

Using spatially distributed statistical models for avalanche runout estimation

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ABSTRACT: State of the art physical-dynamical avalanche models are a commonly used tool in avalanche research and practice. Research and practical experience have shown that an accurate assessment of input parameters (boundary conditions, friction parameters, numerical settings) is required for the application of these models. Along with the computational effort when covering large areas, these factors limit the applicability of sophisticated physically-based models for regional-scale studies. In recent years simple spatially distributed models with limited input parameter requirements have been successfully applied to regional-scale case studies on different gravitational mass movement processes (rockfall, landslides, debris-flows). These models often combine a one dimensional empirical or simple physically-based method for estimation of process intensities along a predefined longitudinal profile with different hydrologically-based algorithms for flow propagation and spreading. This approach allows the two dimensional application of the one dimensional models to terrain, represented by raster elevation models. However, publications on the application to snow avalanches have been scarce in comparison to other mass movement processes. We present an application of a simple, spatially distributed empirical model for snow avalanche runout estimation to different avalanche paths in Austria and discuss the possibilities and limitations of the employed approach.

Key words: avalanche, avalanche modeling, raster-based modeling, regional-scale, hazard-indicator maps

1. INTRODUCTION

State of the art physical-dynamical avalanche simulation models (e.g Zwinger et al., 2003; Sampl and Zwinger, 2004; Christen et al., 2010) are commonly employed tools by avalanche practitioners and researchers alike. However, it has been stressed by some authors, that an accurate assessment of required input parameters is essential for the application of these models (Ancey, 2005; Fischer et al., 2015). Especially with respect to modelling of avalanche prone areas on a regional-scale, the assessment of required input parameters as well as considerations regarding needed computation time can make the application of sophisticated physical-dynamical models inconvenient.

In recent years a number of simple spatially distributed models with limited input parameter requirements have been developed and successfully applied to regional-scale case studies on different gravitational mass movement processes. Gamma (1999) presented a random-walk based model for debris

flows which has been applied for the production of hazard-indicator maps for debris flows in Switzerland (Zimmermann et al., 1997); a similar approach is also reported by Wichmann and Becht (2003). Huggel et al. (2003) developed a similar model and used it for the assessment of hazards related to glacier lake outbursts; the model has also been applied to other phenomena (e.g. Stolz, 2006; Scheuner, 2007; Huggel et al., 2007). Scheidl and Rickenmann (2010, 2011) suggested a combination of an empirical and a simple physical approach for intensity-estimation for debris flows in combination with a random walk algorithm for assessment of debris flow deposition on the fan area. Horton et al. (2013) published a model primarily aimed at regional assessment of debris flow susceptibility, but also applicable to other processes. Their model has, amongst others been used for regional to national-scale debris flow case studies (e.g. Blahut et al., 2010; Fischer et al., 2012). Recently Mergili et al. (2015) also published a random-walk based model and demonstrated its applicability to different mass movement processes. Similar approaches have also been developed and applied for runout estimation of rock fall related phenomena (e.g. Meissl, 1998; Dorren and Seijmonsbergen, 2003; Wichmann and Becht, 2006; Jaboyedoff and Labiouse, 2003, 2011).

Compared to the relatively large number of mod-

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els and studies on different mass movement processes the application to snow avalanches has been limited or under-reported up to now. Apart from Horton et al. (2013), who report applicability of their model to snow avalanches and Barbolini et al. (2011), who also present a similar model approach aimed at regional-scale assessment of potential avalanche runout zones, reports on modelling of snow avalanches with the described model type appear to be scarce.

Here we present an application of a simple spatially distributed empirical model to snow avalanche runout estimation for different avalanche tracks in Austria. The model is subject to ongoing development, thus the contribution aspires to highlight the general applicability of this type of model to snow avalanches, discuss possibilities and limitations of the employed model approach and highlight potential areas for further model development and improvement.

2. General Concepts and model description

Most approaches for distributed spatial modelling of gravitational mass movement processes are comprised of three main steps. The first step usually involves the *estimation of potential source- or release-areas*, either by manual assessment or by means of an automatic or semi-automatic modelling approach. Based on the identified source areas in the subsequent modelling steps the extent and spatial distribution of different process intensity parameters (e.g. velocities, runout, additional indices) is calculated. This usually involves a method for *topographic routing* of the flow or mass movement process through a digital raster elevation model and a *procedure for calculating process intensities and runout*.

2.1. Estimation of Potential Release Areas

Different authors have worked on automatic or semi-automatic approaches for estimation of potential avalanche release areas (PRAs), mainly based on parameters derived from raster-based digital elevation models (e.g. Rauter, 2005; Maggioni, 2005; Falkner, 2009; Bühler et al., 2013; Veitinger et al., 2015). The main parameter in all of these studies is the local slope while varying additional parameters are incorporated to refine the release area estimation (different curvature thresholds, terrain roughness, wind-shelter indices, topographic landform classification, etc.). In addition to topographic parameters also the extent of sufficiently dense forests is often incorporated into the analysis. However, depending on the scope of the study manual refinement of the automatically defined release areas might be useful or necessary (e.g. Barbolini et al.,

2011). For the examples presented in this study release areas were defined manually in a GIS environment, based on existing observations and slope thresholds.

2.2. Topographic Routing

Many algorithms for topographic routing of mass flows through a raster elevation model originate from the field of hydrology. The approaches can be divided into three categories: (i) *single flow direction (SFD)* algorithms (O'Callaghan and Mark, 1984; Jenson and Domingue, 1988), (ii) *multiple flow direction (MFD)* algorithms (e.g. Quinn et al., 1991; Freeman, 1991; Fairfield and Leymarie, 1991; Holmgren, 1994; Tarboton, 1997) and (iii) algorithms involving *random walks* or *stochastic elements* (e.g. Gamma, 1999; Wichmann and Becht, 2003; Scheidl and Rickenmann, 2010; Mergili et al., 2015) or adaptations and combinations of these (Horton et al., 2013; Barbolini et al., 2011).

Here, we use a slightly modified version of the *multiple flow direction* algorithm described by Holmgren (1994), which has also been employed by Barbolini et al. (2011) and Horton et al. (2013). The modification to Holmgren's algorithm consists of including the possibility for superelevation of the central flow cell in order to allow the spreading algorithm to overcome smaller obstacles (also see Scheidl and Rickenmann, 2010, 2011), which would otherwise delimit the flow path in the purely hydrologic application of the algorithm.

As a first step of each model run the possible outgoing flow directions for every cell of the input raster elevation model are calculated (see figure 1). First we use the modified version of Holmgren's algorithm to obtain the proportion of flow p_i^{fd} which is distributed from a central cell (cc) to any of its eight neighbouring cells by:

$$p_i^{fd} = \frac{(\tan \beta_i)^x}{\sum_{j=1}^8 (\tan \beta_j)^x} \quad \forall \begin{cases} \tan \beta > 0 \\ x \in [1; +\infty[\end{cases} \quad (1)$$

where i, j represent the flow directions to the eight neighbour cells in a gridded elevation model, $\tan \beta_i$ is the gradient from the central cell to the neighbouring cell and x is the variable exponent after Holmgren (1994). Depending on the chosen value for x it is possible to produce varying degrees of flow spreading ranging from single flow directions ($x \rightarrow \infty$) to multiple flow directions ($x \rightarrow 1$).

The gradients $\tan \beta_i$ to the neighbouring cells are obtained by:

$$\tan \beta_i = \frac{z_{cc} + dz - z_i}{\Delta s} \quad (2)$$

where z_{cc} and z_i are the elevations of the central cell and neighbour cell, Δs is the distance between cell centers (different in cardinal and diagonal directions)

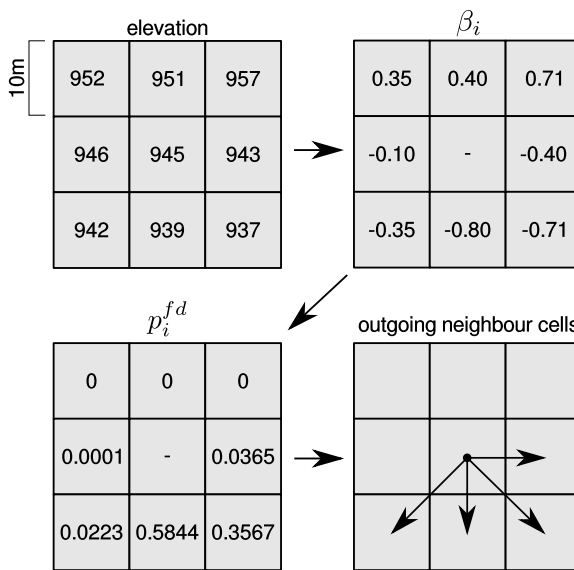


Figure 1: Exemplary calculation of outgoing flow directions (i.e. eligible neighbour cells) with the described algorithm for a 3x3 raster neighbourhood. In this example $x = 4.0$, $dz = 2.0$ and $p_{lim} = 0.01$. Note that the neighbour on the left of the central cell is not selected, because $p_i^{fd} \geq p_{lim}$ is not satisfied.

and dz is the optional superelevation of the central cell, used to overcome obstacles in the flow path. In a subsequent step we introduce a minimal flow proportion threshold p_{lim} , which is used to eliminate neighbouring cells which receive only a small proportion of outgoing flows. Eligible neighbour cells are then selected based on the criterion that $p_i^{fd} \geq p_{lim}$. In this study p_{lim} has been set to a fixed value of 0.05. Subsequently the flow is routed from the designated startcells along the predefined flow-directions as long as the used stopping criterion is not satisfied.

2.3. Runout Estimation

In the model approaches mentioned in the introduction, runout estimation, or more general the estimation of process intensities (e.g. velocity, kinetic-energy, flow-heights, etc.) along the flow path, is mostly accomplished by means of empirical or simple physical methods or a combination of both. Many authors use versions of the PCM-Model, initially developed for runout estimation of snow avalanches along a pre-defined path by Perla et al. (1980) (e.g. Gamma, 1999; Wichmann and Becht, 2003; Horton et al., 2013; Mergili et al., 2015). Different implementations of the travel-angle approach (e.g. Heim, 1932) are also utilized by many models. Barbolini et al. (2011) investigated the applicability of the well known $\alpha - \beta$ model for snow avalanches (Lied and Bakkehøi, 1980) in a spatially distributed form, but refrained from its use due to challenges arising from automatic β -point selection.

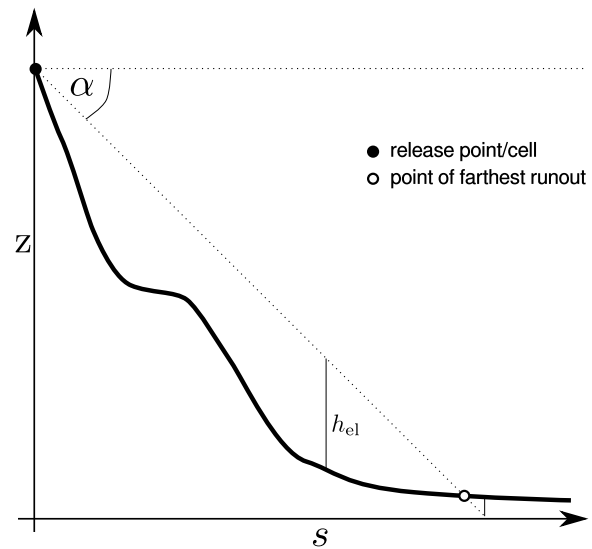


Figure 2: Schematic illustration of the used runout estimation approach. For every cell along the flow path $h_{el} = f(s, z, \alpha)$ is calculated; z is derived from the raster elevation model and s is summed up along the flow path. In any given cell along the flow path the propagation is continued if $h_{el} > 0$, when $h_{el} \leq 0$ the propagation of the flow is stopped.

The model used in this study uses a simple travel-angle (α) for estimation of avalanche runout lengths. Beginning from the release cells, the height of the "energy-line" above the current cell h_{el} is calculated (see figure 2). When the criterion $h_{el} \leq 0$ is fulfilled, the propagation is terminated.

3. Application to test cases and results

In order to show the capabilities and limitations of the presented model it has been applied to different avalanche paths in Austria. For each of the paths records of past avalanche activity exist, allowing a comparison of observed and modelled extent of areas affected by avalanches. We carried out a number of simulations with varying parameter combinations $\{\alpha, x, dz, p_{lim} = 0.05\}$ for each avalanche path and compared the model results to reference data, which consists of *release areas*, a *delineation of the avalanche track* and the *envelope of observed dense flow runouts*.

Figure 4 shows exemplary results of the model application to two different test cases in Austria. In both cases the overall flow path and runout of the avalanche is reproduced quite well, however in figure 4 (b) the lateral dimensions of the avalanche path are clearly overestimated in the orographic left and right direction. This behaviour can be observed primarily if the avalanche path has a plane or slightly convex shape perpendicular to the main flow direction and might be attributed to the lack of a mechanism ac-

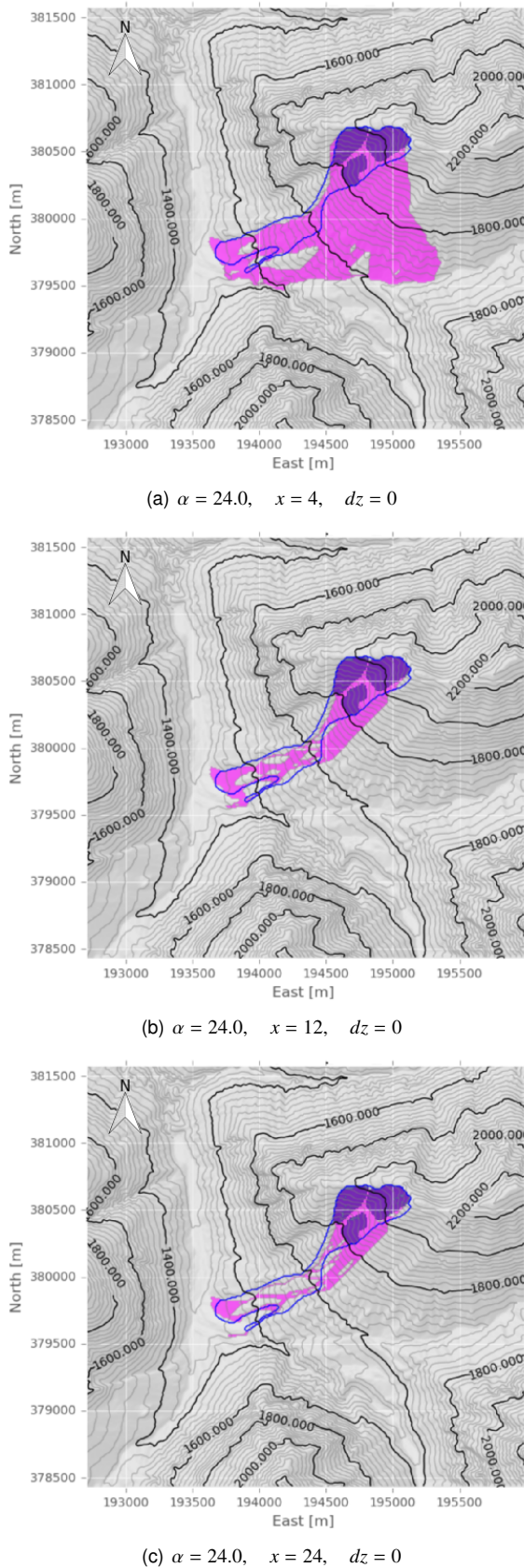


Figure 3: Influence of the exponent x on the lateral spreading of modelled potential avalanche runout areas for the "Ahorntal Avalanche" in Austria. CRS-EPSSG: 31287; source of elevation data: geoland.at

counting for inertia effects in the current model implementation.

Figure 3 illustrates the effect of varying the parameter x . As expected, higher values of x produce more confined flow paths, while lower values introduce increased lateral flow spreading. Also in this example the overall alignment of the observed and modelled area is satisfactory, given adjusted parameter settings.

In all presented maps (figures 3 and 4) the release areas are shown in purple, simulated avalanche runout is represented in pink and the blue outline represents the extent of the reference data for the respective avalanche path.

4. Conclusion and Outlook

We have presented an application of a spatially distributed model for the preliminary assessment of potential avalanche runout zones, specifically targeted at applications to regional-scale studies. The applicability of the presented model has been demonstrated, however also limitations could be identified:

- The preliminary results suggest, that the presented model is better able to reproduce avalanche paths in case of channelized or mainly concave avalanche paths, whereas plane or convex terrain presents a challenge for the flow routing algorithm.
- Currently only the perimeter of the area, that can be reached by avalanches is modelled. Estimates of potential process intensities (velocities, flow heights, etc.) are not provided.

In order to improve the presented model approach and to address some of the mentioned shortcomings the following points will be considered for further development:

- The incorporation of a mechanism accounting for inertia effects or persistence of flow directions (e.g Gamma, 1999; Horton et al., 2013; Mergili et al., 2015) will be investigated in order to reduce unrealistic lateral spreading of the flow on plane and convex cross-slope geometries.
- The implementation of additional methods for calculation of runouts and flow intensities (e.g. Lied and Bakkehøi, 1980; Perla et al., 1980) could also broaden the scope for the applicability of the model.

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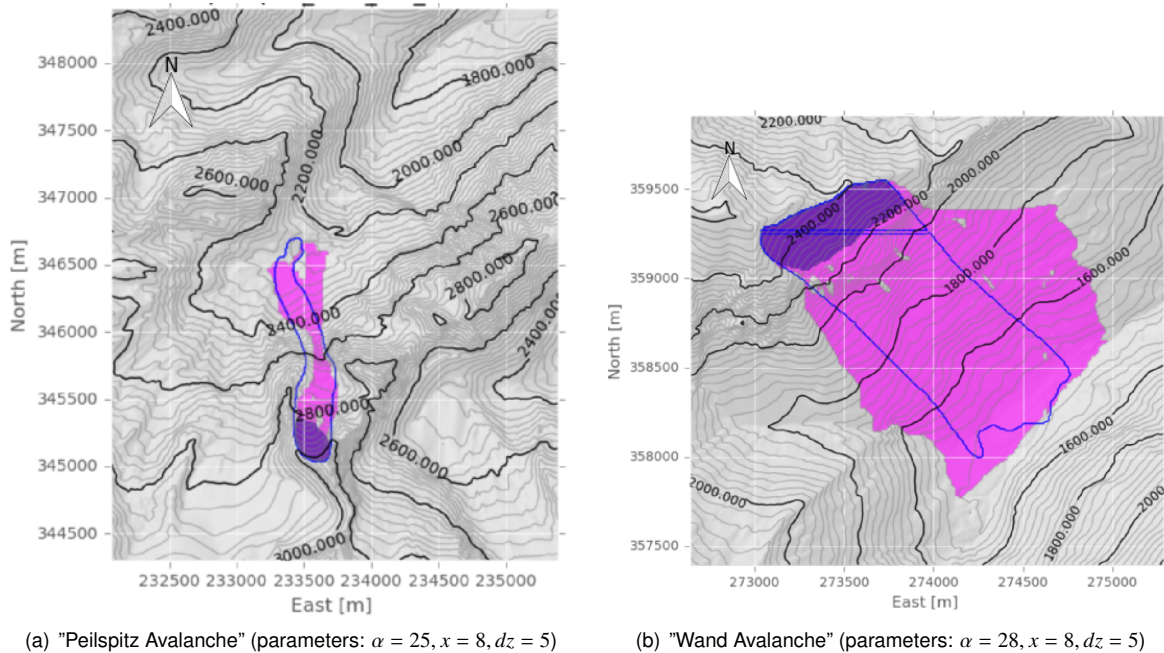


Figure 4: Modelled runout for the "Peilspitz Avalanche" and the "Wand Avalanche" in Austria. CRS-EPSSG: 31287; source of elevation data: geoland.at

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