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CREATION OF THE SNOW AVALANCHE SUSCEPTIBILITY MAP OF THE KRKONOŠE MOUNTAINS USING GIS

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Abstract

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This article deals with the development of the snow avalanche susceptibility map in the Czech part of the Krkonoše Mountains using the free Geographic Information System (GIS) GRASS. The area susceptibility map consists of two components: the morphological risk map, which is derived from the digital terrain model (DTM) and describes the slope steepness, aspect and curvature of the slope, and the protecting vegetation influence map, which is based on supervised image classification (spectrozonal aerial photos) and takes into consideration the importance of vegetation cover. The final map also includes starting zones calculated on the basis of significant changes in slope steepness and approximate shapes of avalanche paths based on these zones. In the map development, the layer of measured paths of avalanche cadastre in the Czech part of the Krkonoše Mountains was used, partly to gain the morphological characteristics of starting zones and partly to check the quality of the map.

snow avalanche, avalanche starting zone, avalanche cadastre, applied geoinformatics, the Krkonoše Mountains, supervised classification, GIS GRASS

The Krkonoše Mountains are the highest Czech mountain range and are also the only area with high avalanche activity. On the Czech side of the range, 54 avalanche tracks are registered, while on the Polish side, there are 51. In 1962, the avalanche cadastre was created, and thus in the Czech part, all avalanche falls and their descriptions, using the international classification and photo-documentation, have been recorded since that time. The information is detailed and it could help with the development of the computing model of area snow avalanche susceptibility, both with finding out significant characteristics of high-risk areas and with the model validation.

Using GIS software to judge the area avalanche susceptibility is convenient, especially because of the advanced possibilities of terrain analyses, but also others (e.g. image processing). The choice of GRASS software, which is part of the OSGeo Project (The Open Source Geospatial Foundation), was supported mostly because it provides enough high-quality tools for this type of analysis, and thanks to its availability, it will be easy for others to repeat the process described below.

The development of the computing avalanche susceptibility model, including approximate shapes of possible paths from automatically detected starting zones, could be a useful tool, for example, in areas where there is no detailed avalanche cadastre or in landscape planning to judge the influence of intervention in the landscape regarding the avalanche risk.

MATERIALS AND METHODS

As entry data, the digital terrain model (DTM) in raster representation with a pixel size of 5 m, which was created by spline interpolation from 3D vectors (contours, breaklines and points), was used. On its basis, basic morphological characteristics were derived (slope steepness, aspect, profile and tangencial curvature). To calculate the curvature, DTM was smoothed by a median filter with matrix size 5 × 5, which suppressed the smaller terrain unevenness. The next source of data was the vector layer of avalanche paths from the avalanche cadastre in the Czech part of the Krkonoše Mountains. To gain the characteristics of starting zones, only the higher parts of avalanche paths were digitalized using local knowledge (based on fieldwork) and the orthophotomap. The resulting layer of 66 starting zones[1] was randomly divided into two parts, and thus a testing file for characteristics derivation and a validation file for results evaluation were created.

The foundation for the protecting vegetation influence map was spectrozonal aerial photos in TIF format taken in August 2004. The photo scale is 1:15 000 and their spatial resolution is 0.5 m.

The area avalanche susceptibility map was made in several steps. First, the morphological risk map was created, followed by the protecting vegetation influence map. Finally, these two were combined. The same principle is mentioned in e. g. CIOLLI and ZATELLI (2000). Other authors, e.g. HREŠKO (1998), BARKA and RYBÁR (2003) or BISKUPIČ and BARKA (2010) describe a computing model which does not separate these two components and where the influence of vegetation cover is connected to the roughness factor, which enters into the final calculation with morphological parameters.

In addition to the area snow avalanche susceptibility map, starting zones meeting the given condition (the minimum change in slope steepness of 10°) as described by CIOLLI a ZATELLI (2000) were localized. In this study, the condition is extended by the necessity of a convex course of the mentioned change, and further extension means the calculation of approximate shapes of avalanche paths based on such localized starting zones, using the flow characteristics.

Slope steepness plays a crucial role in the area of snow avalanches. If it is too small, the component gravity force along the slope is not strong enough to initiate an avalanche.

On the other hand, on too steep slopes, big lasting deposition is not possible and so a coherent snow mass does not occur here. The influence of slope orientation is important in relation to the predominant airflow. This influences leeward and windward sides of slopes, resulting in the distribution of snow in the given area. The slope orientation also influences the amount of sunshine falling on the snow cover and thus its temperature regime and consequent metamorphic processes inside it. A different stratification and different forms of snow result. In the winter season, the northern slopes are in the shade and thus colder, which may result in dangerous forms of snow (depth hoar). In spring, the southern slopes are more dangerous. These undergo destructive changes due to sunshine, which causes the amount of water to rise and big wet snow avalanches to appear. The shape (curvature) of the slope (flat, convex or concave) represents certain differences in terms of avalanche risk, but its influence is usually very small. It could be more significant on moderate slopes.

The equation for computing avalanche risk suggested by HREŠKO (1998) and later modified by BARKA and RYBÁR (2003) also contains all of the aforementioned factors along with the factor of elevation. In this study, the factor of elevation is not included in the terrain analysis, mainly because it is not the quantity which directly describes the terrain shape. Its influence is connected to the amount and frequency of snow fall and air temperature. The influence of elevation on the vegetation zones is included in the protecting vegetation influence map. If necessary, it is possible to change the map according to elevation using DTM.

The layers of slope steepness, aspect, profile curvature and tangential curvature were created for the zonal statistics of the starting zones testing file. On the basis of the gained results and theoretical knowledge, the values of individual factors (steepness, aspect, curvatures) were stated for the multi-criteria analysis which was used for the evaluation of the whole area of interest. The created map of morphological risk was checked by the validation starting zones file.

The protecting vegetation influence map was created by supervised image classification (spectrozonal photos), which resulted in the division of the area into basic categories found in the area (without vegetation, grasslands, dwarf pine, deciduous stand and coniferous stand). Then, the layer was reclassified into the necessary form containing only three classes (see Tab. III).

As indicated before, from the avalanche point of view, there might be significant places with bigger changes in slope steepness (> 10°). If the course of this change is convex, there could be places with a higher tensile load of the snow layer, and also, in cases of leeward slope, the accumulation of snow (cornice formation) may appear, causing the load to grow. Both these facts accompanied by meeting other conditions, such as minimal slope steepness, represent a higher risk of avalanche. To find such potential starting zones, the methods of map algebra were used.

With the help of the existing protecting vegetation influence layer, starting zones which belong to the category of dense forest were removed because avalanche risk is eliminated by the vegetation. From other starting zones, approximate shapes of avalanche paths were computed. This calculation was done using flow characteristics which trace

1 The number of starting zones is higher than the number of avalanche tracks, because some tracks have more starting areas due to their shape (e.g. letter Y).

a flow down a least-cost path in an elevation model. Of course, the movement of snow mass is not identical to surface water flow, but the gravitational principle, on which the calculation is based, remains the same.

The final snow avalanche susceptibility map was created by combining of two components – factors (morphological map, protecting vegetation influence map) and approximate shapes of potential avalanche paths and their outlines from the avalanche cadastre of the Czech part of the Krkonoše Mountains.

RESULTS AND DISCUSSION

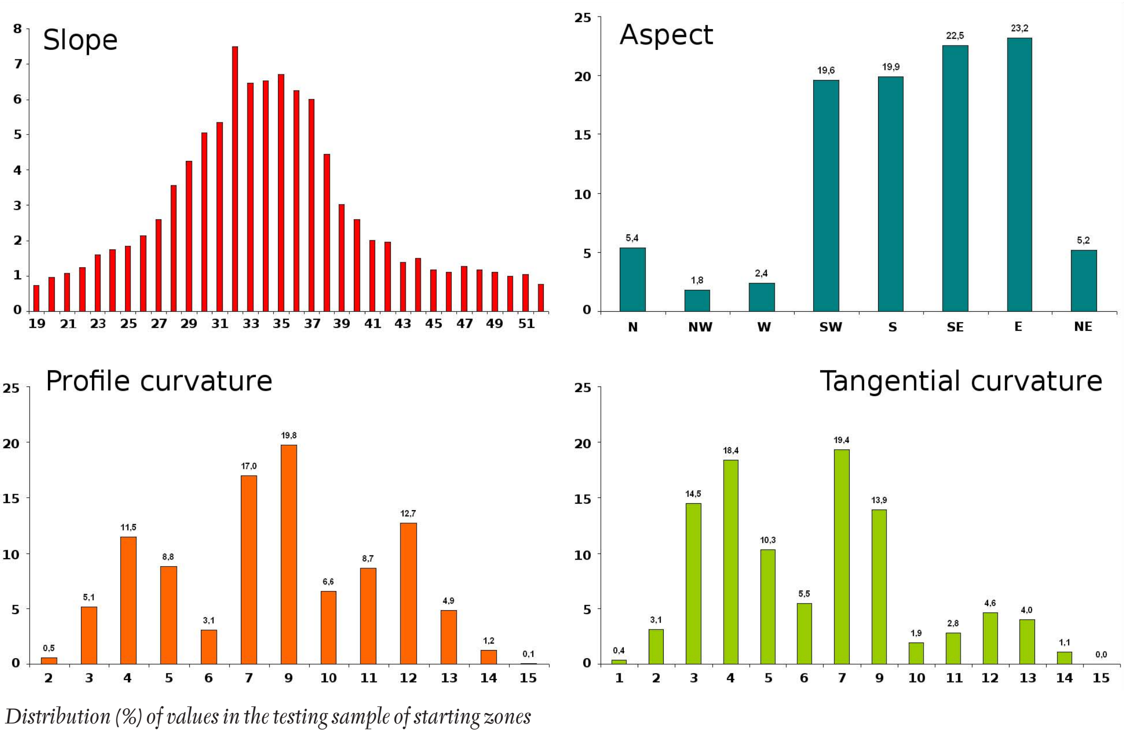
The calculation of the morphological risk map was done by multi-criteria analysis with four factors representing the main morphometric characteristics of the terrain. The values of slope steepness, aspect and tangential curvature factor were defined regarding the results of zonal statistics of the starting zones testing file and layers derived from the DTM. According to inconclusive results in profile curvature factor, this was defined based on the fact that on convex slopes, the tensile load is higher in the snow cover, and thus the risk of an avalanche starting is higher (further in e.g. MCCLUNG and SCHAERER, 2006).

The obtained zonal statistics are in compliance with results published in a similar study in which the author tests the fruitfulness of predicting models using a statisticalprobable method WofE with differently chosen factor combination, and claims that the best result was gained by the combination of variables such as slope steepness, elevation, slope aspect and tangential curvature (BLAHŮT, 2006). The main difference is the absence of the elevation factor for the reasons described above and separate assessment of vegetation cover.

The most significant influence on avalanche fall is slope steepness, thus also its factor has the highest weight, followed by aspect factor. The curvature factors are quite secondary. In calculation, the slope aspect values were divided into eight basic world directions and curvature values into 15 classes as shown in Tab. I. The results of zonalstatistics are shown in Fig. 1 and the factor values are in Tab. II.

I: *Slope curvature classes*

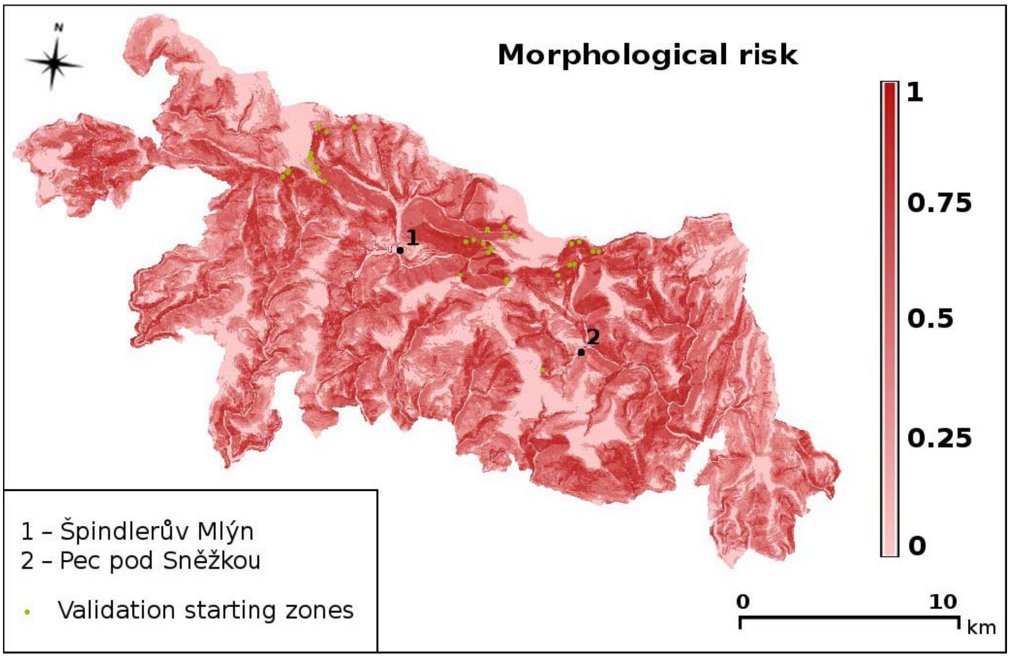
Class	Curvature radius (m)	Shape
1	Less then 50	Concave
2	50–100	
3	100–250	
4	250–500	
5	500–750	
6	750–1 000	
7	1 000 and more	
8	-	Flat
9	1 000 and more	Convex
10	750–1 000	
11	500–750	
12	250–500	
13	100–250	
14	50–100	
15	Less then 50	



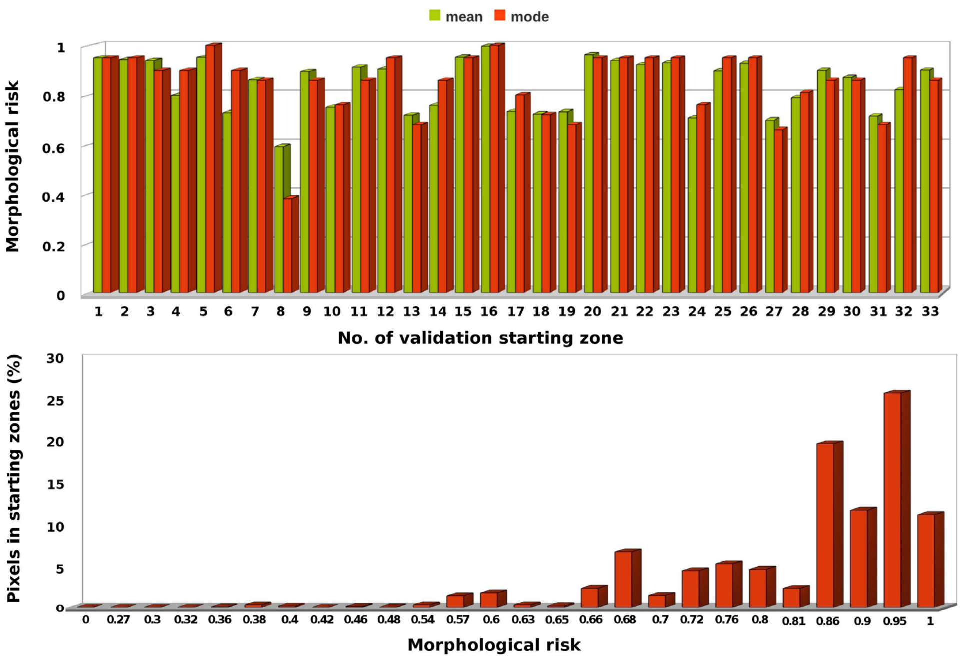
1: *Distribution (%) of values in the testing sample of starting zones*

II: *Values of the 4 factors used in the multicriterial analysis*

Slope (°)	Slope factor	Aspect	Aspect factor	Profile curvature class	Profile curvature factor	Tangential curvature class	Tangential curvature factor
28–39	1	SW – E	1	9–15	1	1–7	1
19–28 & 39–52	0.9	NE – N	0.8	1–8	0.95	8–15	0.95
14–19 & 52–60	0.6	NW – W	0.7				
10–14 & 60–70	0.4						
0–10 & 70–90	0						



2: *Morphological risk map*



3: *Results of the Morphological risk map validation*

New layers containing values of these four factors were created by the reclassification of the original layers. By multiplying them, the final morphological risk map was obtained (Fig. 2).

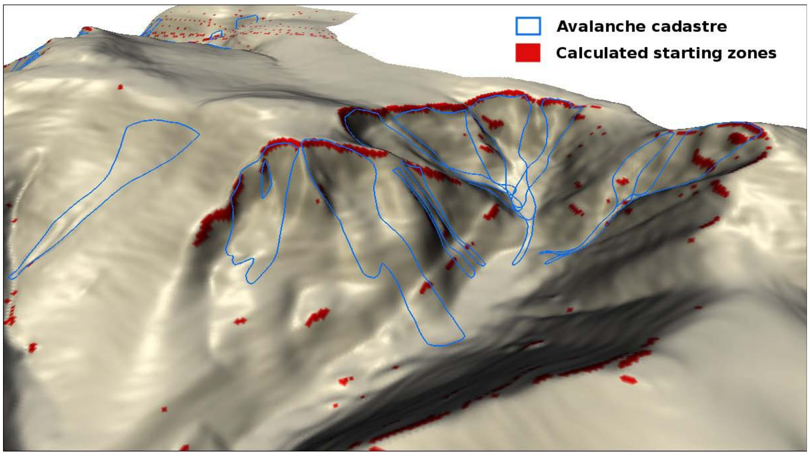
Validation of the map was carried out by the starting zones validation file. The mean and the mode of the risk value for each spatially isolated starting zone were calculated and also the distribution of values in the whole validating file (Fig. 3).

With the help of map algebra, the areas with the change in slope > 10° (with a convex course of this change) were identified as potential starting zones. This calculation was tested with different values of spatial resolution of the DTM. The best results were gained with a resolution of 15 m/pixel, which eliminated smaller surface unevenness, but higher breaks remained. The situation from Obří důl valley is shown in Fig. 4.

The protecting vegetation influence map was based on the results of supervised classification. This was conducted by the SMAP (Sequential Maximum A Posteriori) classifier which does not classify pixel into a certain class only on the basis of its spectrum vector, but also considers similar surroundings. It was also necessary to create training sites for the supervised classification. This was done by manual digitalization of the orthophotomap. In total, five layers entered the classification. These were all three channels of spectrozonal photos (near infrared, red and green), the first component of the carried principal component analysis (PCA) and the calculated NDVI (Normalized Difference Vegetation Index).

The spatial resolution of spectrozonal photos was 0.5 m, but the classification was done with a resolution of 1 m, which significantly accelerated the whole process. In total, 7 classes were classified as shown in Tab. III.

After the classification, the classes of young and mature coniferous stands were combined (they were classified individually because of their different spectral signatures). The second post-classification change was the elimination of the shade class, which was done according to the area character and not very convenient time of photographing (4th and 8th of August; 8:50–9:40 AM and 9:50–10:45 AM) represent rather a big problem for the classification, which was at least partially eliminated by their removal and later interpolation. The next was the reclassification of some areas regarding the vegetation zones. In some places, dwarf pine was replaced for coniferous stand in the classification and vice versa, and some areas covered by grass (bilberries) were wrongly classified as deciduous forest. That is why, using the DTM, the areas assessed as dwarf pine at levels up to 1 200 meters above sea level were reclassified as coniferous forest and opposite, coniferous forests at levels over 1 350 meters above sea level were reclassified as dwarf pine. The borderline for the change of deciduous forest into grasslands was 1 120 meters above sea level. Border limits of elevation



4: *Calculated starting avalanche zones*

III: *Vegetation classes*

Classification	Postclassification	Vegetation factor map classes	Vegetation factor
Without vegetation	Without vegetation	Bare and grass	1
Grasslands	Grasslands		
Dwarf pine	Dwarf pine	Dwarf pine	0.5
Deciduous stand	Deciduous stand	Dense forest	0
Coniferous stand – young	Coniferous stand		
Coniferous stand – mature			
Shadows	-	-	-

for dwarf pine and coniferous forest were set up regarding the description of natural conditions in the national park (KRNAP[online], 2011) and the borderline for the deciduous forest was derived by the interpretation of orthophotomap and the DTM. The next change was removing image noise, which is present in the form of tiny areas of one class included in a bigger unit of another class. They might be wrongly classified pixels or very small correctly assessed areas which might be ignored (e.g. small rock outcrops). The minimum area size was set to 5 m^2 according to frequently spread dwarf pine. The pixel size of 1 m meant removing all homogenous areas created by 4 or fewer pixels. The last two steps were the final interpolation of the values in areas where these were removed (shades, image noise) and the application of a low-frequency (mode) filter which matched each pixel with its new value on the basis of the pixel values which surrounded it. Entry data and final classification are shown in Fig. 5.

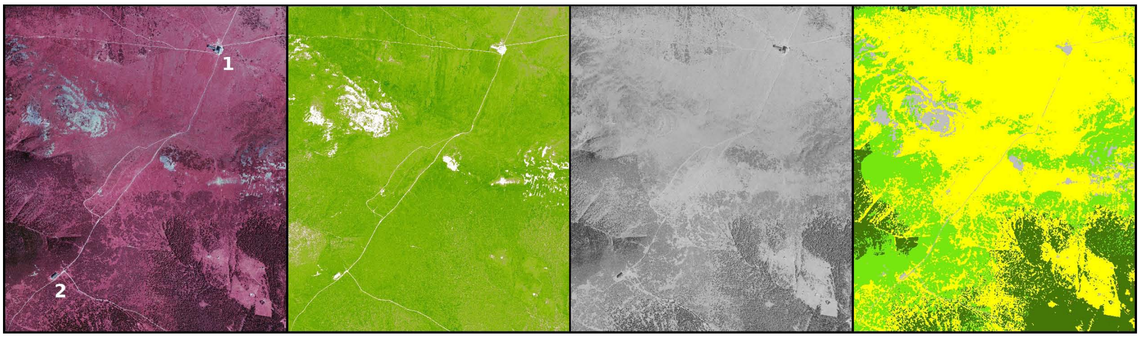
The classification was validated by control layer which was gained by manual digitalisation of homogenous areas around randomly chosen points in the area of interest, in the total number of 1 000. Validation was carried out by the method of error matrix and other two indicators. The Kappa coefficient, which gives the number of mistakes we have avoided in comparison to absolutely random classification of pixels, and the total percentage of correctly classified pixels. Results are in Tab. IV.

The protecting vegetation influence map was created just by matching one of three values with each type of vegetation cover, as is shown in Tab. III.

The final area avalanche susceptibility map was made by the combination (multiplication) of the morphological risk map and the protecting vegetation influence map and its values, the same as its entry layers, range from 0 to 1. The validation of the final map was done in the same way as in the case of the morphological map, but here the layer of all starting zones was used (Fig. 6).

From the results, we can see that most starting zones range from 0.8 to 1 which is a high degree of avalanche susceptibility. Other important values are represented in the interval from 0.4 to 0.5 (middle degree). These are paths with high morphological risk which is partly suppressed by dwarf pine.

The final step was computing the approximate shapes of avalanche paths from previously detected starting zones. With the help of the protecting vegetation influence map, the locations found in the areas with dense forest were removed because the risk of an avalanche is so small that it can be theoretically ignored. Then the flow characteristics from the rest of the starting zones, until the moment when the slope was lower than 10°, were calculated. The reference slope angle of 10° comes from mathematical analysis and worldwide experience that large avalanches in typical mountain terrain generally stop at slope angles near or below 10° (MCCLUNG and SCHAERER, 2006).

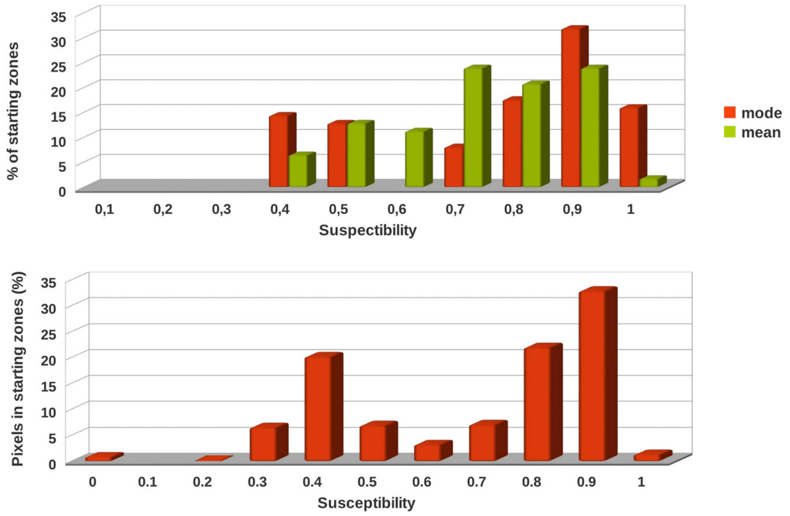


5: *Data of classification; from the left: spectrozonal image (1 – Luční bouda, 2 – Výrovka), NDVI, 1st component of PCA, classification result (grey – without vegetation, yellow – grass, light green – dwarf pine, dark green – coniferous stand)*

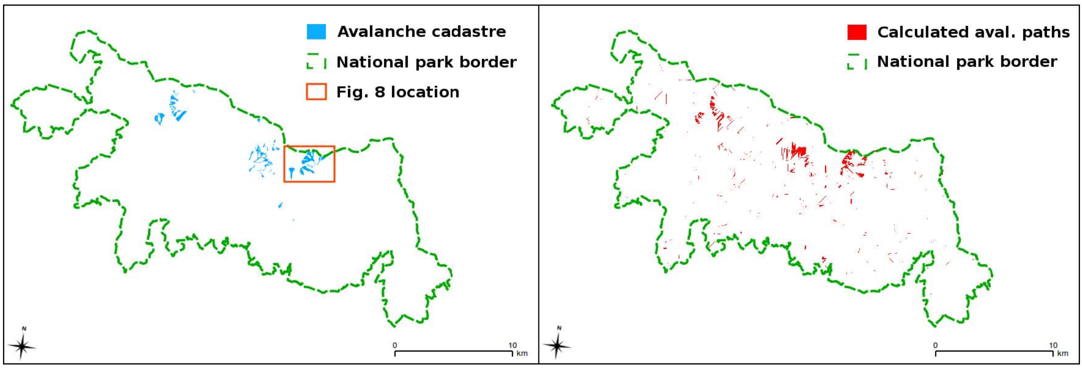
IV: *Error matrix of classification result. Kappa index and % of correct observed pixels*

	Reference map – validation sample of starting zone						
	Class	1	2	3	4	5	Row Sum
Classification map after postclassification correction	**1**	62 485	3 033	68	3	1 412	67 001
	2	8 220	1 761 760	26 933	24 191	131 713	1 952 817
	3	15	934	164 361	0	7 824	173 134
	4	16	48 163	0	120 154	54 176	222 509
	5	1 164	10 261	77 283	8 794	3 225 235	3 322 737
	Col Sum	71 900	1 824 151	268 645	153 142	3 420 360	5 738 198

Kappa	0.870828
% Observed correct	92.955924



6: *Validation of the map of avalanche susceptibility*



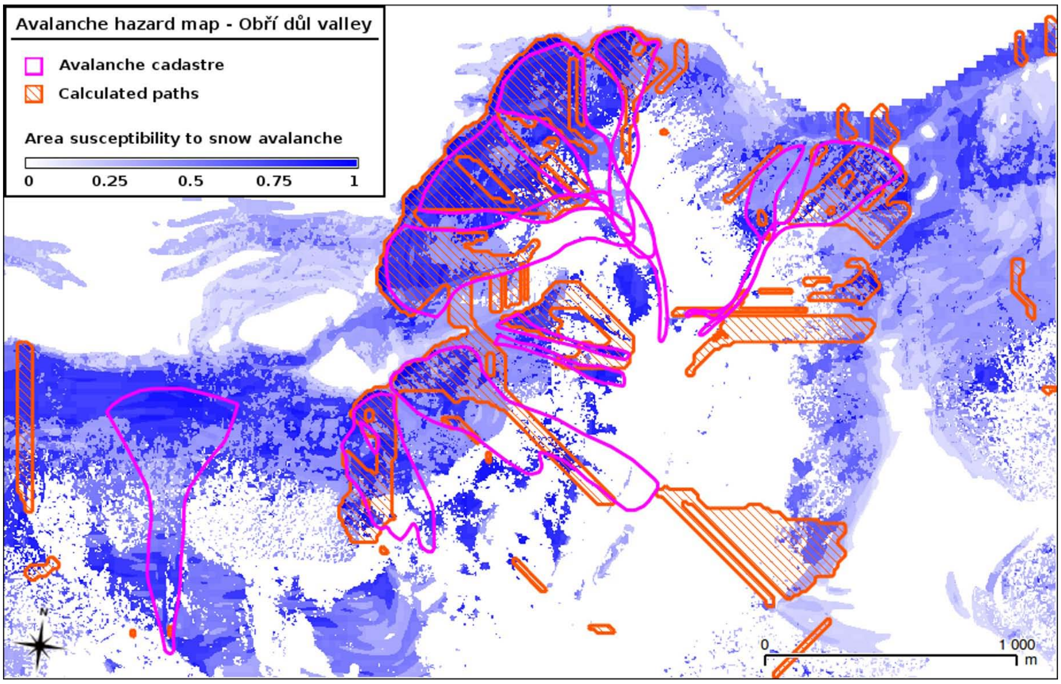
7: *Comparison of calculated avalanche paths and avalanche cadastre*

The comparison of calculated avalanche paths and outlines of avalanche cadastre is in Fig. 7. The final map composition containing the terrain susceptibility layer as well as the outline of the calculated approximate shapes of avalanche paths with its outline from the avalanche cadastre is in Fig. 8.

This map provides clear information on the existence of avalanche sites in the chosen area. Compared to the real state, all the recorded starting zones belong to the areas with high or middle susceptibility, depending on the vegetation present. On the other hand, there are places displaying a high susceptibility stage in the map, but there has not had any avalanches recorded so far. These are high-risk places from the morphological and vegetation point of view, but avalanches do not start here, probably due to other factors which are not taken into consideration in this model. These are mainly climatic factors, such as the falls frequency and wind direction and speed which significantly influence the height of the the snow cover. The most frequent wind direction is partially reflected by the aspect of the slope, but in the mountain terrain, there are more complex anemoorographic systems. Especially their quality processing could be another step which would increase the accuracy of the map.

Another way to improve accuracy would be the implementation of the snow cover layer into the computing model. Unfortunately, such a layer is not available. To gain it by measuring in the terrain would be very demanding, but certain results could be reached using the methods of remote sensing and creating a snow cover surface digital model. After being deducted from the DTM, the desired layer would develop.

The results of calculation of the starting zones and the approximate shapes of avalanche paths notably correspond to the real situation. Most of the real starting zones were detected by the calculation. However, there are some places with recorded avalanche activity which do not meet the given conditions (e.g. Modrý důl), these were thus not found by the calculation. In such places a combination of other factors can be of a critical influence. On the other hand there are localities marked as potential avalanche release areas, but there has been no avalanche activity recorded until today. These localities deserve a special attention because its inactivity in the past does not mean that



8: *Final avalanche hazard map – Obří důl valley*

it will stay that way in the future. The snow stability in such areas could also be caused by other factors (e.g. climatic factors), which are, nevertheless, not taken into account in this model.

CONCLUSIONS

The study shows that methods of applied geoinformatics can be successfully used to solve the issue of snow avalanches. The success of analysis directly depends on the entry data, especially on the quality of the DTM and vegetation stand map.

The calculation is based on the morphology of the area and on its vegetation cover. The achieved results show, that these two groups of factors are indeed of a great importance and that the final map of snow avalanche susceptibility corresponds to the real situation.

A further improvement of this model should also consider the climatic factors. Its aim should especially be to take into account the anemo-orographic systems and the snow fall frequency and distribution. The reason is that these factors have an essential influence on the height of snow cover in certain place.

The quality of the suggested model will have to be further proved also in other localities, especially because of the fact that in the Krkonoše Mountains most avalanche paths are to be found in glacial cirques with typical morphology.

SUMMARY

The area snow avalanche susceptibility map was made in the free Geographic Information System (GIS) GRASS environment. The chosen area was the Czech part of the National Park Krkonoše Mountains. The entry data was a digital terrain model in raster representation with a pixel size of 5 m and spectrozonal aerial photos with 0.5 m resolution. From the digital terrain, the basic morphological characteristics were derived (slope steepness, aspect and curvature) and with the help of the known starting zones, their typical values were found in these high-risk places. On their basis, the morphological risk map of the whole area was created. The second step was the development of the vegetation stand map. This was made by the supervised classification of spectrozonal images and it takes into account the protecting influence of different types of vegetation (grass, dwarf pine, forest). Both these maps were combined into the final area susceptibility map, which also included calculated starting zones in relation to significant terrain breaks and approximate shapes of avalanche paths calculated with the help of flow characteristics. The gained results are in compliance with the real state, but at the same time, show some drawbacks, especially the lack of climatic factors (fall frequency, wind direction and speed) which should be dealt with in other studies on this model.

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