Spatial modelling of snow avalanche run-outs using GIS

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Abstract. For several decades avalanche run-outs are subject to exhaustive research because of their importance in land use planning. Recent advances in GIS and availability of spatial data enable to perform analyses which help to make decisions concerning spatial planning within avalanche prone locations. Estimating avalanche run-outs is crucial step in the avalanche zoning process. The main objective of this work is to develop method for outlining the avalanche paths based on computer simulations running in GIS environment. The process consists of two parts: estimation of avalanche release zones and determination of avalanche run-outs. Primarily avalanche release zones were estimated by using an existing model proposed by Hreško. The model was modified and calibrated with the use of avalanche data extracted from avalanche database. The alpha-beta regression model developed in Norway is used to estimate avalanche run-outs. Avenue script enabling automated estimation of run-outs was implemented into ArcView, Computer simulations run on ArcView, ArcInfo and SAGA. Finally the results of the model calculation were visually assessed and compared with avalanche cadastre map,

Keywords: snow avalanches, GIS, run-out modelling, Western Tatras Introduction

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1 Introduction

In the course of several decades estimation of avalanche run-out based on topographical parameters has been carried out in some countries within Europe and North America. Early attempts were taken in USA [4] and Norway [7]. Since then in many countries and mountain ranges in the world [2,8,9,10] the so called alpha-beta regression model [7] has been introduced. Later on with advance of computers and geinformatics and their application within natural hazards zoning, GIS has been widely adopted. Terrain models [14] and GIS have been used either to estimate the potential avalanche release zones [5,11], model avalanche run-outs [2,8] or asses the protective function of forest against avalanches [3,13].

Four thousand avalanche paths are registered within five Slovak mountain ranges. Several hundreds of the avalanche tracks intersect with the roads, hiking trails and places often frequented by winter travellers and backcountry skiers. Avalanches have been observed during last 50 years and their findings have been documented either in written form or drawn into avalanche cadastre maintained by Slovak Centre of Avalanche Prevention - SCAP. Several disastrous avalanches with extreme run-outs occurred for last decade, proofed that avalanche cadastre suffers from spatial accuracy and it is not up to date. Thus its suitability for land use is in question.

So far several works dealing with estimation of potential avalanche trigger zones using GIS have been elaborated in Slovakia [1,2,3,5,6,13]. Most of them were carried out as part of research at local universities.

The aim of this work is to model snow avalanches as spatial phenomenon and outline the avalanche tracks. To reach this goal avalanche trigger zones have to be estimated. For this purpose the avalanche trigger model developed by Hreško [5] is implemented as automated procedure into ArcInfo. The model is based on the morphometric parameters and the terrain roughness. The aim is to change the original model according to the results of the statistical analysis of avalanche database and investigate whether the result fit into avalanche cadastre map. Verification of the altered model is done by visual assessment.

The result from avalanche trigger model serves as an input for alpha-beta regression model which estimates the run-outs. The model is based on regression relationship between angles describing the avalanche track. The intention is to assess the agreement between simulation results and historical avalanche map, as well as examine the proposed procedure for avalanche zoning.

2 METHODS

2.1 Western Tatra Mountains - Žiarska valley

The study area - Žiarska valley is located in the Western Tatras which belongs to the Carpathian mountain range, sub province Western Carpathians. The area is outlined by the main ridge on the north and two adjacent ridges from sides (Baranec ridge from the east and Príslop ridge from the west). The valley lies between 49,14°N, 19,69°E and 49.20°N, 19,72°E. The highest point reaches 2178 m a.s.l. on the peak of Baranec and the lowest point is situated on the place where river Smrečianka abandons the valley, 800 m a.s.l.. Glacier shaped the valley, leaving distinctive imprints characterized by rugged topography.
The valley is considered as one of the most avalanche prone valleys in the whole area of Carpathian Mountains. This environment represents an excellent opportunity for studying and modelling extreme avalanche run-outs. The valley is frequently visited by backcountry skiers and several roads and cabins are located there as well. There are 68 avalanche paths. Most of them originate in the alpine zone, disturb the upper tree line and reach the bottom of the valley. Winter season 08/09 with disastrous avalanches showed the importance of avalanche run-out modelling. Numbers of installations have been damaged due to improper land use planning without respect to extreme avalanches.

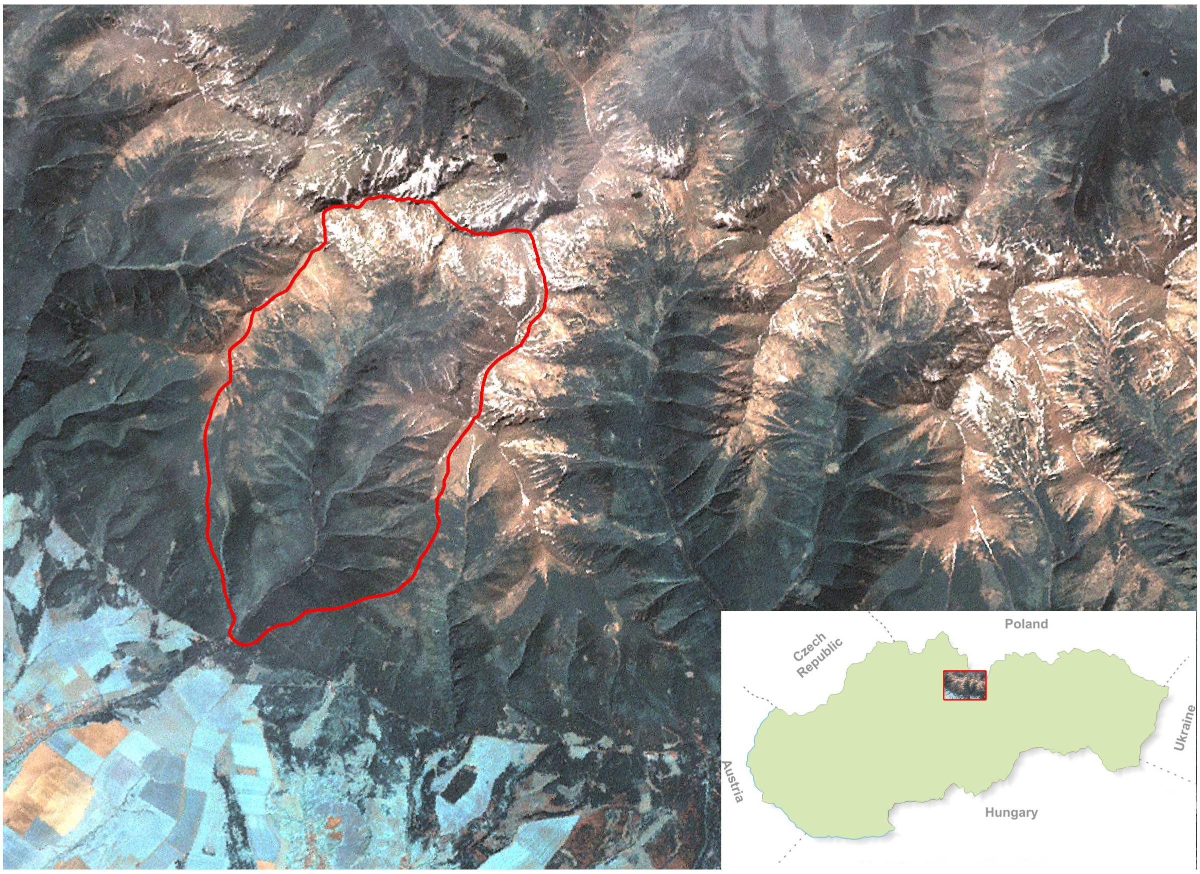

Fig. 1. Borders of the study region marked with polygon. Landsat image created by merging bands 3, 2, 1 and sharpened with panchromatic band.

2.2 Statistical analysis of Avalanche database SLPDB

The Avalanche database contains information on avalanches that has occurred within the territory of Slovakia. The database consists of information on release zones (elevation, exposition, aspect, type of snow etc.), transport zones (shape, topographic parameters), deposition zones (shape, height, type, etc.), casualties and damage (number of people involved and injured, deceased, forest damages). The first record is dated to 1937. For the purpose of release zones identification, relevant information (aspect and elevation of release zones) has been extracted from the database. Based on the avalanche database parameters the avalanche trigger zones model has been calibrated.

2.3 Data sources and pre-processing

The accuracy of the model results complies with accuracy of the data inputs. Therefore relative high accuracy of data inputs is required. Both models are based on topographical factors which require an accurate digital elevation model (DEM). 5 m interval contours were used as a base for creating the DEM. They were scanned from “The base map of Slovak republic” at scale 1:10 000. Consequently they were vectorized and the DEM was computed using spline function with tension [12]. Because of the presence of artificial undulations in the DEM (profile curvatures varied from concave to convex around contours), DEM pre-processing was performed. Random points with elevation attribute were extracted from the DEM. Points from valley and gully bottoms contours (in strips 20 m wide on each side of thalwegs) were added to random points. As a result new elevation data points were created. Using spline interpolation function resulted into generation of new DEM. Final DEM was without depressions in the valleys. It can be argued that there are more accurate ways of digital elevation model creation e.g. digital photogrammetry, aerial or terrestrial laser scanning or geodetic survey, but these methods are much more costly and time consuming. All topographical factors were extracted from DEM.
The land cover layer was obtained by analyzing large scale vegetation maps. Aerial imagery with resolution 1m acquired between 2002 and 2003 was another important data input for estimating the terrain roughness. The orthoimagery dataset was provided by the Slovak Museum of Nature Conservation and Speleology.

2.4 Avalanche release zones model

Avalanche trigger or release zones can be described as areas with certain topographical features which allow deposition of snow masses. Certain conditions these snow masses tend to release as snow avalanches until. Hreško [5] proposed a simple equation model for avalanche release zones estimation. The equation and model factors were changed according to the results of statistical analysis of the Avalanche database. This step was done to link the real avalanche situations with the proposed model.

$$Av = (Al + Ex + Fx + Fy) * S * Rg \qquad (\mathbf{1})$$

Where **Av** is the value estimating potential avalanche trigger zones, **Al** is the elevation factor, **Ex** is the aspect factor, **Fx** is the profile curvature factor, **Fy** is the plan curvature factor, S is the slope inclination factor and **Rg** is the roughness factor.
The landcover layer and DEM are the two main data inputs for the model calculation. Each of the factors (Al, Ex, Fx, Fy, S, Rg) were classified according to table 1 and using map algebra the final grid layer (Av) was calculated. Avalanche prone areas reach higher values of Av.

Table 1. Factors used to estimate trigger zones.

Elevation (m a. s. l.)	*Elevation Factor(Al)*	*Plan Curvature*	*Curvature Factor(Fy)*	*Profile Curvature*	*Curvature Factor(Fx)*
1200 - 1450	0,1	(-4) –- (-0,2)	1	4 – 0,2	1
1450 - 1700	1	(-0,2) – 0,2	1	0,2 – (-0,2)	1
1700 - 1950	2	0,2 – 0,5	1	(-0,2) – (-0,5)	1
1950 - 2200	0,5	0,5 – 4	0,5	(-0,5) – (-4)	0,5

Cover type	*Roughness Factor (Rg)*
forest (coniferous, deciduous, mixed)	0,5
open forest with dwarf-pine, rough stony debris and slope with lesser blocks	1,2
deciduous shrub wood	1,4
open forest	1,5
dwarf-pine and slope with juts of parent rock under 50 cm	2,5
grass with sporadic dwarf-pine, and small size slope debris	2,8
compact grass areas and rock plates	3

Slope (°)	*Slope Factor (S)*	*Aspect*	*Aspect Factor (Ex)*
0°- 10°, 70°- 90°	0	N	0,8
10°- 19°, 60°- 70°	0,4	NE	0,5
19°- 25°, 55°- 60°	0,8	E	0,7
25°- 30°, 50°- 55°	1,2	SE	1,5
30°- 35°, 45°- 50°	1,6	S	2
35°- 45°	2	SW	1
		W	1,7
		NW	0,4

The consequent reclassification according to the table 2 resulted into final the grid layer which represents avalanche prone areas.

Table 2. Final reclassification.

Equation (1) result Av	*Avalanche trigger hazard*
0 – 15	Low
15 – 22,5	Medium
22,5 – 30	High
30 – 36	Very high

Model builder module in ArcGIS was used to fully automate potential trigger zones estimation. For consequent avalanche run out modelling the pixels reaching an Av > 22,5 were selected. The final output was visually compared with the avalanche cadastre map, and imported into ArcScene to create 3D bird's eye views.

2.5 Avalanche run out modelling

For the purpose of this work a model developed in Norway by Lied and Bakkehøi was implemented into GIS. The model predicts the maximal avalanche run out, using terrain parameters of the avalanche chute. Avalanche dynamics is not taken into account. The authors based the model on analyses of hundreds of well known avalanche chutes. They chose a reference point (the β point) with β angle defined as the average gradient of the avalanche path profile from the position where the slope decreases to 10º to the trigger zone (Figure 2).
The α is the angle sighting from the extreme run out position to the trigger-zone. Least square regression analysis showed correlation between α and β angle and the relation have form of equation (2) [7] .

$$\alpha = C0 + C1\beta \qquad (2)$$

The model was calibrated on dataset of 30 avalanche paths with well known run-outs. With the assistance of avalanche expert knowledge of J. Peťo from SCAP maximum run outs were measured in terrain using GPS. A survey of aerial imagery accompanied the fieldwork to increase the accuracy of the measurements. Topographical parameters of each path were extracted in ArcGIS and regression analysis performed using the statistical package NCSS. Acquired regression coefficients together with avalanche trigger zones (where Av ≥ 22,5) served as the input parameters for script written in Avenue for ArcView3.x. This script approximates the avalanche movement as flowing water. It creates flowlines from certain points (avalanche trigger zones), than it finds β point, calculates the β angle and consequently based on the equation 2, it estimates the α angle. Later it estimates the α point and clips flowline at this place.

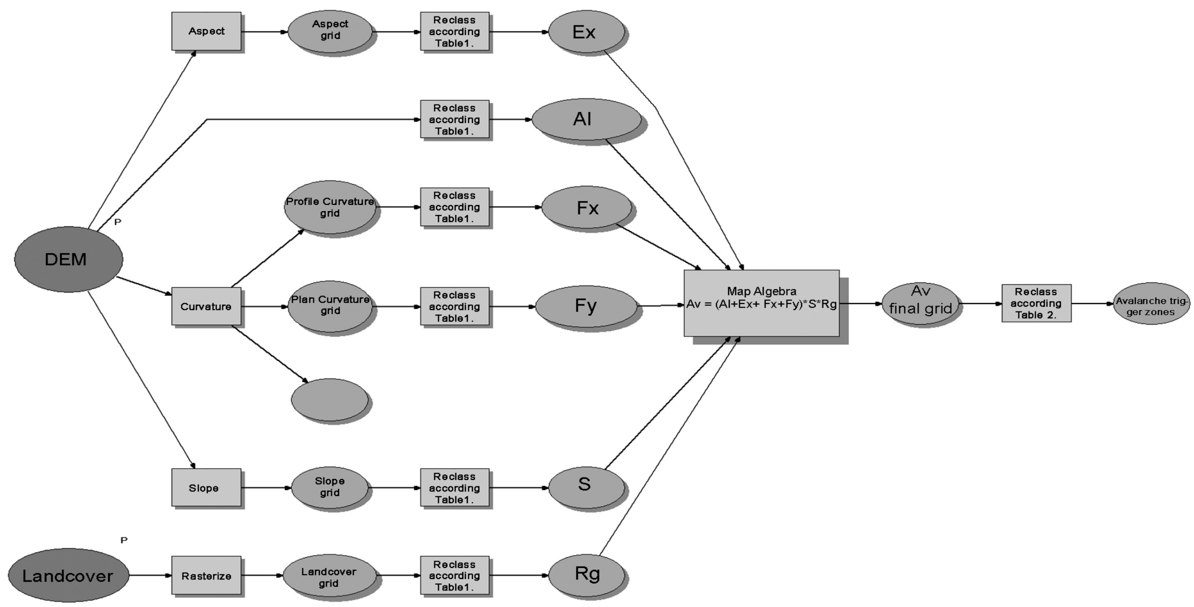

Fig. 2. Workflow of the model

The script runs automatically and beside the input points it requires a DEM in form of TIN. Because the avalanche movement is modeled as water some problems are occur. At one point all the flowlines connect and continue as one flowline which is natural behavior of the water but not common to avalanches. This problem was solved by the channel network module in SAGA GIS. The proposed method enabled almost automated estimation of avalanche paths. Due to the lack of time and computer capacity the method was used only on selected slopes.

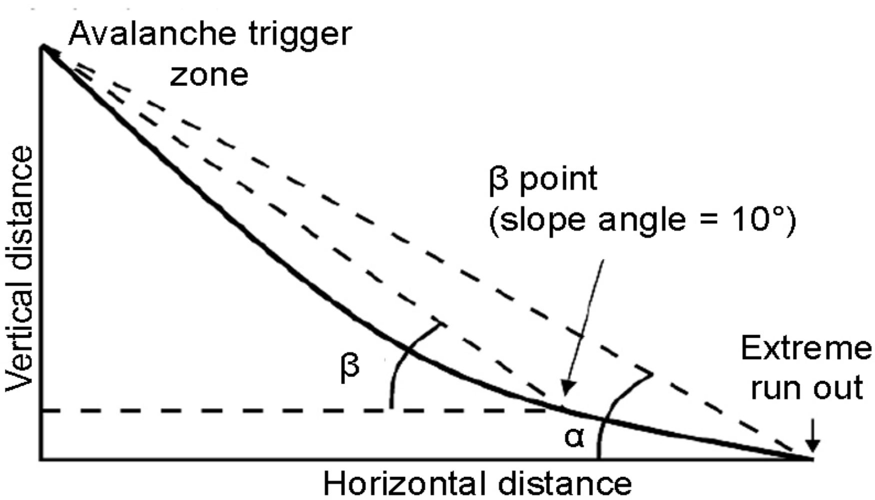

Fig. 3. Topographical run-out model.

3 Results

3.1 Statistical analysis of Avalanche database summary

A statistical analysis focuses on two factors: elevation and aspect. The aim was to find out what types of slopes are most avalanche prone. Altogether 571 avalanches records with valid height and aspect information were analyzed. Elevation analysis showed that most of the avalanches were triggered from interval 1700 - 1950 m a. s. l.. Specifically 339 avalanches what representing 59.3% of all analyzed avalanches.

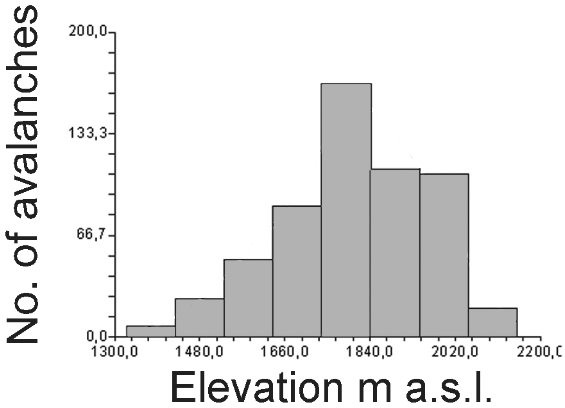

Fig. 4. Avalanche distribution according the elevation gradient.

Elevation (m a.s.l.)	*No. of avalanches*	*% of avalanches*
1200 - 1450	7	1,23
1450 - 1700	150	26,27
1700 - 1950	339	59,37
1950 - 2200	75	13,13

Table 3. Avalanche distribution in relation to the elevation.

The most avalanche prone slopes have south aspect with 137 avalanches occurred, followed by west and south-east aspects with 117 respectively 103 avalanches. 60,47% of all the avalanches occurred on slopes with S, W, and SE orientation.

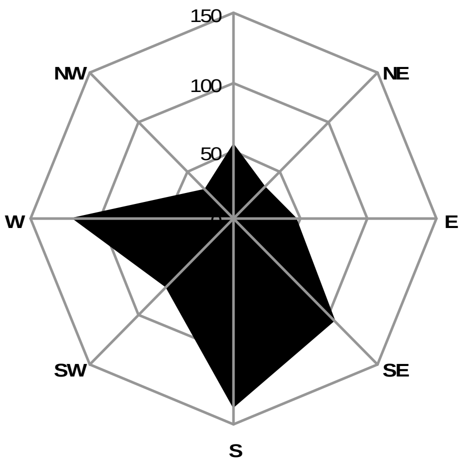

Fig. 5. Avalanche distribution in relation to the aspect.

Aspect	*No of avalanches*	*% of avalanches*
N	54	9,12
NE	33	5,57
E	46	7,77
SE	104	17,57
S	137	23,14
SW	71	11,99
W	117	19,76
NW	30	5,07

Table 4. Avalanche distribution in relation to the aspect.

3.2 Avalanche trigger zones

It was expected that trigger zones estimated by the model will occur in upper parts of historical avalanche paths. Several historical path and modeled trigger zones show some inconsistency. Field investigation and aerial imagery inspection indicated large forest succession in these places for last 25 years. Due to this succession avalanche activity was reduced to minima.

Using up to date land cover maps and orthoimagery input for the model resulted in the proper estimation of potential avalanche trigger hazard. The model revealed that 67,45% of the studied area falls into the zone with small avalanche trigger potential 21,56% with medium 10,4% with high and 0,59% as very high avalanche trigger potential. See figure 5.

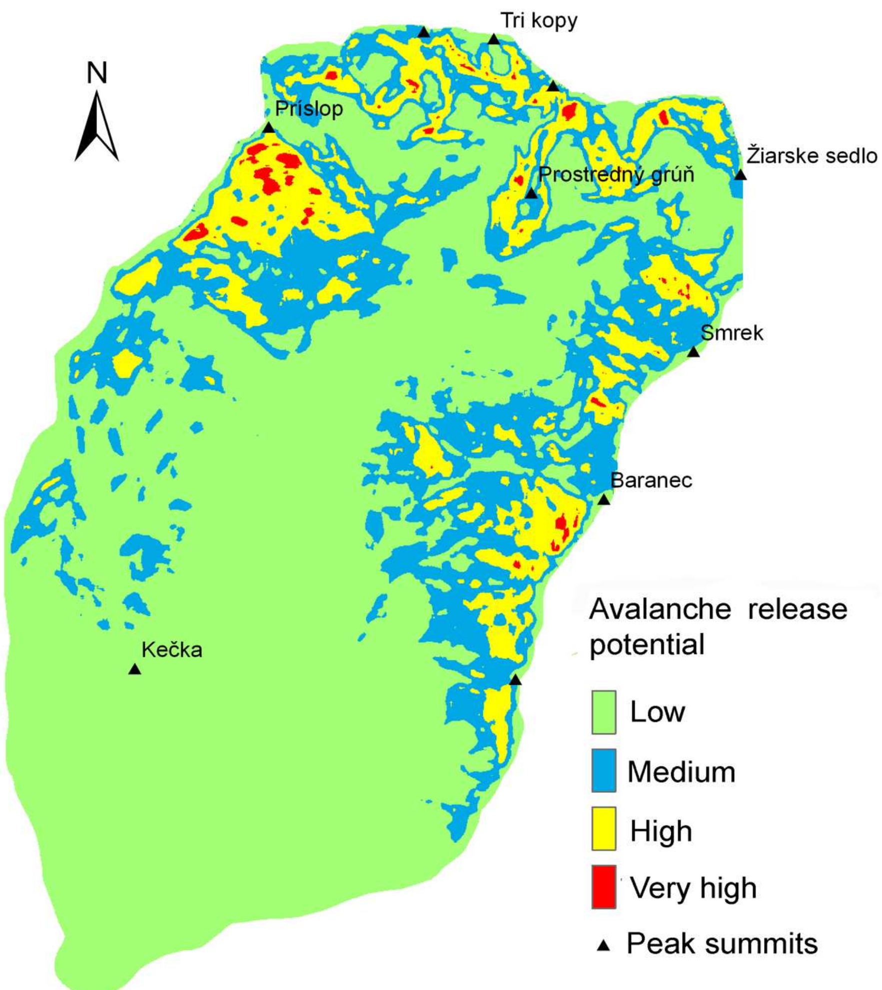

Fig. 6. Avalanche release potential within studied site.

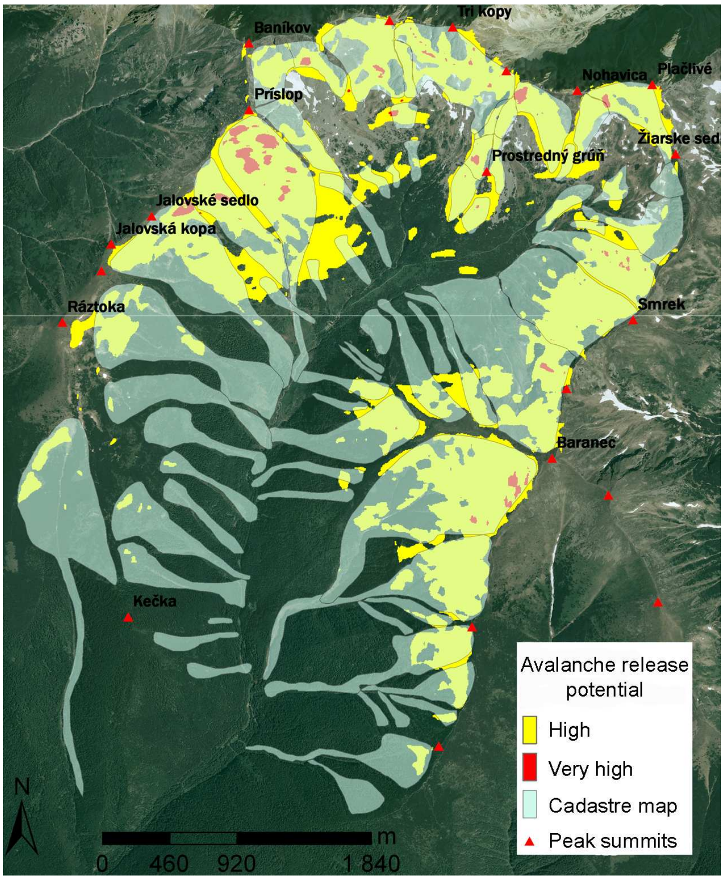

Fig. 7. Avalanche release potential compared with cadastre map.

See figure 6. Ridges were properly classified as places with minimal avalanche trigger potential. On the other hand steep gullies and vast steep slopes covered with grass were estimated as areas with high or very high risk potential.

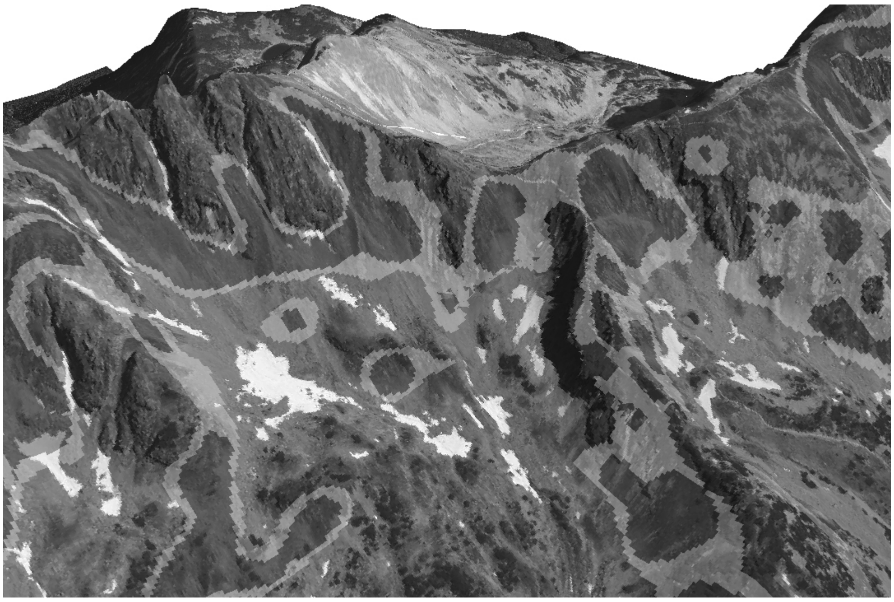

Fig. 8. Avalanche release potential Av>22,5.

3.3 Avalanche run-outs

Using the scripting language Avenue in GIS allowed implement statistical run out modeling in automated way. This was done on selected slopes. Thirty well known avalanche tracks in Žiarska valley plus in two neighboring valleys (Račková, Jamnická) were mapped using GPS and α and β angles were calculated. The obtained data were used to estimate the regression coefficients. The final regression equation for the Western Tatras is:

$$\alpha = 0{,}91\beta - 0{,}04° \qquad (3)$$

Correlation coefficient for this regression is 0,95 coefficient of determination is 0,9 and standard Error of predicted α angle is 1,1. Final run-outs are compared with avalanche cadastre (Figure 7).

Fig. 9. Output of the run-out model compared with avalanche cadastre – white polygons.

In several cases the model failed to represent run-outs naturally, e. g. run-ups and channeled curvy run-outs. This happens because the avalanche movement is approximated as water flow. Circumstances occurred in narrow channels where all the flowlines gathered together and from a certain point on, they flowed together. This was partially solved by channel module in SAGA. Unfortunately in some extremely curved channels satisfying results were not obtained and different methods should be used for determining avalanche width.

4 Conclusion

The visual assessment of the avalanche trigger model shows agreement with avalanche cadastre in some cases. The model did not estimate several trigger zones located mainly in the lower parts of the valley. This can be explained by the succession undergone in these trigger zones. Field investigation proofed that the trigger zones are naturally reforested and therefore avalanche activity is reduced. This conclusion is also supported by direct avalanche observations which did not report any avalanche for last 15 years. It is crucial to use the most up to date data on landcover because only this can guarantee the proper estimating of the actual trigger areas. The release zones evolve in space and time according to the development of the avalanche activity and the forest succession.

The avalanche trigger model is easy to implement into GIS environment. It is simple to calculate the model factors and after several improvements the model might be used in avalanche zoning. It will be interesting to see the future development of the model. Coupling the model with meteorological data could help to improve the results. Particularly it could enable to estimate actual trigger zones in real time depending on the weather situation. This would be a big help for people traveling in avalanche prone areas.

The alpha-beta regression model implemented into GIS showed several discrepancies with real behaviour of the snow avalanches. In many cases it was not possible to find the beta reference point. This is caused by the relative steepness of the study region. Most of the avalanches do not reach the beta point and they terminate either on the steep valley bottom or the opposite slope. The model was devolved in Norway taking into account local topography which differ form topography in Western Tatras. It cannot be stated the model doesn't t work at all. It works, but just for specific slopes. The model is suitable for straight down sloping paths with no run-ups in the depositional area.

The examined method for avalanche zoning showed that many improvements will have to be done to use this method for landuse planning. It is an advantage especially for avalanche zoning in small scales that models are implemented into GIS and can perform the simulations in automated manner.

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