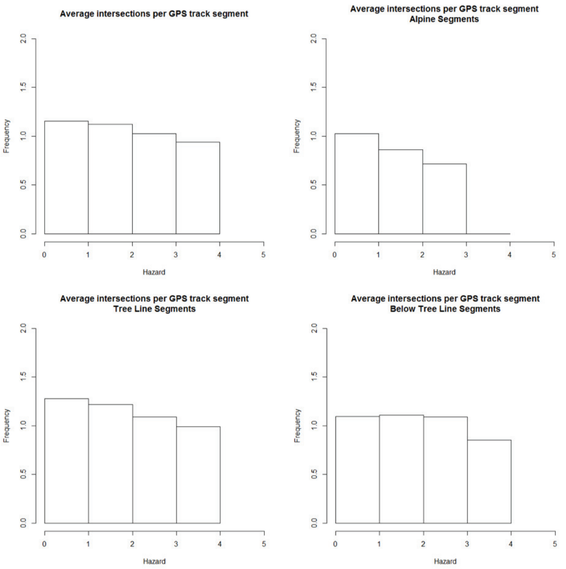

Figure 6: GPS track intersections by hazard rating and elevation band

5. CONCLUSION

To our knowledge, this is the first study that explicitly quantifies the exposure of heli-skiing guides to avalanche terrain. While our study was exploratory in nature, the results of this study indicate that guides were exposed to potential avalanche release areas in 27.5% of the terrain skied and chose to enter such terrain on average 2.42 times per run or 19.4 times per day. The analysis also confirmed that guides tend to reduce the frequency of their exposure to potential release areas as avalanche hazard increase.

The fuzzy logic algorithm implemented shows promise for the identification of potential avalanche release areas especially in large or remote regions where avalanche location data may be limited or unavailable. Furthermore, the addition of a fuzzy forest density parameter was demonstrated to be a valuable addition to modeling potential avalanche release areas. However, we view this study as a proof of concept and suggest that the approach should be tested in other snow and avalanche climates, and over more winters before these results can be generalized.

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