Identification of areas potentially affected by extreme snow avalanche combining expert rules, flow-routing algorithms and statistical analysis

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ABSTRACT: An innovative methodology to perform avalanche hazard mapping that combines open source GIS tools, expert rules, computational routines, and statistical analysis is herewith briefly presented. The method provides a “semi-automatic” definition of areas potentially affected by avalanche release, motion, and run-out and is based on a combination of an ad-hoc developed “flow-routing algorithm” and a statistically-based estimation of the run-out distance of avalanches. The proposed methodology allows obtaining a preliminary, cost-efficient assessment of the avalanche hazard zones, especially for those areas where historical information is lacunose or even missing. Furthermore it allows including confidence bonds into the analysis, providing different avalanche outline as a function of the safety requirements.

KEYWORDS: Snow avalanche, hazard mapping, GRASS GIS, flow-routing algorithm, run-out angle.

1 INTRODUCTION

Hazard mapping is a well-known and widely applied methodology in avalanche hazard assessment and management. Hazard maps are used for land-use planning in hazardous areas as well as for risk assessment and mitigation (McClung, 2005). Depending on map scale, contents, and methods used in data collection and processing, it is possible to distinguish between two types of avalanche hazard maps: hazard registration maps containing the maximum boundaries of historically known avalanches and hazard zoning maps (Gruber et al., 1998; Sauermoser, 2006), outlining zones with different degrees of hazard drawn on the basis of known historic events, geo-morphological investigations, and statistical and/or dynamic computational models.

In both cases the knowledge of avalanche history in the investigated area is a crucial factor. It either represents direct information about zones potentially affected by avalanches for registration maps or an essential source of data for model calibration when hazard zoning maps have to be generated.

However, in many practical situations the lack of historic records is substantial; nevertheless, a preliminary, swift mapping of the avalanches is required. Our study addresses these situations with a model capable to perform avalanche hazard mapping over large undocumented areas.

2 MODEL DESCRIPTION

The model is implemented within an open source geographic information system (GRASS GIS) and consists in two modules (Figure 1): the first module allows a semi-automatic identification of potential avalanche release zones while the second module (in the following referred to as AFRA – Avalanche Flow and Run-out Algorithm) provides an automatic definition of the areas potentially affected by avalanche motion and run-out under extreme conditions.

The model is enabled to simultaneously perform calculations of several different avalanches as well as to predict avalanches with multiple release areas.

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2.1 Release area module

The recognition process for potential release zones is carried out, identifying all areas that present morphological and land cover features typical of snow avalanche releases (McClung and Schaerer, 1993; Maggioni and Gruber, 2003; Maggioni 2004).

It has been introduced a parameter, called extreme avalanche release index \( I_E \) (Eq. 1), that is a function of morphological and land cover features typical of snow avalanche release areas.

\[
I_E = f(\theta) \cdot C_f(K_i) \cdot Z_f(z) \quad 0 \leq I_E \leq 1
\]

Where \( f(\theta) \) is the slope factor (Eq. 2), a decreasing function of the slope that indicates the propensity of the area to retain the snow (Salm et al., 1990).

\[
f(\theta) = \frac{0.291}{\sin \theta - 0.202 \cdot \cos \theta}
\]

\( C_f \) is the curvature factor, a function of the tangential curvature \( k_i \) (Neteler and Mitasova, 2007) that goes from one in concave zone to zeros in convex ones. In this way convexe areas are excluded from potential release zones and used to separate single release areas. Slope and curvature are calculated using a D.E.M. with a grid size of 10 x 10 meters cells. \( Z_f \) is an increasing function of the altitude. Finally, the extreme release index in dense forest area is set equal to zero; the presence of protective forest can usually be detected on a land cover maps. \( I_E \) values close to 1 determine the zones more favourable to snow masses accumulation, and thus more inclined to release of extreme avalanches.

The procedure represent \( I_E \) on a map (Figure 2). At the moment, a completely automatic delimitation cannot guarantee a sufficient level of accuracy. The final delimitation of the release areas has to be carried out manually (blue boundary in Figure 2).

2.2 Avalanche flow and run-out module (AFRA)

The avalanche flow algorithm identifies the cells that can be potentially affected by avalanche motion. The algorithm integrates the DEM data and the delimited release areas and sequentially transfers the flow from release areas to lower cells. A variety of flow-routing algorithms have been proposed in the literature and the theoretical advantages and disadvantages for different applications have been discussed (Desmet and Govers 1996, Tarboton 1997).

In order to better represent snow avalanche characteristics, a specific flow-routing algorithm - based on the FD8 multiple flow direction algorithm (Gruber and Peckham 2008) - has been developed. The algorithm (Equation 3) directs the material to every adjacent downslope cell on a slope-weighted basis:

\[
H_i = H \frac{\tan \varphi \cdot L_i}{\sum \tan \varphi \cdot L_i}
\]

where \( H_i \) is the fraction of material draining through neighbour \( i \), \( H \) is the upslope material accumulated in the current cell, \( \varphi \) is the slope towards neighbour \( i \), \( k \) is the total number of downhill directions and \( Li \) is the geometric weight factor for flow towards neighbour \( i \) (0.5 for cardinal and 0.354 for diagonal directions, Quinn et al. 1991). The slope \( \varphi \) (Eq.3) is calculated using the height of the cell plus the material \( H \) on top of it. This adjustment to the original FD8 algorithm allows the flow to
overcome small counter-slope tracts, favors the spreading of the material over the empty cells, and takes into account storage areas like dams and small ridges.

The avalanche flow algorithm identifies the path of an avalanche but does not deliver an outline for the downstream avalanche limits, since a description of the run-out processes is not incorporated into it. In order to reasonably estimate the extension of run-out zones, we included in the algorithm a statistically-based estimate of avalanche run-out distance.

According to widespread literature (McClung and Mears 1991, De Blasio et al. 2006, Delparte et al. 2008) rapid gravitational flows maximal run distance can be expressed as a function of the angle of reach $\alpha$ (Equation 4).

$$\alpha = \arctan(\Delta H/\Delta L)$$

where $\Delta H$ is the material fall height and $\Delta L$ is the horizontal run-out. The $\alpha$-angle represents thus the slope of the line connecting the uppermost point of the release zone with the lowest point attained by avalanche debris.

We based our statistical model on a database of 204 extreme avalanches, collected during expertises and research activity, and scattered throughout the Italian mountain ranges (Alps and Apennines). The average return period of the considered avalanches is about 50 years (ranging approximately from a minimum of 30 years to a maximum of 100 years). Topographical information about these avalanches has been taken from the Cadastre maps available for the considered zones.

The database contains for each avalanche several topographical parameters inferable from the maps, including the length distance ($\Delta L$) and height distance ($\Delta H$), allowing the $\alpha$-angle to be estimated.

The degree of correlation of $\alpha$ with all the topographical parameters included in the database has been tested and statistically evaluated. A dependence of $\alpha$ has been found to exist on the average slope of the release area $\gamma$ and the height above the sea level of the uppermost point of the release area $Z_{\text{max}}$.

A multiple regression of the $\alpha$ angle over the two variables $\gamma$ and $Z_{\text{max}}$ gives the following equation:

$$\alpha = 14.91 + 0.447 \cdot \gamma - 0.0016 \cdot Z_{\text{max}}$$

with a coefficient of correlation $R=0.63$ and a regression error $\varepsilon=3.98^\circ$.

This equation has been implemented in the flow-routing algorithm giving a confining parameter in the results of the avalanche flow algorithm.

Figure 3 shows an example of implementation of the procedure. Several different potential release areas are outlined on both sides of the valley (see Figure 2), flowing in the same track and run-out zone. The potential release areas identified, together with the DTM, work as input data for the AFRA module, which in turn gives the zones potentially affected by avalanche motion and run-out under extreme avalanches.

The avalanche hazard map provided in Figure 3 is drawn with different confidence levels. The darker part is generated using the average (extreme) angle of reach $\alpha$, calculated from Equation 5, while the lighter one is obtained accounting for the regression error, that is using $\alpha-\varepsilon$.

Figure 3. Example of application of the procedure.

3 CONCLUSIONS

An innovative methodology to perform avalanche hazard mapping is presented. The method combines open source GIS tools, computational routines, and statistical analysis in order to provide a “semi-automatic” definition
of areas potentially affected – under extreme conditions – by avalanche release, motion, and run-out. The method allows rapid, cost-effective, mapping of large areas. It requires as input parameters only a digital terrain model and an indication of the areas covered by (protective) forest.

The proposed method does not intend to contrast current mapping methods based on avalanche dynamic models. Conversely, it is complementary to them. In practical situations where a preliminary and swift mapping of large areas is needed the procedure illustrated in this study could represent a valid alternative. This is especially true for those cases where the avalanche’s history is poorly known or even completely missing, given that our procedure does not in principle require any site-specific historical information.

Most of the procedure’s steps can be done in an “automatic” way. Subjective judgments of users are thus very limited. With this respect, the applications have shown so far that manual control in the definition of avalanche release area is particularly useful to obtain better results.

The method, thanks to the use of a specifically implemented flow-routing algorithm, allows us to easily conduct bi-dimensional mapping of exposed areas. The avalanche flow algorithm provides reasonable flow behavior in the track and run-out zones in cases of complex topography (such as multiple release zones or sharp bends along the track). However, it is necessary to remember that the proposed flow algorithm does not include any description of physical processes: neglecting effects of inertia could lead to a possible underestimate of run-up flows.

The estimate of the run-out distance is based on a statistical analysis of historical avalanche data. Such an approach allows to us obtain an assessment of the average behavior under extreme conditions, but also provides the possibility to explicitly include confidence bonds in the analysis by using standard errors of statistical estimation.

4 REFERENCES
