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Spatial modelling of debris flows in an alpine drainage basin

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Abstract A model to describe the spatial distribution of torrent bed type debris flows in alpine drainage basins was developed and validated by field measurements. In addition to the determination of debris flow initiation sites, process pathway and erosion and deposition zones were identified. Potential process initiation sites were derived from channel slope, upslope contributing area and a material contributing area. Process pathway and travel distance were modelled by a grid-based "random walk" in conjunction with a 2-parameter friction model and Monte Carlo simulation. Erosion and deposition zones were derived by threshold functions of channel gradient and modelled velocity. A high magnitude rainstorm event in 2002 in the Lahnenwiesgraben drainage basin was used to validate the model. It is suggested that the model output may be used for the investigation of spatially distributed sediment transfers and for natural hazard zonation.

Key words debris flows; deposition; erosion; friction model; natural hazard zonation; Northern Limestone Alps; random walk; sediment transfer; travel distance

INTRODUCTION

Debris flows are common features in mountain drainage basins and they play a decisive role in sediment routing. They act as a sediment transport link between hillslopes and channels and thus have an important impact on the sediment budget. Debris flows influence the spatial and temporal distribution of sediments in alluvial channels, either because they deposit sediments in channels or because the deposits provide a source for increased sediment transport further downstream. Therefore, knowledge of the role of debris flow routing will aid in the construction of sediment budgets, and in interpreting the measurements of sediment transport in mountainous basins (Benda & Dunne, 1987).

Beside slope inclination and vegetation, the availability of water and the physical properties of the debris are most important for the initiation of debris flows. In a downslope direction, the flow increases in volume by entraining additional sediments, water and organic debris, and tends to become more destructive with travel distance. Debris flows can affect regions far from the initial failure sites, and in inhabited areas they usually cause damage to infrastructure and land resources, and may even claim lives. Therefore, methods for predicting initiation sites must be complemented by methods for predicting erosion and deposition areas (Benda & Cundy, 1990).

Our work forms part of the project sediment cascades in alpine geosystems (SEDAG), aiming at quantifying and modelling the sediment budget of mountain drainage basins (Haas *et al.*, 2004). In this paper, we describe models to identify process initiation sites, process pathway and run-out distance of debris flows (including lateral spreading and identification of erosion and deposition areas). The model output may be used for the investigation of spatially distributed sediment transfers and for natural hazard zonation. Field observations of initiation, erosion and deposition of debris flows in the Lahnenwiesgraben drainage basin after a high magnitude rainstorm event in the year 2002 are used to validate the models.

STUDY AREA AND DATA

The Lahnenwiesgraben drainage basin with an area of 16.6 km^2 is located in the Northern Limestone Alps, Bavaria, Germany and drains into the River Loisach. A wide range of fluvial and gravitational processes occur within the basin, including slope type and torrent bed type debris flows. For a more detailed description of the natural conditions see Haas *et al.* (2004).

In the early morning of 21 June 2002, a high magnitude rainstorm event triggered several slope type debris flows. Most channels remained stable, but a further event in the early afternoon caused failures in most of the steep torrents. These torrent bed type debris flows destroyed the forest road at several sites while large volumes of debris were transported and deposited. In this paper we focus upon torrent bed type debris flows, methods for modelling slope type debris flows are described elsewhere (Wichmann *et al.*, 2002; Wichmann & Becht, 2003, 2004).

In order to calibrate and validate the models, several debris flows were mapped in the field after the event (erosion and deposition heights and volumes). The consequences of the event for fluvial transport rates are discussed in Haas *et al.* (2004).

The model version presented here only requires data that can be derived directly from a digital elevation model (DEM). The DEM of the drainage basin was interpolated with ARC/INFO's Topogrid command at a resolution of 5 m. Elevation information was obtained from photogrammetric contour data (scale 1:10 000, contour interval 20 m, © Bayer. Landesvermessungsamt München (Bavarian Ordnance Survey), http://www.bayern.de/-vermessung, Az: VM-DLZ-LB-0628). Interpolation errors are relatively small and are mostly encountered in regions with steep rock walls (>60°). Due to forest cover, some elevation accuracy is already lost in the original data. Further problems arise from the fact that parts of the forest road had not been built when the elevation data was obtained. Thus, the forest road alignment is not represented in the DEM.

METHODS

The models described here were calibrated by empirical functions and field observations. We developed the models as module libraries (coded in C++) for a new GIS called SAGA (Böhner *et al.*, 2003). The determination of debris flow initiation sites is possible with the knowledge of the type and characteristics of the starting zone. Initiation sites of torrent bed type debris flows were derived in several steps (Zimmermann *et al.*, 1997; Wichmann & Becht, 2003, 2004). The channel network was extracted from the DEM by thresholds of upslope contributing area and plan curvature. The FD8 algorithm of Freeman (1991) in combination with a threshold for single flow direction was used to derive the upslope contributing area of each cell. Grid cells with a flow accumulation value higher than 2500 m^2 and a concave plan curvature (Zevenbergen & Thorne, 1987) less –0.02 were classified as channel cells. The thresholds were found by comparing the resulting grids with the channel network visible on orthophotos and topographic maps.

The failure mechanisms are complex, but beside high discharges there must be at least enough material available in the channel. On this account, a material contributing area was delineated to specify the amount of sediment input from the hillslopes (Zimmermann *et al.*, 1997). Starting from the channel network, a special algorithm recursively searches uphill until a maximum distance to the channel network (250 m) or a minimum slope gradient in flow direction (20°) is reached. This material contributing area may be weighted in relation to its sediment production. The weights (values between zero and one) can be chosen to reflect the natural conditions, e.g. vegetation cover, weathering rates and delivering process. As this information is rather difficult to obtain and has not been available up to now, we manage without this feature. This results in a maximum material contributing area for each channel cell (worst case scenario). Possible initiation sites were extracted from the channel network by combining empirically derived thresholds of upslope contributing area, slope and material contributing area. We used a minimum material contributing area of 10 000 m^2 and applied a threshold function derived by Zimmermann *et al.* (1997) for debris flows in Switzerland: $s = 0.32a^{-0.2}$, where s is the local channel gradient in percent and a is the upslope contributing area in km^2 (with increasing discharge downstream, lower channel gradients suffice for debris flow initiation). The last step is to use a filter along the channel network to remove redundant starting cells. The resulting grid shows the spatial distribution of potential debris flow initiation sites within the drainage basin and is used as input for modelling process pathway and travel distance (Fig. 1).

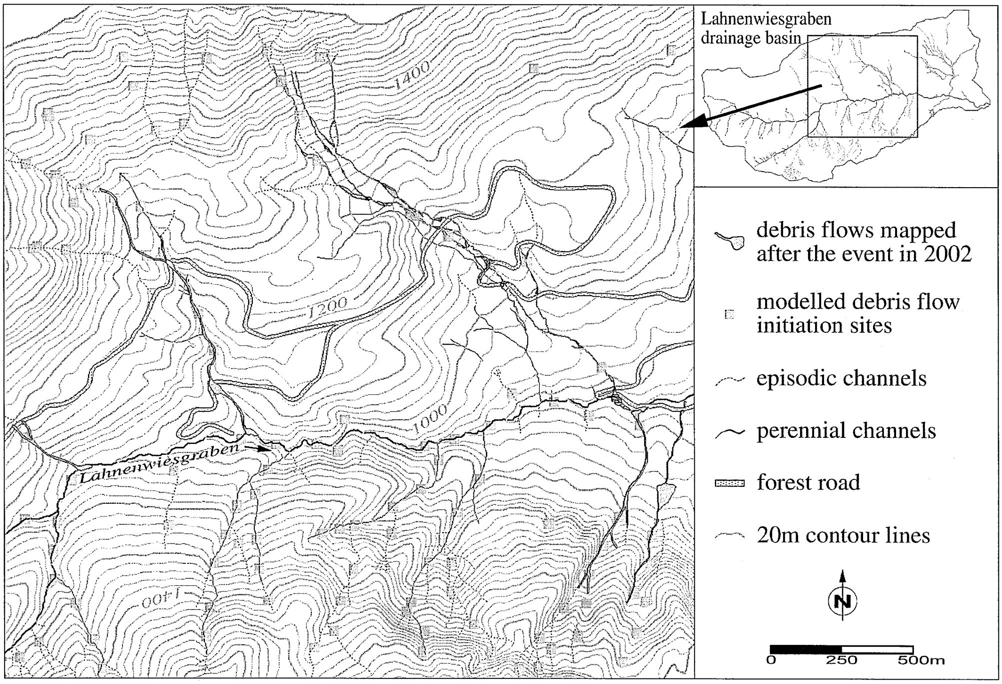

Fig. 1 Debris flows mapped after the event in 2002 and modelled debris flow initiation sites. The magnified map shows the central part of the Lahnenwiesgraben drainage basin.

The downstream movement of debris flows was modelled by a grid-based "random walk" (Price, 1976; Gamma, 2000) in conjunction with a 2-parameter friction model (PCM model, Perla *et al.*, 1980) and Monte Carlo simulation. Wichmann & Becht (2003) provide a more detailed description of the model. The "random walk" is a combination of single and multiple flow direction algorithms and can be adjusted by three calibration parameters (slope threshold for lateral spreading, parameter for divergent flow, persistence factor). On steep slopes near to the slope threshold, only neighbours with high gradients are allowed in addition to the steepest descent. In flat regions almost all lower neighbours are potential flow path cells and the tendency for divergent flow is increased. A higher weighting of the previous flow direction (persistence factor) is used to reduce abrupt changes in flow direction. A general tendency towards the steepest descent is achieved as the transition probabilities are weighted by slope (Gamma, 2000). We used a slope threshold of 20°, a divergence factor of 1.3, a persistence factor of 1.5 and calculated 1000 iterations from each initiation site. The parameters of the "random walk" were calibrated by field observations and are comparable with values used by Gamma (2000) for debris flows in Switzerland. Along with the identification of the next cell in the flow path, the local change in velocity is calculated with the PCM model. The model was originally developed for snow avalanches, but has also been applied to debris flows (Rickenmann, 1990; Gamma, 2000; Wichmann *et al.*, 2002; Wichmann & Becht, 2003, 2004). It is assumed that the motion is mainly governed by a sliding friction coefficient (μ) and a mass-to-drag ratio (M/D). We used a constant M/D of 75 m along the flow path and a spatially distributed friction coefficient μ derived from an estimating function of upslope contributing area a ($\mu = 0.13a^{-0.25}$; Gamma, 2000) to account for different rheology with higher discharges. A minimum threshold for μ is set to 0.045 and a maximum threshold to 0.3 (Gamma, 2000). It is possible to use different functions for different scenarios (Gamma, 2000; Wichmann & Becht, 2004). Here, we focus upon maximum run-out distances.

To model the sediment transfer throughout the basin, erosion and deposition zones need to be identified. Benda & Cundy (1990) developed an empirical model to estimate erosion volumes and deposition sites of debris flows from channel gradient and the junction angle between the contributing and receiving channel. We used threshold functions of channel gradient and/or modelled velocity to determine erosion and deposition zones and relative volumes assuming transport-limited conditions. The model may be run in two modes:

(a) Relative erosion and deposition heights are determined along the process pathway and specified (e.g. measured) volumes are scaled accordingly after model calculations. This mode may be used for stochastic forcing of sediment supply and routing as proposed by Benda & Dunne (1997).

(b) The volume of the initial failure is specified and further erosion depths along the process pathway are calculated using the slope and velocity thresholds. The entrained material is used for deposition and deposited material influences the following runs of the Monte Carlo simulation. Thus the filling of sinks and barriers and the plugging of the channel can be simulated.

It is possible to use a combination of slope and velocity thresholds to minimize artefacts resulting from the usage of one threshold alone (e.g. there is no material deposited in flat parts of the profile if the velocity is still high; deposition = min {height(velocity); height(slope)}; erosion = max {height(velocity); height(slope)}). The curves in Fig. 2 are used for calculating relative erosion and deposition heights along the process pathway. The

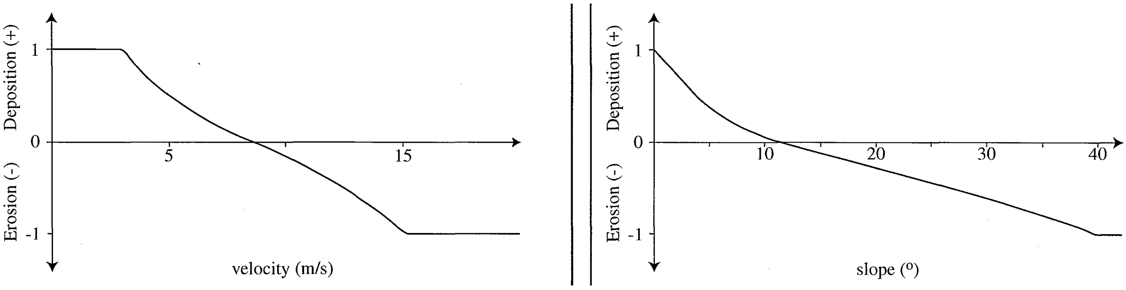

Fig. 2 Estimating functions of velocity and slope used for calculating erosion and deposition heights along the process pathway.

values, calibrated by field observations, do not necessarily correspond to physical reality as velocity is modelled and slope depends on grid resolution.

RESULTS

The examples presented here were calculated with the model settings discussed in the previous section. Figure 1 shows some of the debris flows mapped after the event in 2002, together with the modelled debris flow initiation sites. As we performed no weighting of the material contributing area, nearly all steeper channels are prone to debris flow initiation. This worst-case scenario reproduced all torrent bed type debris flows of the event in 2002. Figure 3(a) shows the Herrentischgraben sub-basin in greater detail. The pattern is quite complex as some of the debris flows unite downstream. Figure 3(b) shows the modelling

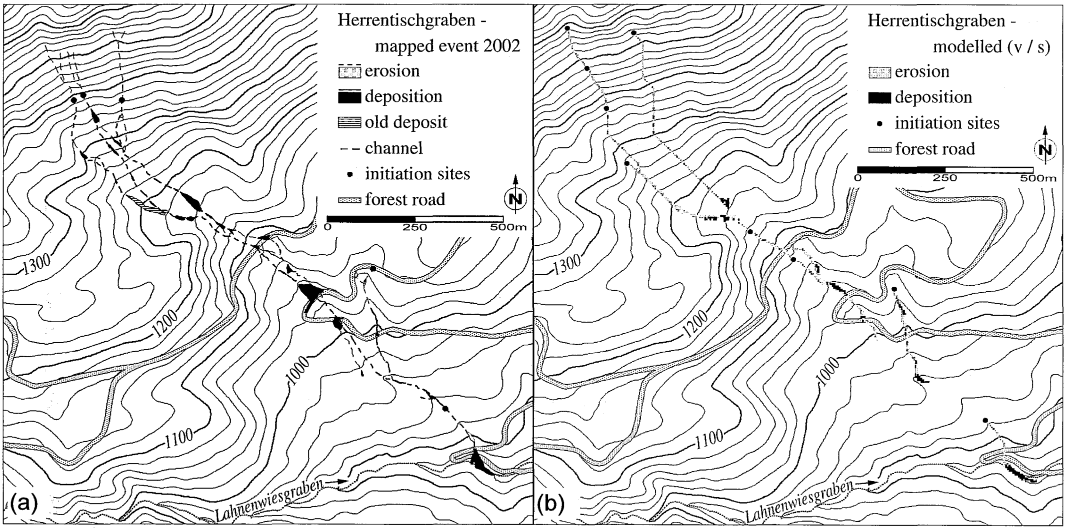

Fig. 3 Maps of (a) observed and (b) modelled debris flows in the Herrentischgraben sub-basin (Lahnenwiesgraben). Erosion and deposition zones are modelled by a combination of velocity and slope thresholds.

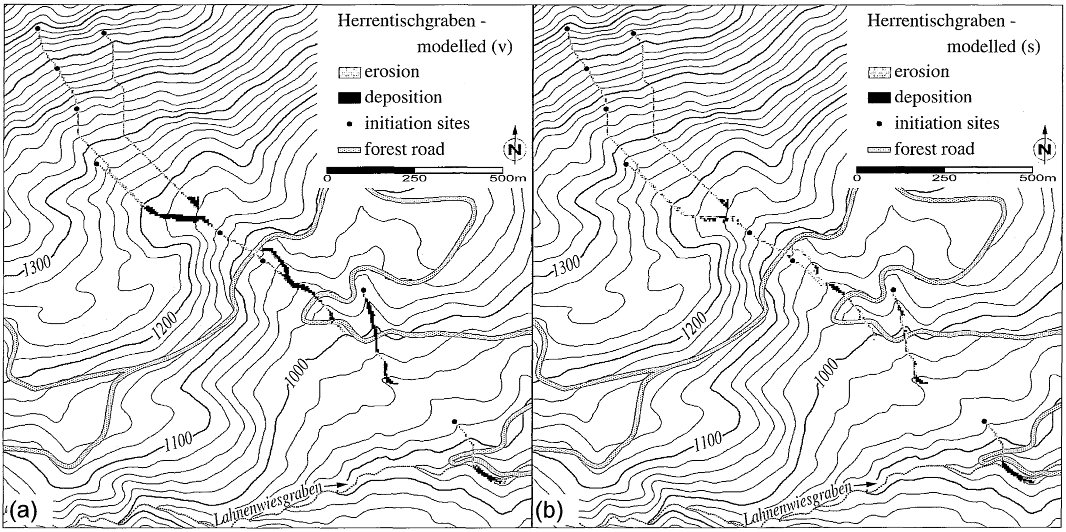

Fig. 4 Maps of modelled debris flows in the Herrentischgraben sub-basin (Lahnenwiesgraben). Erosion and deposition zones are modelled by (a) velocity and (b) slope thresholds.

results obtained by the usage of a combination of velocity and slope thresholds. The initiation sites match quite well with the observed ones, only the highest site mapped in Fig. 3(a) is missing. Besides that, the corresponding channel is not represented in the DEM very well. This debris flow may be classified as slope type debris flow (see the corresponding deposition area just below the initiation site). Process pathways and travel distances resemble the mapped ones, the exact location is not reproduced due to inaccuracies of the elevation data (nearly the whole sub-basin is covered by forest). These inaccuracies become most apparent by comparing erosion and deposition zones. As the forest road alignment is not included in the DEM, the extent of the deposits on the road was modelled too small (no lateral spreading and no deposition because of high slope gradients). The results obtained by using velocity and slope thresholds alone are shown in Fig. 4(a,b). Using the velocity threshold function to predict erosion and deposition zones resulted in a slight overestimation of depositional areas. The usage of the slope threshold reproduced the observed pattern quite well, only the extent of some depositional areas was underestimated.

CONCLUSIONS

Both predicted process area and erosion and deposition zones resemble the pattern of the observed event. This is remarkable as only data obtained from a DEM was used for modelling. The good results may be supported by mainly transport-limited conditions during the event in 2002.

The model can be used by engineers and resource planners to recognize and zone hazard areas. In addition, the model can be used in geomorphic process studies to assist in predicting erosion and deposition zones. The accuracy of the DEM has a major impact on the results and further investigations with different data and resolutions is needed to extend and validate the model.

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