

Modelling Of Geomorphic Processes In An Alpine Catchment

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Abstract

Within the SEDAG project the sediment yield of various processes (including soil erosion, rockfall, debris flows, shallow landslides and full-depth avalanches) is studied in two catchment areas in the Northern Limestone Alps, Germany. As a first step in examining the sediment budget, several models were developed to 1) identify locations at which the processes may start and 2) to determine which areas would be affected.

Different approaches are used to determine locations of process initiation, including cartographic modelling, multivariate statistical analysis and more physically based approaches. Process paths are modelled by a combination of single and multiple flowdirection algorithms, which are incorporated in a random walk model. The model can be adjusted to different processes by three calibration parameters. Total process area is determined by Monte Carlo simulation and run-out distances are modelled by one or two parameter friction models. First results are presented.

1. Introduction

The work presented here is part of the SEDAG project (sediment cascades in alpine geosystems), within which a research team from five universities is studying the sediment transfer by various geomorphic processes. It is intended to obtain more detailed information about the sediment budget and landscape evolution of two catchment areas in the Northern Limestone Alps, Germany (see figure 1). Therefore the spatial interaction of hillslope and channel processes - including soil erosion, rockfall, debris flows on slopes and in channels, shallow landslides and full-depth avalanches – is studied (see Heckmann et al. 2002, Keller & Moser 2002, Schrott et al. 2002, Unbenannt 2002). It is attempted to develop new spatially distributed modelling approaches to describe the sediment cascade. The modelling task is to identify starting zones of the processes (disposition modelling, e.g. Becht & Rieger 1997) and to determine which areas would be affected (process modelling, e.g. Wichmann et al. 2002, Wichmann & Becht 2003). It is intended to explore and illustrate the potential effects of land management strategies and climate change on landscape evolution. Because of the detailed modelling of process path, run-out distance and erosion and deposition areas, the models can also be applied to natural hazard assessment.

For both catchments, each with a surface area of about 16km², digital elevation models with a raster size of 5m have been calculated from photogrammetric contour data with ARC/INFO's TOPOGRID. Additional data layers with geomorphological, geologic and land use data were prepared in the same resolution.

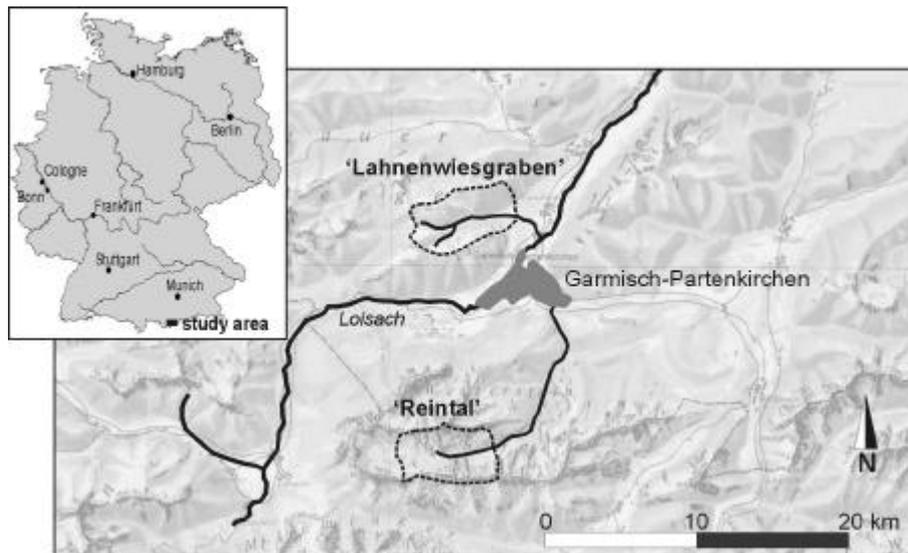


Fig. 1: Location of study areas (taken from Heckmann et al. 2002).

A new open source GIS (SAGA, system for an automated geo-scientific analysis), developed by the working group 'geosystem analysis' at the Department of Physical Geography, University of Goettingen, is used to build the models. SAGA is capable of processing raster and vector data of various formats and is based on a graphical user interface. Additional functionality is added by loading external run time libraries, so called module libraries. Thus it is possible to extend SAGA without altering the main program. The module libraries are programmed with C++ which is rather easy, because many object classes and basic functions are already provided. All models presented here are coded as such module libraries.

2. Methods

2.1 Process starting zones

Different approaches have been used to determine possible process starting zones: cartographic modelling, multivariate statistical analysis and more physically based approaches.

2.1.1 Cartographic Modelling

Areas susceptible for process initiation may be derived by qualitative and quantitative analysis of the data layers. This includes the classification and weighting of each parameter map. For example, the following procedure is used to determine possible starting points of debris flows in channels (Zimmermann et al. 1997, BUWAL 1998):

- Extraction of the channel network from digital elevation data by flow accumulation and plan curvature thresholds.
- Extraction of channel cells receiving enough sediment from the hillslopes to produce debris flows. Therefore a maximum distance to the channel network and a minimum slope threshold in uphill direction are specified to determine hillslope cells that may deliver material. This contributing area is weighted in relation to vegetation cover and active process (e.g. a cell with bare soil will deliver more material than a cell covered with vegetation, a cell with landslide activity will deliver more material than a cell

with rockfall activity).

- Extraction of possible starting points by combining empirically derived thresholds for flow accumulation, slope and potential sediment supply. The basic idea is that the triggering of a debris flow is governed by sufficient peak discharge, channel bed slope and available sediment. On steeper channel beds a lower discharge is needed than on lower slopes.

2.1.2 Multivariate statistical analysis

A multivariate regression analysis for alpha-numeric data is used to delineate possible starting zones of debris flows on slopes. A similar approach has been used by Jäger (1997) to determine potential landslide areas. The analysis is based on a binary grid containing mapped debris flows (1: presence 0: absence of debris flow starting zones) and several (classified) grids containing relevant geofactors (e.g. slope, vegetation) in the area under study. In order to get a larger sample, the analysis has been carried out on the catchment area of the observed debris flows instead of using point data. All relevant parameter combinations are examined in SAGA and written to a contingency table that is exported to an external statistical software package (SPSS 2001). A log-linear model is used to calculate the probability of process occurrence. The result is retransformed to a probability map in SAGA. In the special case of using the catchment area instead of point data, one obtains the probability of a grid cell belonging to a catchment that may produce debris flows on slopes.

2.1.3 Physically based approaches

A more physically based approach is used to analyse the topographic influence on shallow landslide initiation (Montgomery & Dietrich 1994, Montgomery et al. 2000). Therefore a hydrologic model (O'Loughlin 1986) is coupled with a slope stability model. Soil saturation is predicted in response to a steady state rainfall for each cell of the digital elevation model. An *infinite-slope* stability model uses this relative soil saturation to analyse the stability of each topographic element. The model was extended to use spatially variable soil properties (soil thickness, effective soil cohesion including the effect of reinforcement by roots, bulk density, hydraulic conductivity and friction angle). Thus it is possible to calculate which elements get unstable for a given steady state rainfall or to calculate the necessary steady state rainfall which causes instability in an element. The latter can be seen as a measure of the relative potential of each element for shallow landsliding. Besides the stability classes stable and unstable, Montgomery and Dietrich (1994) define two further stability classes: unconditionally unstable elements are those predicted to be unstable even when dry and unconditionally stable elements are those predicted to be stable even when saturated.

2.2 Process path and run-out distance

Process pathways are modelled by a combination of single and multiple flowdirection algorithms. The algorithms are incorporated into a random walk model, which can be adjusted to different processes by three calibration parameters (Gamma 2000). The total process area results from Monte Carlo simulation. Run-out distances are modelled by calculating the velocity along the process path by either one or two parameter friction models (Van Dijke & Van Westen 1990, Perla et al. 1980).

2.2.1 Random walk

The process path is modelled by a grid based random walk similar to the *dfwalk* model of Gamma (2000). All lower neighbours of a central cell in a 3 x 3 window are potential flow path cells. To reduce this set \mathbf{N} , two parameters are available: a slope threshold and a parameter for divergent flow. Possible flow path cells are determined by

$$\mathbf{N} = \left\{ n_i \mid \left\{ \begin{array}{ll} \gamma_i \geq (\gamma_{max})^a & \text{if } 0 \leq \gamma_{max} \leq 1 \\ \gamma_i = \gamma_{max} & \text{if } \gamma_{max} \geq 1 \end{array} \right. , i \in \{1, 2, \dots, 8\}, a \geq 1 \right\} \quad (1)$$

and

$$\gamma_i = \frac{\tan \beta_i}{\tan \beta_{thres}}, \quad \beta_i \geq 0, \quad i \in \{1, 2, \dots, 8\} \quad (2)$$

where

γ_{max}	=	$\max(\gamma_i)$
β_i	=	slope to neighbour i
β_{thres}	=	slope threshold
a	=	parameter for divergent flow

\mathbf{N} is reduced to the neighbour of steepest descent if the slope to the neighbour is greater than the slope threshold. This results in a single flow direction algorithm like D8 (Jenson and Domingue 1988). Otherwise equation 1 provides a set of potential flow path cells. The probability for each cell to be selected from this set as flow path is given by

$$p_i = \begin{cases} \frac{\tan \beta_i \cdot p}{\sum_j \tan \beta_j} & \text{if } i' \in \mathbf{N} \\ \frac{\tan \beta_i}{\sum_j \tan \beta_j} & \text{if } i' \notin \mathbf{N} \end{cases} \quad i, j \in \mathbf{N} \quad (3)$$

If the set contains the previous flow direction i' , abrupt changes in direction can be reduced by a higher weighting of i' . Therefore the persistence factor p is introduced which is also contained in the calculation of the sum. The calculated transition probabilities are scaled to cumulated values between 0 and 1, and a random number generator is used to select one flow path cell from the set.

For each starting point, several random walks are calculated (Monte Carlo simulation). Each run results in a slightly different process path. A high enough number of iterations assures that the whole process area is reproduced. By summing up how often a cell is selected as process path, one obtains a relative measure of process intensity, i.e. which cells are more likely affected by the process.

The approach offers the following properties (for more details see Gamma 2000):

- the slope threshold allows to adjust the model to different relief. In steep passages near to the threshold, only steep neighbours are allowed in addition to the steepest descent. In flat regions, almost all lower neighbours are possible flow path cells. The tendency for divergent flow is increased. Above the slope threshold a single flow direction algorithm is used.
- the degree of divergent flow is controlled by parameter a .
- abrupt changes in flow direction are reduced by a higher persistence factor
- a tendency towards the steepest descent is achieved as the transition possibilities are weighted by slope.

With these properties it is possible to calibrate the model to different geomorphic processes. A higher persistence factor implies a stronger fixation in the direction of movement

(accounting for inertia) as it may be observed by debris flows or wet snow avalanches. A process like rockfall may be modelled with no persistence and a higher degree of divergence.

2.2.2 1-parameter friction model

A general method for defining the run-out distance of rockfall was developed by Scheidegger (1975) and extended by van Dijke & van Westen (1990) and Meißl (1998). With this method, the velocity of a rock particle is calculated along a profile line that is divided into a number of triangles. We adapted this method to grid based modelling (see figure 2). The velocity on the processed grid cell depends on the velocity on the previous cell of the process path. It is updated as soon as a new cell is delineated as flow path by the random walk model. The area between the rockfall source and the point at which the velocity becomes zero is considered to be the potential process area.

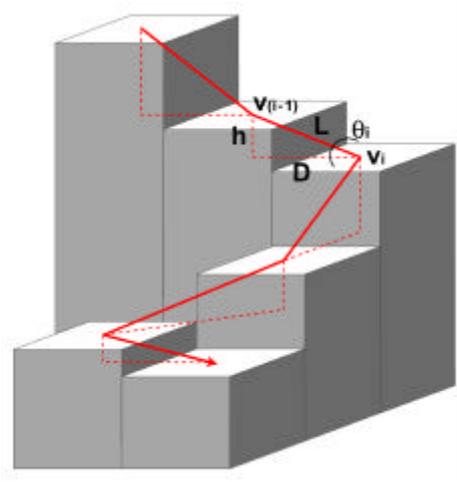


Fig. 2: Grid based approach to separate the flow path into triangles. Labels refer to 1- and 2-parameter friction model.

After a block is detached from the rock face, it is falling in free air (equ. 4). The impact on the talus slope is accounted for by reducing the velocity to a specified amount (75% after Broilli (1974), equ. 5). Instead of using a separate grid with coded impact areas as done by Meißl (1998), a slope threshold is used to verify if the talus slope is reached. After the impact, the block is modelled either as sliding or rolling (equ. 6 and 7).

Falling:
$$v_i = \sqrt{2gh_f} \quad (4)$$

Impact:
$$v_i = \sqrt{2gh_f} - r\sqrt{2gh_f} \quad (5)$$

Sliding:
$$v_i = \sqrt{v_{(i-1)}^2 + 2g(h - \mu_s D)} \quad (6)$$

Rolling:
$$v_i = \sqrt{v_{(i-1)}^2 + \frac{10}{7}g(h - \mu_r D)} \quad (7)$$

where	v_i	=	velocity on element i [m/s]
	$v_{(i-1)}$	=	velocity on previous element [m/s]
	g	=	acceleration due to gravity [m/s ²]
	h_f	=	height difference between start point and i [m]
	r	=	energy loss [%]
	h	=	height difference between $(i - 1)$ and i [m]
	D	=	horizontal distance between $(i - 1)$ and i [m]
	μ_s	=	friction coefficient (sliding) [-]
	μ_r	=	friction coefficient (rolling)[-]

The model is calibrated by 3 parameters: a slope threshold to determine if the block is in free fall (due to the grid data structure, a slope = 90° does not exist), a reduction parameter to account for the energy losses because of the impact on the talus slope and a friction parameter. It is possible to use spatially distributed friction parameters to account for different geological materials and the effect of vegetation. The module is producing several output grids to facilitate the calibration process (including a grid with all cells in which free fall occurred and a grid with modelled maximum velocities).

2.2.3 2-parameter friction model

A 2-parameter friction model (Perla et al. 1980) is used to calculate the run-out distance of snow avalanches and debris flows. Originally developed for snow avalanches, it has also been applied to debris flows more recently (Rickenmann 1990, Zimmermann et al. 1997). The process is assumed to have a finite mass and the position in space or time of the center of mass is calculated. It is assumed that the motion is mainly governed by a sliding friction coefficient (\mathbf{m}) and a mass-to-drag ratio (M/D). M/D has a higher influence on velocity in steeper parts of the track whereas the velocity in the run-out area is dominated by \mathbf{m} . Again the process path is divided into segments of constant slope and an iterative solution is used to calculate the velocity along the path. The velocity on the processed grid cell depends on the velocity of the previous cell and is calculated by:

$$v_i = \sqrt{\alpha_i * \left(\frac{M}{D}\right)_i (1 - \exp^{\beta_i}) + (v_{(i-1)})^2 \exp^{\beta_i}} \quad (8)$$

$$\text{and} \quad \alpha_i = g (\sin \theta_i - \mu_i \cos \theta_i) \quad (9)$$

$$\beta_i = \frac{-2L_i}{\left(\frac{M}{D}\right)_i} \quad (10)$$

where	v_i	=	velocity on element i [m/s]
	$v_{(i-1)}$	=	velocity on previous element [m/s]
	g	=	acceleration due to gravity [m/s ²]
	θ_i	=	slope to element i [°]
	L_i	=	slope length between $(i - 1)$ and i [m]
	μ_i	=	friction coefficient (sliding) [-]
	$\left(\frac{M}{D}\right)_i$	=	mass-to-drag ratio [m]

At concave transitions in slope, Perla et al. (1980) assume the following velocity correction for $v_{(i-1)}$ before v_i is calculated with equation 8:

$$v_{(i-1)}^* = \begin{cases} v_{(i-1)} \cos(\theta_{(i-1)} - \theta_i) & \text{if } \theta_{(i-1)} \geq \theta_i \\ v_{(i-1)} & \text{if } \theta_{(i-1)} < \theta_i \end{cases} \quad (11)$$

The correction is based on the conservation of linear momentum. For the case $q_{(i-1)} < q_i$ the authors expect that velocity decrease due to momentum change is compensated to a larger extent by velocity increase due to the reduced friction as the process tends to lift off the slope. If the process stops at a mid-segment position, the shortened segment length s may be calculated by:

$$s = \frac{\left(\frac{M}{D}\right)_i}{2} \ln \left(1 - \frac{(v_{(i-1)})^2}{\alpha_i \left(\frac{M}{D}\right)_i} \right) \quad (12)$$

In our grid based approach we do without solving equation 12 and the process stops as soon as the square root in equation 8 becomes undefined.

The model is calibrated by the two parameters m and M/D . To overcome the problem of mathematical redundancy of a two parameter model (different combinations of m and M/D can result in the same run-out distance), the parameter M/D is taken constant along the process path. It is calibrated only once to obtain realistic velocity ranges. The parameter m is then calibrated by matching observed and modelled run-out distances.

2.3 Erosion and deposition modelling

To model erosion and deposition of material and thus the sediment transfer throughout the catchment, simple methods using slope and velocity thresholds are tested. The material transfer is linked to the random walk model. To determine the available amount of material for each model run, the total amount is divided by the number of iterations. This amount is eroded and deposited during each iteration and thus influences the following runs. Deposited material may produce sinks in the DEM and a special algorithm is used to fill sinks as soon as they are detected by a following run. The algorithm fills the sink and if needed further cells of the process path upslope with available material up to heights, that assure valid flow directions for the next runs.

In the case of rockfall, a specified amount of material is subtracted from the digital elevation model at the starting location in each model run. This amount is added to DEM at the last cell of the process path (i.e. where the process stops).

A different approach is used for debris flows. The total amount of eroded material is consists of two fractions, (1) a specified amount depending on sediment available in the starting zone and (2) an amount calculated along the process pathway using slope and velocity thresholds. The eroded amount is available for deposition along the process path. The thresholds for erosion and deposition are combined in a way that artifacts resulting from the usage of one threshold alone are minimized. For example no material is deposited in flat parts of the profile if the velocity is still high. And no material is deposited in steep passages even if the velocity is low.

3. First results

This section provides first results obtained for rockfall and debris flows on slopes and in channels. Up to now it is not possible to calibrate the models to full extent, since the data obtained from the individual working groups have not yet been fully analysed. Nevertheless it is possible to show the potential of the models to describe spatially distributed sediment transfers in the Lahnenwiesgraben catchment area.

3.1 Rockfall modelling

The results of rockfall modelling in the Lahnenwiesgraben catchment area are shown in figure 3. Rockfall source areas (mostly uncovered sheer rock faces) are derived from the slope map including the effect of vegetation. The slope map was reclassified to slopes greater 40° (accounting for a cell size of 5m) and then the true surface area of each grid cell was calculated (cell area / $\cos(\text{slope})$). The landuse map was weighted by the fraction of free ground surface (uncovered 100%, full of gaps 50%, grass 25%). Rockfall source areas including relative process intensities result from the multiplication of the two maps.

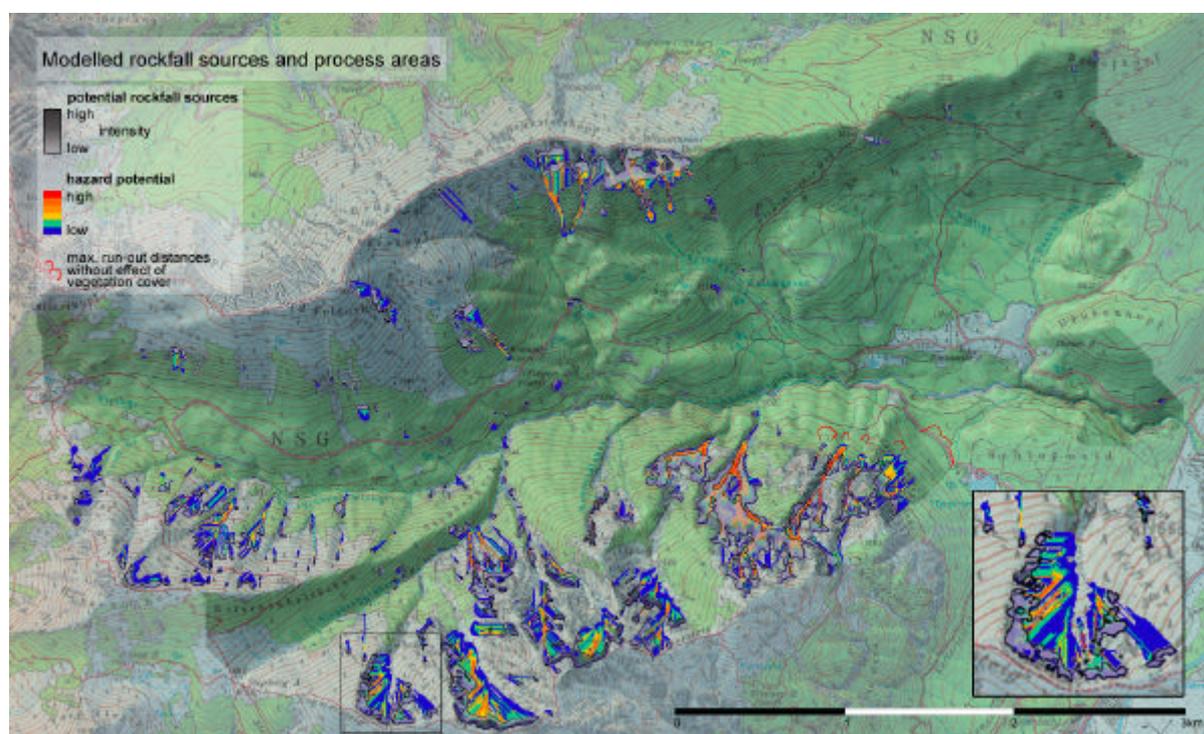


Fig. 3: Results of rockfall modelling in the Lahnenwiesgraben catchment area (background: topographic map, Bayerisches Landesvermessungsamt).

Process paths and run-out distances are modelled with a combination of random walk and 1-parameter friction model. A slope threshold of 30° , a divergence factor of 2 and a persistence factor of 1 are used in the random walk model. The 1-parameter model is calibrated to fit the observed run-out distances on different materials by using spatially distributed friction coefficients (see table 1). Free fall occurs as long as the slope is steeper than 60° . The velocity reduction by impact is 75%.

Modelled run-out distances on scree slopes match the observed deposits. The effect of forest cover must be included in the friction coefficient, otherwise the run-out distances are overestimated (see figure 3, in the SE part of the catchment). This shows the importance of dense forests for rockfall hazard mitigation.

Table 1: Friction coefficients used in rockfall modelling

material / vegetation cover	friction coefficient (μ)
marl	0.4
fluvial materials	0.5
glacial deposits	0.6
dolomite	0.7
limestone	0.8
forest	2.0

The rockfall module was extended to test the model for the simulation of long-term landscape evolution. Instead of using a grid with coded process initiation cells, a slope threshold is used to define a set of potential starting cells. Start cells are selected from this set by random and the process path, run-out distance and erosion and deposition are modelled. The set of potential starting cells is regularly updated to account for changes in elevation. Figure 4(a) shows an artificially produced rock face with a height of 100m. The result after 1'500'000 random walks with 0.01m erosion in each iteration is shown in figure 4(b). The rock face retreated and scree slopes developed with an inclination corresponding to the selected friction coefficient. It is intended to test if the model is capable of reproducing the rockfall deposits (sediment storages) observed in the Reintal study area.

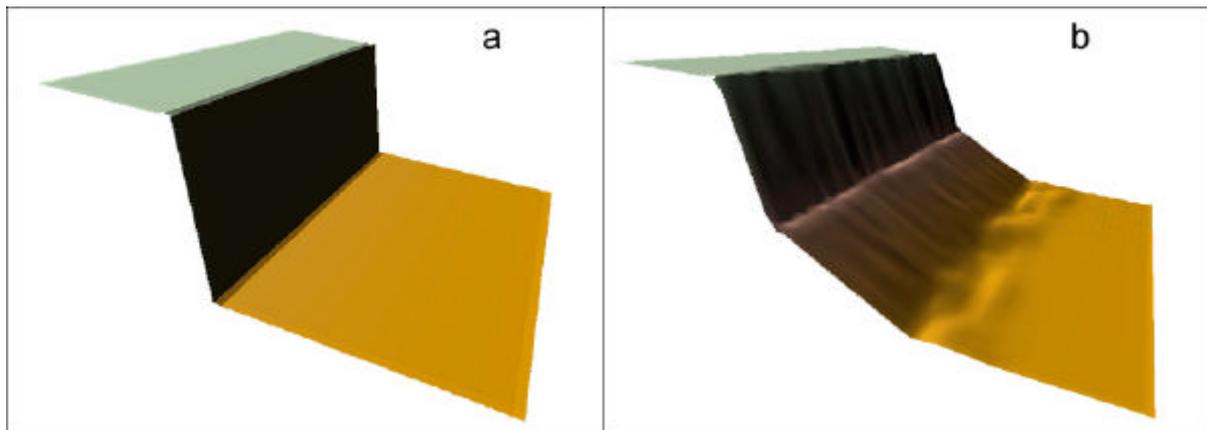


Fig. 4: 3D view of (a) initial rock face and (b) after 375000m³ of material have been eroded and deposited.

3.2 Debris flow modelling on slopes

Process initiation cells for debris flows on slopes in the Lahnenwiesgraben catchment area are derived by multivariate statistical analysis as described in section 1.1.2. The analysis is based on reclassified maps of slope, vegetation, infiltration capacity and flow accumulation. Although material properties are important for the occurrence of debris flows, it was not possible to incorporate geological information into the analysis, because nearly all of the observed debris flows occur on talus slopes composed of dolomite. The results are shown in figure 5.

To determine possible starting cells a separate module is used. Starting from each cell exceeding a user-specified minimum probability, process initiation probabilities are accumulated in downslope direction. Possible starting cells exceed a given threshold of accumulated 'disposition' and must have slopes in a slope range typical for debris flows. The catchment area of each starting cell is delineated and may be weighted by its mean probability to obtain a relative measure of debris flow release potential.

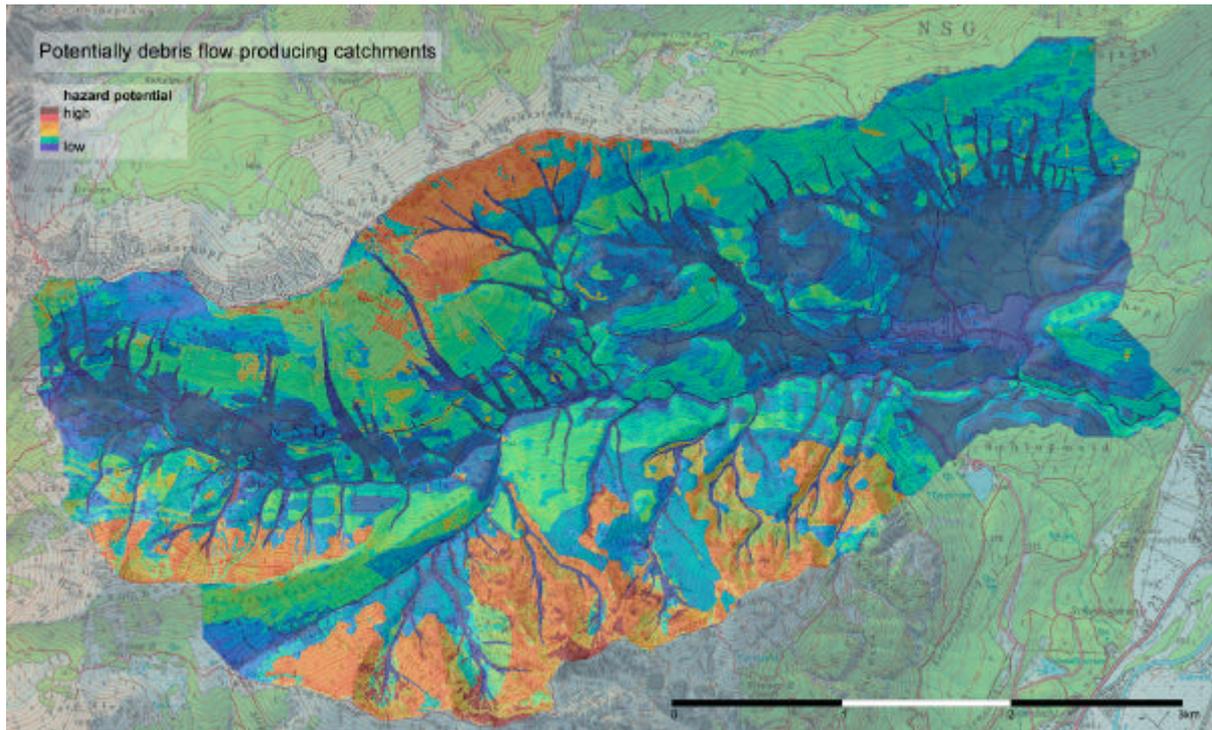


Fig. 5: Map of potentially debris flow producing grid cells in the Lahnenwiesgraben catchment area (background: topographic map, Bayerisches Landesvermessungsamt).

Process paths and run-out distances are modelled with a combination of random walk and 2-parameter friction model. A slope threshold of 20° , a divergence factor of 1.3 and a persistence factor of 1.5 are used in the random walk model. The 2-parameter model is calibrated to fit the observed run-out distances using mean friction coefficients ($\mu = 0.3$ and $M/D = 75$). Figure 6 shows a 3D-view of the ‘Kuhkar’ cirque (looking south). Erosion and deposition are modelled with arbitrary quantities of material to support visualization. Strong erosion occurs in steep parts of the process path and is followed by a zone of slight erosion before deposition sets in. Material is eroded and deposited during every model iteration. The resulting deposit is very similar to observed debris flow deposits.

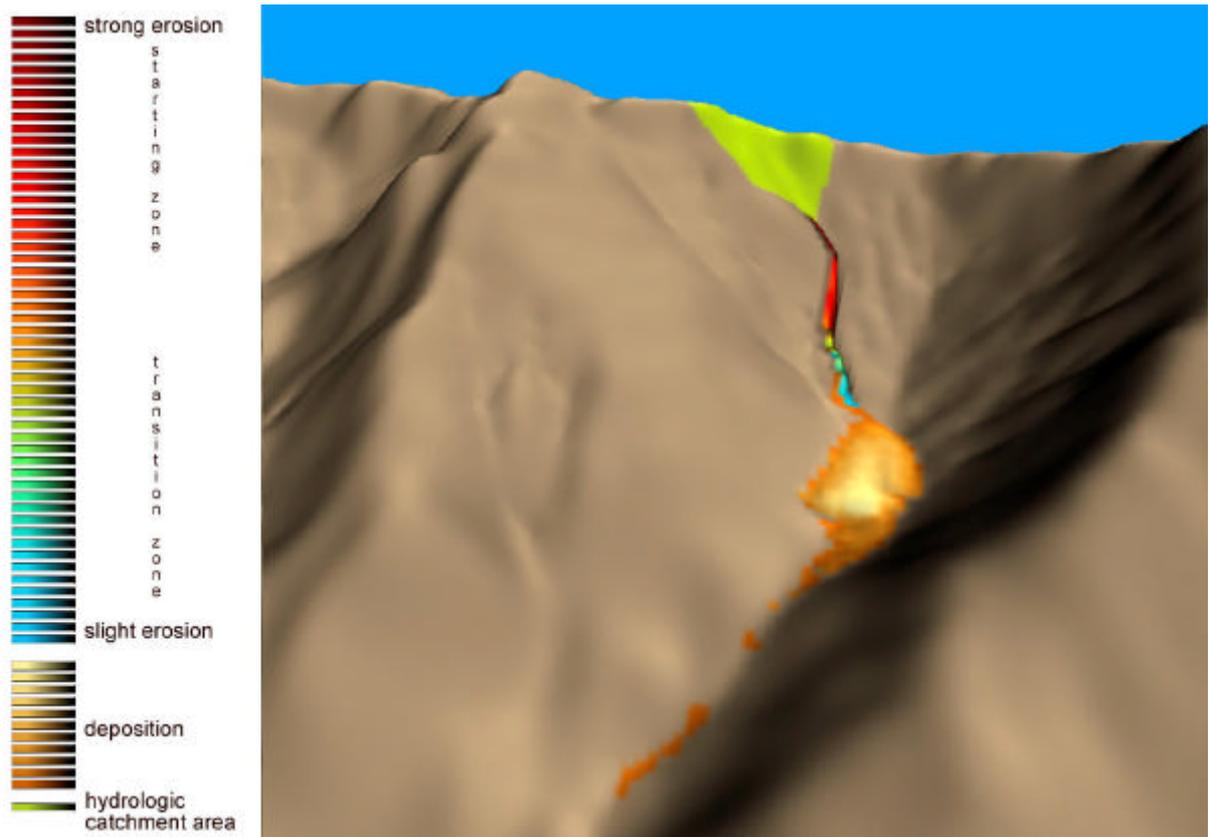


Fig. 6: 3D-view of debris flow modelling on slopes in the 'Kuhkar' cirque / Lahnenwiesgraben catchment area.

3.3 Debris flow modelling in channels

Process initiation cells for debris flows in channels are derived by qualitative and quantitative analysis as described in section 1.1.1. Those cells which have a flow accumulation higher than 2500m^2 and a concave plan curvature are classified as channel cells. All cells within a maximum distance of 250m to the channel network and with a slope (in the direction of flow) steeper than 20° are selected as contributing area. Each cell may be weighted in relation to its intensity of material supply, but up to now not enough information is available to do so. The relation between channel slope and catchment area in figure 7 was derived empirically by Zimmermann et al. (1997) from debris flows in Switzerland. Potential starting cells exceed this threshold and have a minimum material contributing area of 10000m^2 .

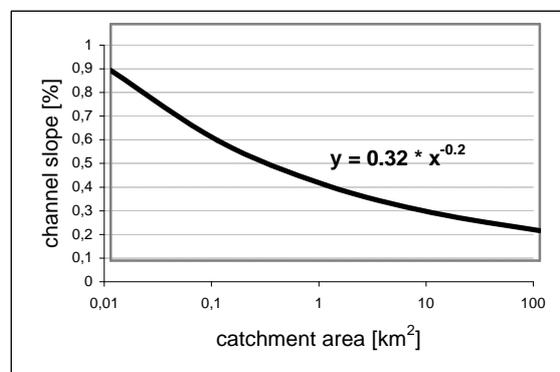


Fig. 7: Relation between channel slope and catchment area. The threshold is used to derive potential debris flow initiation cells (after BUWAL 1998).

The resulting grid contains possible process initiation cells. A filter along the channel network is used to reduce the number of start cells since it is unnecessary to calculate the process path for each cell of the grid. If a starting cell is detected by the filtering algorithm, all lower starting cells in a specified distance along the channel reach (here: 500m) are eliminated. Process path and run-out distance are modelled with a combination of random walk and 2-parameter friction model. A slope threshold of 20°, a divergence factor of 1.3 and a persistence factor of 1.5 are used in the random walk model. The 2-parameter model is calibrated to fit the observed run-out distances. The mass-to-drag ratio is set to 75m and a spatially distributed friction coefficient m is used. The friction coefficient is calculated in relation to the catchment area a of each grid cell (see figure 8, Gamma 2000).

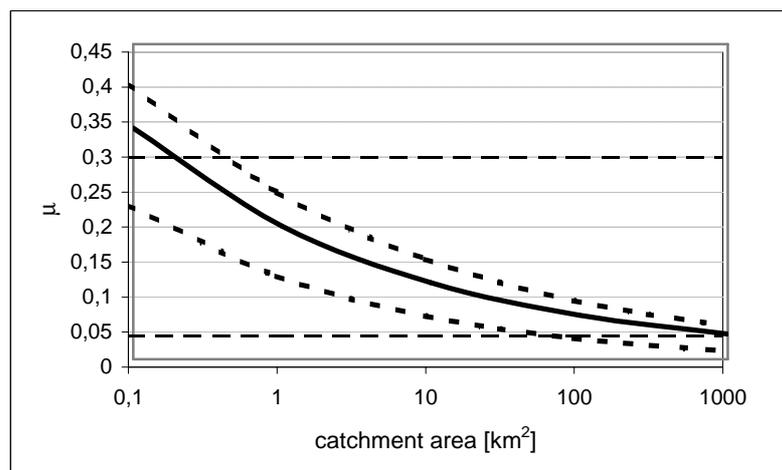


Fig. 8: Relation between friction coefficient m and catchment area a . A minimum threshold is set to 0.045 and a maximum threshold to 0.3. Curves represent minimum (upper dashed line), likely and maximum (lower dashed line) run-out distance (after Gamma 2000).

The relationship is based on the assumption that the friction is reduced with increasing discharge along the process path. Calculated maximum run-out distances ($m = 0.13 * a^{-0.25}$) are shown in figure 9.

Although the material contributing area was not weighted, the results match well with observed debris flows in the catchment area. Material is eroded and deposited along the process path following the rules stated in section 1.3. Most debris flows stop as soon as they reach the main channel with lower slopes. Further transportation of the deposited material is then accomplished by high discharges.

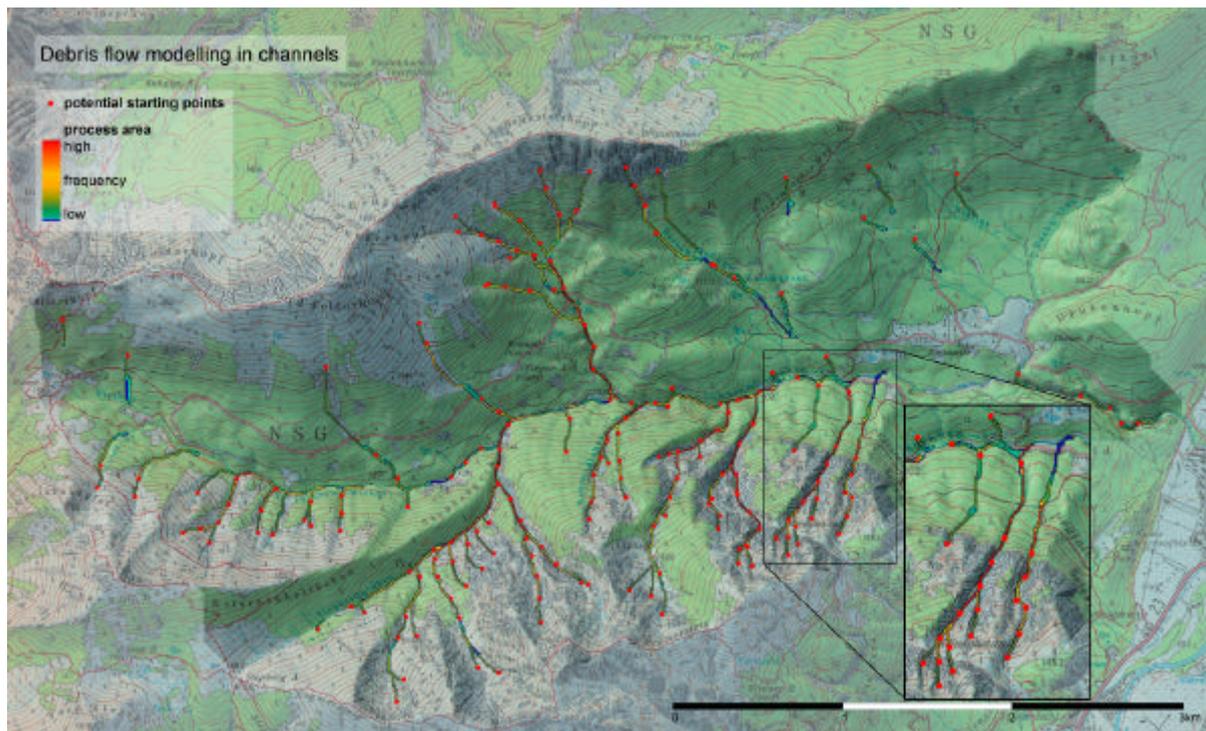


Fig. 9: Debris flow modelling in channels in the Lahnenwiesgraben catchment area (background: topographic map, Bayerisches Landesvermessungsamt).

4. Discussion

The first results presented here look promising and it should be possible to combine the models to describe parts of the sediment cascade in alpine catchments. Further research and data is needed to couple the models with measured sediment yield. Process rates may be obtained from historical data (e.g. dendrochronology, sediment accumulation dating by radiocarbon, geophysical methods) or from measurements of recent process intensities. Further models, e.g. slope wash and channel erosion, are under development.

5. Acknowledgement

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