Development of a simple raster-based model for gravitational mass movement processes applied to the regional assessment of forest stands with direct protective functionality

Andreas Huber*, Frank Perzl, Reinhard Fromm, Jan-Thomas Fischer, Klaus Klebinder, Bernadette Sotier

*Austrian Research Centre for Forests (BFW), Innsbruck, Austria

ABSTRACT: This contribution describes the development of a model suitable for regional scale delineation of zones potentially affected by gravitational mass movement processes (avalanches, rockfall). The model is subsequently used for the identification of forest areas with direct protective function against these processes. With respect to the practical application of the model over larger areas and the accompanying challenges (assessment of input-data, model calibration, computational time) a simple empirical, raster-based process model with limited input requirements is proposed. The model provides the functionality to identify objects in the process area and automatically discards parts of the process areas, which do not affect any objects (e.g. parts of avalanche tracks downslope of objects). Following this method, an intersection of the obtained process areas and a layer representing the forest coverage returns forest patches with a direct protection function against the modeled process. First applications of the developed model approach yield promising results. However, potential for optimization regarding the computational efficiency of the current model prototype and the development and integration of further approaches for runout length estimation and process propagation is identified.

Key words: avalanche, rockfall, protective forests, raster-based modeling

1. INTRODUCTION

In many Alpine countries healthy and well tended protective forests are an important part of integral mitigation concepts against natural hazards originating from steep slopes. For an efficient allocation of resources for maintenance and restoration of such forest stands accurate nationwide inventories of these areas are desirable. The present contribution is concerned with the development of a method for the delineation of forest areas with direct protective functionality against snow avalanches and rockfall processes on a regional scale in Austria. Similar efforts have recently been undertaken in Switzerland (Giamboni and Wehrli, 2008) for different gravitational mass movement processes (rockfall, debris-flow, snow avalanches), highlighting the demand for standardized and comparable procedures for the delineation of protective forests.

Over the past 30 years several models for the estimation of runout lengths, process intensities and process propagation, either based on empirical-statistical or physical-deterministic approaches, have been developed (e.g. Lied and Bakkeheii, 1980; Perla et al., 1980; Christen et al., 2002; Sampl and Granig, 2009; Christen et al., 2010; Meissl, 1998; Stevens, 1998; Guzetti et al., 2002; Dorren, 2012). However, the applicability of these models for regional scale case studies is limited in most cases.

The application of physical-numerical process models, as frequently used for hazard zoning and engineering questions (e.g. Christen et al., 2010; Sampl and Granig, 2009), over large areas seems problematic. The computational time of these models is considerable for regional to nationwide application (c.g. Giamboni, 2008, p.22) and the variability of controlling factors and effort and uncertainties involved in the assessment of model parameters might also make the regional-scale application of these models difficult (Horton et al., 2013).

In recent years relatively simple spatially distributed models based on empirical or simple physical approaches have been successfully used in regional-scale case studies on different gravitational mass movement processes (Zimmermann et al., 1997; Dorren and Seijmonsbergen, 2003; Barbolini et al., 2011; Jaboyedoff and Labouisse, 2011; Blahut et al., 2010, etc.).

With respect to the aspired regional-scale delineation of protective forests models based on this approach also match the requirements emerging from this assignment:
Model calibration and parameter assessment is straightforward for areas where past event inventories are available and adapted model parameters might be used for application in comparable environments.

Simple model approaches can help to keep computational time within reasonable limits also for application over larger areas.

In addition to these considerations also the possibility for identification of endangered objects in the process areas and functionality for "backcalculation" from affected objects to the corresponding process paths and release zones has been identified as a desirable feature in previous studies (Giamboni, 2008; Perzl et al., 2011). However, with respect to this specific problem the authors are not aware of existing models providing this functionality "out of the box". Moreover, none open-source licensing of already available models impedes the adaption or expansion of existing code to meet these requirements.

For the mentioned reasons the decision to develop a model adapted to the practical problem has been taken. The model development is focused on one hand on the applicability of the model on a regional scale (computational time, model calibration) and on the other hand on an open model design allowing for an integration of different modeling approaches.

2. MAIN CONCEPT

The procedure for the identification of forest stands with direct protective function against snow avalanches (or other gravitational mass movement processes) as used in this study is structured into the following steps (see also fig. 1):

2. Process Modeling: Modeling of areas potentially affected by processes originating from the defined release zones (i.e. paths and deposition areas). The protective function of present forest cover is neglected in this step.
3. Hazard Analysis: Identification of objects (buildings, infrastructure) which are located in the areas potentially affected by mass movement processes as obtained from step 2.
4. Delineation of forest with direct protection function: Identification and delineation of forest areas which are located in the modeled process areas and provide protection for downslope objects.

Figure 1: Conceptual approach for the identification of protective forest. a: Identification of release areas (in and outside of present forest cover); b: Modeling of process zones; c: Identification of endangered objects (circled in red); d: Delineation of areas with direct protective functionality within the presently forested area (darkgreen)

3. DEVELOPMENT OF A RASTER-BASED PROCESS MODEL

The developed spatially distributed model is based on calculations on a regularly spaced grid. Required input-data mainly includes a DEM and raster representations of the potential release areas and objects of interest (buildings, infrastructure, roads, etc.). With respect to DEM resolution 10m has been identified as a suitable compromise between spatial resolution and computational effort in similar studies (Blahut et al., 2010; Fischer et al., 2012). Also with respect to the representation of objects a cellsize of 10m is still able to reproduce their extent and location with reasonable accuracy. Since the raster representation of considered objects has to match the provided DEM resolution 10m also appears to be a reasonable value in this respect.

3.1. Model description

Following the procedure described in sect. 2 the basic modeling steps comprise the identification of source areas or release zones, the estimation of runout lengths and the modeling of the spatial distribution of areas affected by the process (i.e. process spreading). For the delineation of forest areas with direct protective functionality further also objects within the modeled process areas are detected and process zones upslope of endangered objects are filtered and intersected with raster-based representations of forested areas.
3.1.1. Disposition analysis

The identification of potential source areas or release zones is based on an analysis of morphological parameters and is performed in a preprocessing step within a GIS environment. This approach has recently been studied and applied for delineation of release areas for snow avalanches (Maggioni and Gruber, 2003; Rauter, 2005; Falkner, 2009), rockfall starting zones (Dorren and Seijmonsbergen, 2003; Loye et al., 2009) or initiation zones for different mass movement processes (Zimmermann et al., 2003; Loye et al., 2009) or initiation zones for different mass movement processes (Zimmermann et al., 2003; Loye et al., 2009), mainly a raster representation of the terrain (DEM), derived morphological variables (slope, curvature, contributing area, slope length) and possible additional factors (e.g. snow distribution, vegetation, lithology) are analyzed to obtain the different disposition towards the initiation of the process at given locations. In the present study the methods for identification of source areas comply with previous work carried out in the Austrian context (Perzl et al., 2011).

The current model prototype requires the definition of release areas in binary format (release area, no release area). In future versions it will also be possible to provide classified values or release probabilities.

3.1.2. Process modeling

The process modeling is divided into two different steps.

1. Estimation of runout lengths: The runout distances are estimated along a process trajectory based on simple empirical energy line based algorithms. Presently the angle of reach approach after Heim (1932) and the $\alpha/\beta$-model after Lied and Bakkehøi (1980) are implemented in the model. While for the angle of reach method a constant travel-angle or geometrical angle is used for all release areas, for the $\alpha/\beta$-model the angle $\alpha$ is calculated for each release cell based on an automated assessment of the $\beta$-angle.

2. Process Propagation and Spreading: In the current model prototype the algorithms implemented for process propagation are limited to the well known D-8 algorithm after O’Callaghan and Mark (1984) (single flow, steepest path algorithm), the MFD (Multiple Flow Direction) algorithm after Quinn et al. (1991) and a combination of both algorithms with a simple slope threshold distinguishing between both algorithms (spreading occurs below a certain slope threshold).

3.1.3. Detection of endangered objects and delineation of protective forests

Within the presented approach forested areas are assumed to provide a direct protective function if:

1. Objects are located in the process zones that have been identified neglecting the effect of present forest cover.
2. Forest cover is present in these zones “above” or upslope of the otherwise endangered objects.

Therefore in the model all paths, which do not affect any objects are discarded in a first step. In a further step all parts of the remaining process areas downslope (in direction of the process) of the affected objects can also be disregarded. Eventually, an intersection of the remaining release zones and paths with a forest layer is employed to identify parts of the present forest providing direct protective function against the investigated process.

3.2. Application to test cases and first results

To test the practicality of the model prototype first model runs were performed for selected test cases addressing (1) the delineation of forests with direct protective functionality against rockfall and (2) the assessment of potential avalanche process zones (track, deposition area).

1. For rockfall runout estimation the travel-angle approach was applied along with the D-8 and MFD algorithm. For these cases also the filtering of process areas and the subsequent delineation of protection forest (simple intersect) was tested. While the D-8 algorithm has the advantage of being the faster method, the resulting protective forest areas are rather inhomogeneous as compared to results obtained with the MFD-algorithm. Figure 2 shows the results of a model run employing the MFD-algorithm.

2. For the assessment of potential avalanche runout the spatially distributed version of the $\alpha/\beta$ model was tested. Model parameters adapted for 80 extreme avalanches in Austria (Lied et al., 1995) were employed for runout calculation and results were compared with observed maximum runouts for the test area (Kaprunertal, Austria). Figure 3 shows a comparison of the employed model (extreme events for Austria, black line) with a model adapted to observed runouts in the test area (blue line). Because of the generally more conservative runout estimation the model parametrized to extreme events was used. Figure 4 shows a comparison of model results with observed runouts for two documented avalanche paths in the test area. The used spreading algorithm is
Figure 2: Application of the model prototype to a test case delineation of forest with protective functionality against rockfall. 

- The forested area (green) and the relevant infrastructure objects (blue) are depicted
- Rockfall source areas (black) are identified
- Rockfall areas affecting objects (orange) are calculated
- Intersection of the process zones affecting objects and the forest layer yields parts of the forest providing direct protective functionality (red). In this case the runout was assessed using the travel-angle approach ($\alpha = 33^\circ$) and the MFD algorithm was used for process spreading. (sources: DEM - Land Tirol, topographic map - BEV)

A combination of D-8 algorithm and MFD algorithm based on a slope threshold below which spreading does occur ($20^\circ$ was used in this test run).

While the modeled runouts are in reasonable agreement with the documented runouts (overestimation in parts is attributed to the model choice), the spreading algorithm tends to underestimate spreading of the flow along the track.

4. CONCLUSION & OUTLOOK

At the current development stage the application of the model prototype to test cases demonstrates the general practicability of the pursued approach for the delineation of protective forests. Besides, points for improvement and further model development are clearly identified:

- The implemented functionality for the filtering of process paths above affected objects provides a tool for the identification of forest patches with direct protective functionality.
- The employed empirical approaches for runout estimation produce reasonable results given the adaption of the models to regional settings or the use of parameters from areas with comparable environment. The additional integration of simple physical-based models for runout prediction (e.g. Perla et al., 1980; Dorren and Seijmonsbergen, 2003) might further extend the applicability of the model to cases where a parametrization of the empirical models is difficult due to a lack of knowledge about historic events or very special local conditions.
- Regarding process propagation the integration of additional flow dispersion algorithms is necessary in order to overcome the limitations of the currently implemented methods (D-8, MFD). While for rockfall the D-8 and MFD algorithms already provide useful results, for modeling of snow avalanches these approaches do not emulate the behavior of the process satisfactorily. Here, the integration of additional flow algorithms including a persistence factor accounting for inertial effects and a more realistic spreading
behavior into the model has to be realized in the next step.

- Eventually with regard to the practical application of the model over larger areas (> 5000 km²) also optimization of the computational efficiency of the code presents a future area of activity.

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References


