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Snow avalanche hazard of the Krkonoše National Park, Czech Republic

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ABSTRACT

This paper presents a snow avalanche hazard map of the most avalanche-prone mountain range in the Czech Republic, the Krkonoše Mountains. The map was prepared using historical records of 1132 avalanches which occurred over the last 54 years and state-of-the-art modelling of avalanche propagation and the spatial distribution of potential avalanche source areas. The map provides not only reliable and easy to understand information for the Mountain Rescue Service of the Czech Republic and mountain tourists, but also for land use managers to identify areas where new avalanche paths may develop under favourable conditions, including the total removal of forest cover.

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1. Introduction

Snow avalanches are among the most frequent hazards in winter mountain conditions even in non-Alpine-type mountain ranges (Jonasson et al., 2005). In most countries where snow avalanches pose a threat, the snow avalanche hazard is monitored and taken into account in spatial planning (e.g. Switzerland – BFF/EISLF, 1984 or Canada – Canadian Avalanche Association, 2002). In the Czech Republic, where snow avalanches are common only in restricted areas, no snow avalanche hazard maps have been produced, although the threat has been regularly monitored by the Mountain Rescue Service of the Czech Republic, which is also responsible for issuing hazard warnings whenever necessary. To date, mostly personal experience of the Mountain Rescue Service personnel has been used to assess the hazard of avalanche paths. Due to the increased use of the mountains during winter by tourists, cross-country skiers and ski touring enthusiasts, the demand for more detailed and publicly available snow avalanche hazard zoning has arisen.

Hazard is usually defined as the spatial and temporal probability of a given process with a specified magnitude, which may threaten humans (Blahut & Klimeš, 2011). In the case of a snow avalanche hazard, the initiation zones and runout distances of avalanches with a specified magnitude have to be determined, along with the probability of their occurrence.

Factors affecting the localisation of the avalanche initiation zones are summarised in a variety of articles (e.g. Blahut, 2008; Bühler et al., 2013; McClung, 2003). The most important factor is a slope with values

between 25° and 55° (McClung & Schaerer, 2004), which is considered to be the most susceptible to avalanche initiation. Other studies (e.g. Schweizer, Jamieson, & Schneebeli, 2003) determined that rugged terrain prevents snow from releasing and in some cases obstructs its motion on the slope. An extreme example of surface roughness is dense forest, where snow avalanche initiation is much less probable (McClung, 2001). Planar curvature was also found to play a role (Bühler et al., 2013) in avalanche initiation, favouring concave landforms.

Snow avalanche runout can be modelled by empirical-based software (e.g. Flow-R – Horton, Jaboyedoff, Rudaz, & Zimmermann, 2013) or numerical-based software (e.g. RAMMS – Christen, Kowalski, & Bartelt, 2010 or SAMOS – Sampl & Zwinger, 2004). Empirical models are able to delimit runout zones but lack information about the height of the snow, impact pressures or velocities. Therefore, empirical models are usually used for medium scale/regional analyses, while numerical models are applied in studies with higher detail.

The snow avalanche magnitude/frequency relationship can be assessed in different ways. A direct approach is limited to areas with a long avalanche record. Indirect approaches analyse the age of trees growing in the avalanche path (Schläppy et al., 2014), compare potential release areas and avalanche return periods (Maggioni, Gruber, Purves, & Freppaz, 2006) or use information such as release heights for different frequency scenarios (Chrustek, Świerk, & Biskupič, 2013).

The Main Map reflects the requirement of the Mountain Rescue Service of the Czech Republic to

have more objective information about the spatial and temporal occurrence probabilities of snow avalanche occurrences in the region with the largest recorded number of avalanches. It combines accurate, detailed and the most recent terrain information with state-of-the-art modelling software (RAMMS) and historical records of snow avalanche occurrences on permanent paths.

2. Study area and snow avalanche research

Krkonoše (also known as the Giant Mountains) is the highest mountain range (Sněžka Mt., 1,602 m a.s.l.) in the Czech Republic. Since 1963, most of the mountain range has been protected as the Krkonoše National Park (KRNAP) with an area of 550 km². The climate of Krkonoše is characterised by an average annual temperature of 0°C at its highest parts, strong winds and usually abundant snow precipitation, which may occur at any time during the year. In winter, the snowpack usually reaches a height of between 100 and 300 cm. Snow accumulation has a very specific spatial pattern, which is governed by winds directed by mountain relief (anemo-orographic system, Jeník, 1961) blowing from the west and transporting snow to the eastern slopes. It results in very regular snow distribution in the summit regions (Janásková, 2006) with relatively low snow accumulation on the west-facing gentle wind-ward slopes and much higher snow accumulation on steeper lee-ward slopes.

Krkonoše forms part of the European Variscan/Herzycian mountain ranges mostly comprising crystalline schists with several insets of quartzites and crystalline limestones. The central part, near the border with Poland, is formed of granites, with the Alpine orogeny and Quaternary glaciations forming several plateaus at an elevation of between 1300 and 1450 m a.s.l. These are dissected by streams and glacial cirques, 11 of which hosted glaciers during the last glaciation (~13 ka BP, Engel et al., 2010).

Krkonoše has the highest snow avalanche activity in the Czech Republic. Fifty-six permanent avalanche paths with regular snow avalanche occurrences and several other sites with occasional snow avalanche releases have been identified. Despite the fact that snow avalanches have always been considered a major threat in Krkonoše, no comprehensive statistics about avalanche fatalities exist. The available literature (Kociánová, Kořízek, Spusta, & Brzeziński, 2012) documents over 40 victims of snow avalanches since 1918. Thus, it is not surprising that it was one of the first places in non-Alpine countries to introduce regular snow monitoring, which began in 1954 (Vrba, 2003). A snow avalanche inventory has been compiled every year since its establishment in 1961 by Vrba and Spusta (1975) (Pavlásek, Blahut, & Juras, 2015; Spusta & Kociánová, 1998; Spusta sen, Spusta jun, & Kociánová,

2003, 2006; Vrba & Spusta, 1991). Currently, snow avalanches are monitored and inventoried by both the KRNAP administration and the Mountain Rescue Service of the Czech Republic.

3. Data and methods

A digital database of snow avalanche occurrences and their characteristics was compiled for the period between 1961 and 2015 (Pavlásek et al., 2015). The database provides detailed information including avalanche type, dimensions and release height for 1132 recorded avalanches. Avalanche release areas were delimited based on data provided by the KRNAP Administration (2010).

Detailed terrain information was provided by a LiDAR aerial survey (KRNAP Administration, 2012). The raw point cloud data with an approximate density of 30 pts/m² was processed into a digital terrain model (DTM) and a digital model of forest cover. Due to the large amount of data, computations were made separately for each individual map sheet (312 × 250 m) and then merged together. Initially, raw data in LAS format was classified on ground and other (unclassified) points. Subsequently, the height of each unclassified point above ground was calculated. This information was used to produce a digital model of forest cover in the form of a grid. The value of each cell was represented by the height of the highest point above the ground. The DTM grid was interpolated from points classified as the ground. Both of the models were then produced with 5 m resolution.

Snow avalanches were modelled using two different approaches. Firstly, a statistical model was developed to identify areas with conditions favourable for snow avalanche release zones outside the known permanent avalanche paths. This model was prepared for the entire KRNAP. The known avalanche release areas were used as training points and DTM derivatives (slope, aspect, altitude, planar and profile curvature, flow accumulation, internal relief, surface roughness and forest cover) were used as factor maps. Two scenarios were prepared: (i) for the actual conditions considering the existing forest cover and (ii) for a theoretical scenario of the total deforestation (in this case the forest factor map was not included in the calculation) of the study area.

Training points were compared with the factor maps using the C4.5 algorithm, which generates a decision tree by assigning a class to an object using the attribute with the highest value of a splitting criterion (information gain) (Quinlan, 1993). This step is also known as tree growth, in which the node with the highest value of the criterion is split to best classify the set of objects. As information gain was used as the criterion, the C4.5 algorithm selects an attribute with the highest information gain (the difference between

the entropy of the original node and the entropy of the newly split nodes). The split adds two child nodes to the tree. This process is repeated recursively until the set of objects is empty. This strategy is known as the divide and conquer approach. Finally, the classification error of the node is calculated as the sum of the classification errors of the child nodes. For more details on the C4.5 algorithm, see [Quinlan \(1993\)](#) or [Wu et al. \(2008\)](#). This algorithm has been successfully used to predict landslide susceptibility in previous studies ([Saito, Nakayama, & Matsuyama, 2009](#); [Yeon, Han, & Ryu, 2010](#)), outperforming other machine learning methods such as support vector machines and neuro-fuzzy systems ([Pradhan, 2013](#)).

A C4.5 decision tree with pruning was employed in this study. The setting of the decision tree was as follows: the confidence factor used for pruning = 0.25 and the minimum number of instances per leaf = 2. We used 10-fold cross-validation to avoid overfitting. The resulting raster showed areas prone to snow avalanche release.

Snow avalanches on 56 inventoried permanent paths were modelled using RAMMS modelling software ([Christen et al., 2010](#)). The RAMMS Avalanche module solves two-dimensional depth-averaged mass and momentum equations on three-dimensional terrain using both first- and second-order finite volume methods ([Christen et al., 2010](#)). The model predicts avalanche velocities, flow heights and pressures. Initial conditions for avalanche release are specified by defining a slab area with a fixed fracture height. Single or multiple release areas are easily specified using computer-aided design drawing features ([Bartelt et al., 2013](#)). The RAMMS Avalanche module employs the two-parameter Voellmy friction model ([Voellmy, 1955](#)) with the following parameters: Coulomb friction (μ) and velocity-squared dependent turbulent friction (ξ). These two parameters can be set globally by the user or can be calculated by the model based on actual topography and surface characteristics (e.g. roughness depending on vegetation cover) ([Gruber & Bartelt, 2007](#)). Calculations are automatically stopped when the total mass flux decreases to a value below a fraction of the maximum mass flux ([Christen et al., 2012](#)).

The volume of snow released during each avalanche described in the inventory ([Pavlásek et al., 2015](#); [Spusta & Kociánová, 1998](#); [Spusta sen et al., 2003, 2006](#); [Vrba & Spusta, 1991](#)) was calculated using three different snow depths of the release areas and the release area extent derived from the plots of the footprints of the permanent avalanche paths ([KRNAP Administration, 2010](#)). The downslope limit of the release area was defined using expert knowledge. The first snow depth was defined as the most frequent snow height of the release area (i.e. modus) from the inventory; the second snow depth represented the highest recorded snow height and the third snow depth, the highest recorded

snow height increased by 25% (representing an extreme event not recorded in the historical database). These three avalanche initiation volumes were modelled to define the low, moderate and high snow avalanche hazard for each release area in the database. The return periods of these three avalanche volume classes and the respective friction parameters (μ and ξ) were used from the RAMMS manual ([Bartelt et al., 2013](#)). Each avalanche path was classified, according to its morphology, into one of the following classes: channelled, un-channelled, gully or flat ([Bartelt et al., 2013](#)).

4. Results and discussion

In total, 56 inventoried permanent avalanche paths were modelled using RAMMS software ([Christen et al., 2010](#)) to obtain high, medium and low hazard runout areas. Potential release zones outside the permanent paths were statistically modelled. Basic areal statistics are summarized in [Table 1](#). Hazard zones on permanent snow avalanche paths cover 5.744 km², which is 1.044% of the KRNAP area. Potential release zones cover an additional 11.389 km², which is 2.071% of the KRNAP area. By merging the results of these two models, 3.115% of the KRNAP area has some level of hazard. This figure may not seem significant but most of these hazardous zones are located in the most visited areas of the national park, posing a significant risk to winter visitors.

Free riding and ski touring are restricted due to nature conservation in the KRNAP. From eight ski touring routes authorised by the national park ([KRNAP Administration, 2015](#)), five cross permanent avalanche paths for a total length of 6.3 km and all of them are in potential release areas (3.7 km). Only one building lies within the permanent avalanche path hazard zone. It is a mountain hut called 'Děvín' in the Modrý Důl Valley situated at the border between a medium and low hazard zone (see the magenta star on the map). This hut was nearly hit by several avalanches, with an avalanche passing only 20 m away from the hut in February 2015 (see photo B on the [map](#)).

The [Main Map](#) is used by the Mountain Rescue Service of the Czech Republic and selected content

Table 1. Quantitative summary of snow avalanche hazard areas in the KRNAP.

Map class	Map footprint (km ²)	Total area (km ²)	% of KRNAP
High hazard on permanent paths	3.335	3.335	0.606
Medium hazard on permanent paths	0.793	4.128	0.751
Low hazard on permanent paths	1.616	5.744	1.044
Potential avalanche release area	4.730	4.730	0.860
Potential avalanche release area after deforestation	6.659	11.389	2.071

of this map is shown in an Android app: <https://play.google.com/store/apps/details?id=com.intergraph.avalanches> and Windows Phone app: <https://www.microsoft.com/en-us/store/apps/lavinyinfo/9nblggh5pslt>. These apps are called 'Laviny.info' (only in Czech) and they show permanent avalanche path hazard zoning and potential initiation areas as well as up-to-date avalanche warnings issued by the Mountain Rescue Service of the Czech Republic. We believe that publishing this map and providing free public access to the applications will raise awareness about the actual avalanche hazard and thus contribute to the reduction of injuries and fatalities among the winter visitors to the KRNAP.

5. Conclusions

The [Main Map](#) summarises information about the snow avalanche hazard in Krkonoše – the largest snow avalanche-prone area in the Czech Republic. The mountains have a long history of snow avalanche observation with continuous records spanning over the last 54 years, during which time 56 permanent avalanche paths have been identified. The [Main Map](#) shows hazard levels of the runout zones on these permanent paths as modelled by RAMMS, which was calibrated using the available historical records of release snow heights and avalanche types. Therefore, we are convinced that the modelling results are reliable for use in practice. This new information improves planning of safe routes for tourists and skiers. In addition, the Mountain Rescue Service of the Czech Republic is implementing this map into their safety and rescue plans to ensure operational safety. Avalanche hazards outside the permanent paths were assessed using advanced statistics (C4.5 algorithm) to search for areas with morphological and vegetation conditions similar to those on the historical avalanche paths. This data-driven method is based on the best available input information and also provides a scenario for where the forest cover is completely removed. The resulting distribution of potential avalanche release areas could be considered by forest management authorities to identify regions for planting protective forests and to avoid harvesting in potential snow avalanche release areas.

In total, 3.115% of the KRNAP was identified to be in an avalanche hazard zone. This does not describe the actual avalanche hazard but identifies potential avalanche release areas, which may develop under a forest clear-cut scenario (1% of the KRNAP). The limited areal extent of snow avalanche hazard zones stresses how localised this phenomenon is and encourages the implementation of effective risk mitigation measures, which may bring restrictions to a very small portion of the national park for short periods during the winter season. Although the existing ski

touring routes cross 10 km of avalanche hazard zones, which is 9.7% of their total length, no changes to them are likely. Routes are planned as a result of different needs, balancing nature conservation with tourism. The low number of potentially endangered houses does not call for any mitigation. However, the snow avalanche hazard has to be considered in future development plans, including possible deforestation.

Software

Statistical analysis was performed using R software. Raw LiDAR data were processed using the LAStools and the Perl programming language. Hazard modelling of the avalanches was performed using the RAMMS software. All of the results were imported into an ESRI ArcGIS grid and converted into ESRI shapefiles. ESRI ArcMap 10.2 was used to compile the final map.

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