Statistical avalanche run-out modelling using GIS on selected slopes of Western Tatras National park, Slovakia

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ABSTRACT: Without doubt avalanche run-out distances play a key role in landuse planning within avalanche prone areas. The Žiarska valley in Western Tatras is considered as one of the most avalanche prone valleys in the whole area of Carpathian Mountains. This environment represents a perfect opportunity for studying and modelling extreme avalanche run-outs. The valley is frequently visited by backcountry skiers as well as roads and several cabins are located there. Therefore a careful land use planning with respect to extreme avalanche run-out is crucial. First of all avalanche release zones were estimated by using an existing model proposed by Hreško. This model was changed and calibrated using avalanche data extracted from a database which is maintained by Slovak Centre for Avalanche Mitigation. The alpha-beta regression model developed in Norway has been used for estimating avalanche run-outs. This model is calibrated for use in Western Tatras. Topographical parameters from well known extreme avalanche paths have been collected using GPS. Data processing and model calibration have been elaborated in GIS environment. Avenue script for ArcView was written to perform automated run-out estimation based on alpha-beta regression model. Model managed fairly well to estimate runouts on some slopes while it failed to model runups. Finally the results were visualized by creating the fly-through simulations and 3D views. Winter season 08/09 with catastrophic avalanches showed the importance of avalanche run-out modelling. Many installations have been damaged due to improper land use planning without respect to extreme avalanches. Comparison between model calculation and avalanche cadastre showed correlation.

KEYWORDS: Snow avalanches, GIS, run-out modelling, Western Tatras.

1 INTRODUCTION

For 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 done in USA (Bovis and Mears, 1976) and Norway (Lied and Bakkehøi, 1980). Since then in many countries and mountain ranges along the world (Fujisawa et al., 1993; Furdada and Vilaplana, 1998; Johannesson, 1998; Barka Jonesand Jamieson, 2004; Lied et al., 1995; Delparte, 2008) the so called alpha-beta regression model (Lied and Bakkehøi, 1980) has been introduced. Later on with advance of computers and geinfomatics and their application within natural hazards zoning, GIS has been widely adopted. Terrain models (Toppe, 1986) and GIS has been used either to estimate the probable avalanche release zones (Hreško, 1998; M. Maggioni and Gruber, 2003), model avalanche run-outs (Barka; Delparte 2008 ;) or asses the protective function of forest against avalanches (Sitko, 2008; Bebi, 2009).

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 for last 50 years and these observations have been documented either in written form or drawn into avalanche cadastre maintained by Slovak Centre of Avalanche Prevention SCAP. Several catastrophic avalanches with extreme run-outs occurred for last decade, shown that avalanche cadastre suffers from spatial accuracy and it is not up to date. Therefore its use for land use planning is in questionable.

So far there have been several works dealing with estimation of probable avalanche trigger zones using GIS in Slovak mountain ranges (Hreško, Barka, Barka and Rybar, Kohut, Sitko). Most of them were carried as part of research at home universities. The aim of this work is to show how GIS might be used to estimate probable avalanche trigger zone and model runouts on selected slopes. Simple equation model (Hreško, 1998) for release zones is implemented and used to automate the mapping of

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release zones in GIS. The model calibration has been based on data from Avalanche database maintained by SCAP. Avalanche path model uses statistical regression model described by Lied and Bakkehøi (Lied and Bakkehøi, 1980). The model is implemented into GIS by script written in Avenue programming language. Despite that the model failed to accurately represent runups and curvy channeled paths, it has worked well with linear straight down sloping paths.

2 METHODS

2.1 *Statistical analyses of Avalanche database SLPDB*

Avalanche database contains information about avalanches that has occurred within the area 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 damages number of people involved, injured, deceased, forest damages). First record is dated to 1937. For the purpose of release zones identification, relevant information (aspect and elevation of release zones) from database has been extracted. Based on these parameters avalanche trigger zones model has been calibrated.

2.2 *Data sources and preprocessing*

The accuracy of the model results goes hand in hand with accuracy of data inputs. Therefore there is requirement for relative high accuracy of data inputs. Both models are based on topographical factors what claim on accurate digital elevation model (DEM). 5 m interval contours were used as a base for creating DEM. They were scanned from "The base map of Slovak republic" at scale 1:10 000. Consequently they were vectorized and DEM was computed using spline function with tension (Mitá□ová and Hofierka 1993). 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 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. This way of DEM creation prevented generation of depressions in the valleys. It might 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 way more costly and time consuming.

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

Table 2. Final reclassification table.

Landcover layer obtained by analyzing the large scale vegetation maps and aerial imagery was important data input for estimating terrain roughness.

2.3 *Probable Avalanche release zones model*

Avalanche trigger or release zone can be described as places with certain topographical natures which allow deposition of snow masses. These snow masses might be until certain conditions released as snow avalanche. Hre□ko proposed simple equation model for avalanche release zones estimation. The equation and model factors were changed according to the results of statistical analysis of Avalanche database. This step was done to link the real avalanche situations with the proposed model.

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

Where **Av** is value estimating potential avalanche trigger zones , **Al** is elevatin factor, **Ex** is aspect factor, **Fx** is profile curvature factor, **Fy** is plan curvature factor, **S** is slope inclination factor and **Rg** is roughness factor.

Landcover layer and DEM are two main data inputs for 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 are reaching higher values of Av.

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 covered by 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

Table 1. Factors used to estimate probable avalanche trigger zones.

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

ArcGIS was used to fully automate probable trigger zones estimation by using model builder module figure 1. For later avalanche run out modelling the zones reaching the Av value at least 22,5 or more were selected. The final output was compared with avalanche cadastre map, visually assed and imported into ArcScene to create 3D bird's eye views.

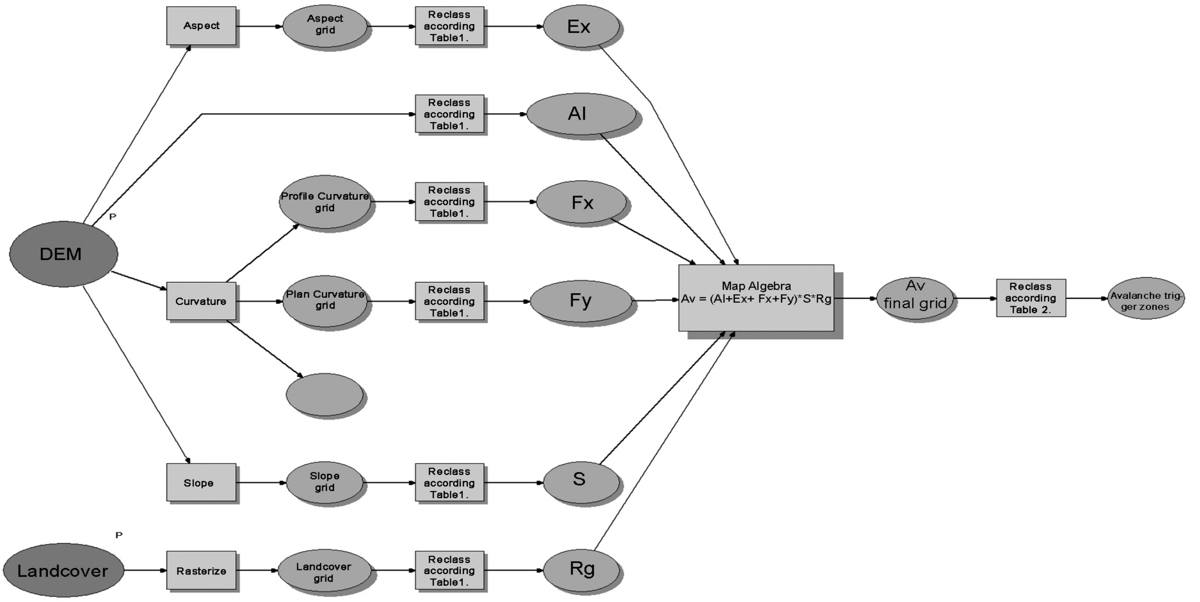

Figure 1. Workflow of the model.

2.4 Avalanche run out modelling

For the purpose of this work model developed in Norway by Lied and Bakkehøi was implemented into GIS. Model predicts 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 (so called the β point) with β angle defined as

the average gradient of the avalanche path profile from the position where the slope decrease to 10° 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 have form of equation (Lied and Bakkehøi, 1980).

$$\boldsymbol{\alpha = C_0 + C_1\beta \quad (2)}$$

Model was calibrated on dataset of 30 avalanche paths with well know run outs. With the help of avalanche expert knowledge of J. Peťo from SCAP maximum run outs were measured in terrain using GPS. Survey of aerial imagery accompanied the fieldwork to increase the accuracy of measurements. Topographical parameters of each path were extracted in ArcGIS and regression analysis performed using statitsical package NCSS. Acquired regression coefficients together with avalanche trigger zones (with Av ≥ 22,5) served as the input parameters for script written in Avenue for ArcView3.x. This script models avalanche movement as flowing water. It creates flowlines from the certain points (avalanche trigger zones) than it finds β points calculates the β angle and based on the equation 2 it estimates α angle. Consequently it estimates α point and cuts flowline in this place. Script runs automatically and beside the input points it needs DEM in form of TIN. Because the avalanche movement is modeled as water some problems raised. In one point all the flowlines connected and continued as one flowline which is natural behavior of the water but not common to avalanches. This was solved by channel network module in SAGA GIS. The proposed method enabled almost automated estimation of avalanche paths. Due to the time lack and com-

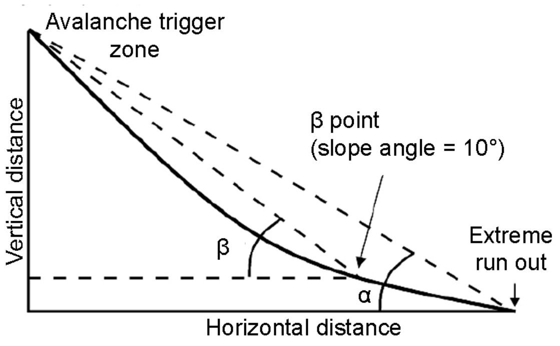

Figure 2. Topographical run-out model.

puter capacity the method was used only on selected slopes.

3 RESULTS

3.1 Statistical analysis of Avalanche database summary

A statistical analysis was focused on two factors: elevation and aspect. The aim was to figure out what kind of slopes are most avalanche prone. Altogether 571 avalanches records with valid height and aspect information were analyzed. Elevation analyze showed that that most of the avalanches triggered from interval 1700 - 1950 m a. s. l. , Specifically 339 avalanches what represents 59.3% of all analyzed avalanches. Further insight to elevation aspect and avalanches see figure 3 and table 3.

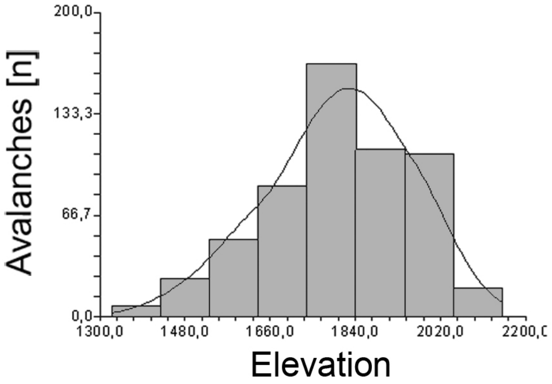

Figure 3. Avalanche distribution within elevation.

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 within 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. More than half of the avalanches occurred on slopes with S, W, and SE orientation. Further details see figure 4 and table 4.

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 within aspect

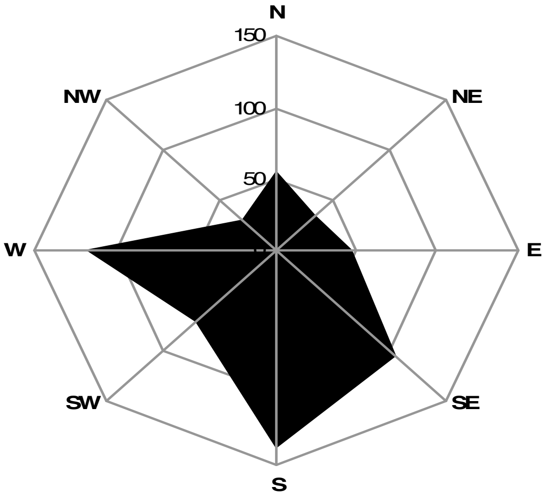

Figure 4. Avalanche distribution within aspect.

3.2 Avalanche trigger zones

Results from the model estimating probable avalanche paths correlates well with avalanche cadastre map figure 7. It was expected that trigger zones estimated by the model will occur in upper parts of historical avalanche paths. Some 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 ortophotos as an input for the model resulted in the proper estimation of potential avalanche trigger hazard. Model revealed that 67,45% of the study 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. Due to the implementing the data from avalanche and database curvature factor estimated release zones reflects the nature of avalanche triggering. It can be seen from figure 6. Ridges were properly classified as places with minimal avalanche trigger potential. On the other hand high or very high risk potential was given to the steep gullies and vast steep slopes covered with grass.

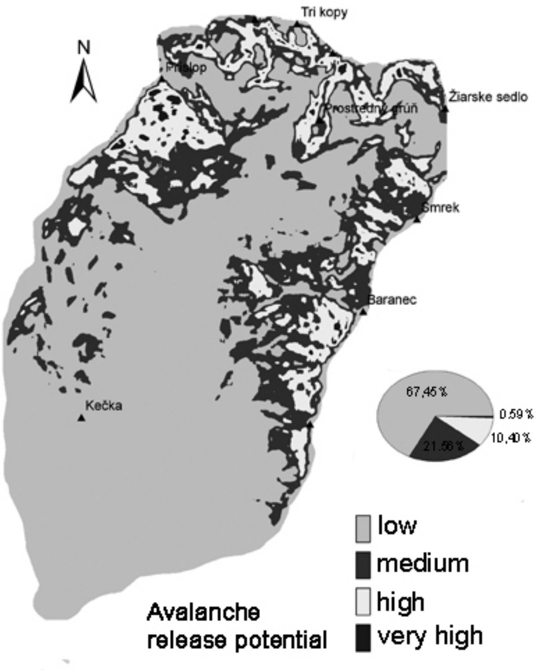

Figure 5. Avalanche release potential within study site.

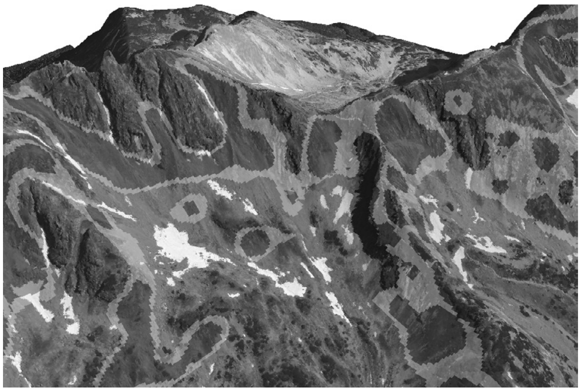

Figure 6. High and very high avalanche release potential.

3.3 Avalanche run outs

GIS with the help of script language (Avenue) allowed implementing statistical run out modeling in automated way. This was done on selected slopes. The final regression equation for the Western Tatras is

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

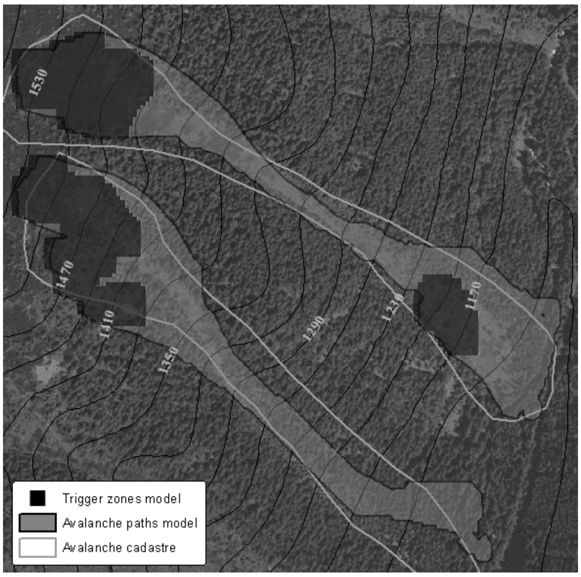

Figure 7. Output of the run-out model.

Correlation coefficient for this regression is 0,95 coefficient of determination is 0,9 and standard error of predicted α angle is 1,1. Figure 7 shows final run outs on the two of the selected avalanche paths. It can be said that in this case model outputs are in well correlation with historical avalanche cadastre map. In some other cases model failed to represent run outs naturally e. g run ups, channeled curvy run outs. Because the avalanche movement was approximated as water flow, circumstances occurred in narrow channels where all the flowlines gathered together and from certain point they flowed together. This was partially solved by channel module in SAGA. Anyway some in some extremely narrow channels satisfying results were not obtained and different methods should be used for determining avalanche width.

3.4 Conclusion

Probable avalanche trigger zones estimated by simple equation model are in good agreement with avalanche cadastre. This easy to use model is easy to implement into GIS environment. It is simple to calculate model factors and the results are in sufficient correlation with real observations represented by cadastre map. Therefore it would be suitable to introduce model in avalanche hazard zoning praxis. Therefore Alpha-beta regression model was implemented into GIS by using script which enabled automated runouts estimation. Model failed to to estimate runups because the avalanche movement was modelled as flowing water Anyway the proposed method might be particular useful in updating avalanche cadastre map on straight down sloping paths with no run-ups in the depositional area.

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