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Investigating sediment cascades using field measurements and spatial modelling

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Abstract Many geomorphic processes contribute to the sediment budgets of high-mountain geosystems. The interaction of these processes to form a sediment cascade can be investigated, interpreted and visualized on the basis of spatial models calibrated by field measurements. We present the results of field measurements and modelling for a talus slope in one of the two study areas of a large interdisciplinary research project (SEDiment cascades in Alpine Geosystems—SEDAG). The sediment yield of a debris flow event (~12 000 t) is compared with the mean annual sediment yields of rockfall and fluvial processes on the talus cone. In addition, modelling and zonation of the potential process domains for rockfalls and debris flows clearly illustrate the concept of a sediment cascade. Results show that the sediment volume, reworked and removed from the cascade by debris flows, exceeds by far the sediment input by rockfall, so that the sediment volume stored on the talus cone is presently decreasing.

Key words debris flow; fluvial erosion; Germany; Northern Limestone Alps; rockfall; sediment budget; sediment cascades; spatial modelling

INTRODUCTION

The sediment budgets of high mountain areas reflect the contribution of different processes, the occurrence of which is characterized by a high spatial and temporal variability. The nature of some processes is (quasi-)continuous, with varying intensity throughout the year, while others can be thought of as single events, initiated by triggering factors. Each process has its own process domain, depending on the local geofactors and subdivided into zones of erosion, transport and deposition. The domains of two or more processes may overlap, so that a zone of predominant incision or deposition is formed. Alternatively, the sediment output of (= the sediment deposited by) one process may constitute the input of another. This concept can be termed a cascading system (Chorley & Kennedy, 1971; Slaymaker, 1991). Sediment budgets can be quantified by summing the total amount of sediment mobilized by the individual processes (e.g. Rapp, 1960). Following the framework presented by Slaymaker (1991), cascading systems, at the macro- or mesoscale, can be quantified by establishing sediment budgets. At the mesoscale (where the SEDAG approach is focused), it is necessary to identify the process pathways, in order to balance the budget accurately.

There is some inaccuracy in previous work, which reflects the use of an approach involving extrapolation of single measurements to the whole study area. It is therefore necessary to establish, as accurately as possible, the extent of process domains. These geomorphic process units, i.e. areas with the same combination of geomorphic processes, can be delineated by extensive geomorphological mapping in the field or by rule-based derivation from digital terrain and remote sensing data (e.g. Bartsch *et al.*, 2002).

In the SEDAG framework, the spatial domain of each geomorphic process contributing to the sediment budget is delineated using spatial models. These models consist of a so-called disposition model and a process model. The first is used to assess potential starting zones of the process, whereas the latter simulates the pathways of the process, i.e. the downslope and lateral propagation as well as the runout length. The superposition of the resulting process domains permits the identification of areas where a certain combination of geomorphic processes is active. Moreover, if the process area can be zoned (zones of erosion, transport and deposition), the overlaying of these model results makes it possible to delineate zones of predominant sediment removal, of (temporary) storage, or of zones where sediment is delivered directly from one process to another. In that case, the cascading system of the sediment budget can be analysed and visualized.

The sediment yield of the geomorphic processes involved have been measured since the year 2000, using different methods (Becht *et al.*, 2004). This paper concentrates on the analysis of the sediment cascades. In order to explain the SEDAG approach within the given framework, a case study from a small part of one study area has been selected.

THE STUDY AREA

The studies forming part of the SEDAG project are being conducted in two study areas in the Northern Calcareous Alps, near the town of Garmisch-Partenkirchen, southern Germany (see for example Heckmann *et al.*, 2002). In this paper, we present results from one of these areas, the Reintal valley. The study area is part of the basin of the River Partnach, a tributary of the River Loisach, which covers an area of 17.3 km^2. It is located in the Wetterstein mountain range, within the Alpine Lechtal nappe and follows a west–east striking, slightly east dipping syncline. Pleistocene glaciers from the Zugspitze mountain and glacial cirques on both valley sides have created an almost ideal U-shaped trough valley with extremely steep north facing rock walls, moderately steep south facing slopes and numerous hanging valleys. With the crests reaching elevations of over 2700 m a.m.s.l., the relief of the study area is 1700 m.

The basin consists almost entirely of Triassic (Ladinian-Karnian) thick-bedded to massive Wetterstein limestone, with only small portions in the higher regions of the basin consisting of Karnian Raibl beds. The Wetterstein limestone is geomorphologically very stable (steep slopes and rockwalls, sharp crests and high peaks, including the Zugspitze, Germany’s highest peak). Due to its purity, karst features and subterranean drainage are common within the basin. As a consequence, hillslope fluvial processes are much less frequent than gravitational processes (bergsturz, rockfall). The valley floor has been filled up to depths of 30–70 m with talus and fluvial sediment (Schrott *et al.*, 2003), and the valley sides are covered with talus cones and talus sheets. On these talus slopes, debris flows can develop following heavy precipitation.

The talus slopes are also subject to recent fluvial incision, deposition from rockfalls (Keller & Moser, 2002) and full-depth snow avalanches (Heckmann *et al*., 2002).

As half of the basin is situated in the alpine and subnival/nival zones, 75% of the area is characterized by poorly developed soil cover (thin Ah-C profile) or has no soil cover at all. Below 1800 m a.m.s.l., forested slopes are found (9% of the basin area), and krummholz vegetation (*Pinus mugo*) can reach elevations of up to 2075 m a.m.s.l. Two thirds of the basin area is lacking in vegetation or covered only by pioneer vegetation (below 2500 m).

MEASUREMENTS OF PROCESSES ON TALUS SLOPES

As indicated in the introduction, measurement and modelling results are presented for a sub-basin of the Reintal basin. This sub-basin is located in the central part of the study area, and it has an area of 0.12 km^2 (projected). Due to the north-facing rockwalls, the sub-basin has a very high relief of 900 m. It can be subdivided into two areas: (a) the rock face and (b) the talus cone. The rockwalls are source areas for primary rockfalls (due to weathering), parts of which are stored on small terraces within the rockwalls, where it can be remobilized by precipitation (secondary rockfalls). Krautblatter (2004) has shown that the deposits of primary and secondary rockfalls in the Reintal basin can be distinguished on the basis of granulometry and grain morphology. On the talus slopes, the rockfall deposits are reworked by fluvial processes and debris flows. The interaction of geomorphic processes observed in this part of the study area complies with the concept of sediment cascades, with the output of one process being the input to another process and/or temporary storage. In recent times, the talus cone, thought to have formed in the late- and post-glacial, has become deeply incised by the initiation of slope type debris flows. Where the talus cone is dissected, finer and more compact sediments are exposed on the lateral slopes that are subject to fluvial dissection ("fluvial erosion" in Fig. 1). In addition, the distal part of the talus cone is truncated by fluvial erosion associated with the River Partnach. Some debris flows have transported sediment directly into the main channel, while dissecting the truncation scarp on the way.

All geomorphic processes occurring on the talus slope and the thickness of the talus deposits have been measured by the SEDAG working groups since the year 2000 (e.g. Keller & Moser, 2002; Schrott *et al*., 2002; Becht *et al*., 2004). The deposition of rockfall material onto the talus cone and the fluvial sediment transport are considered to be (quasi-)continuous processes, the intensity of which varies throughout the year. In this case, mean process rates can be calculated on the basis of all measurements. The sediment yield of debris flows was quantified on the basis of one event in the year 2003 (Fig. 2).

RESULTS OF THE MEASUREMENTS

Here, we present a sediment budget for the sub-basin on the talus cone "Vordere Blaue Gumpe" (Fig. 1). Following heavy precipitation (20 mm in 15 min) on 14 June 2003, several debris flows occurred that could be mapped, including one in the sub-basin

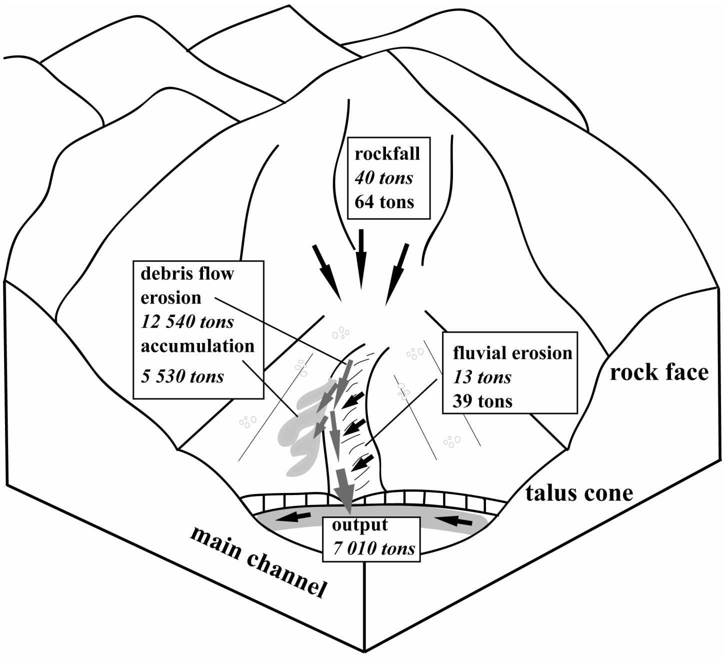

Fig. 1 Processes in the sub-basin and the sediment budget for the rainstorm event on 14 June 2003 (in italics) and the mean annual sediment budget (normal).

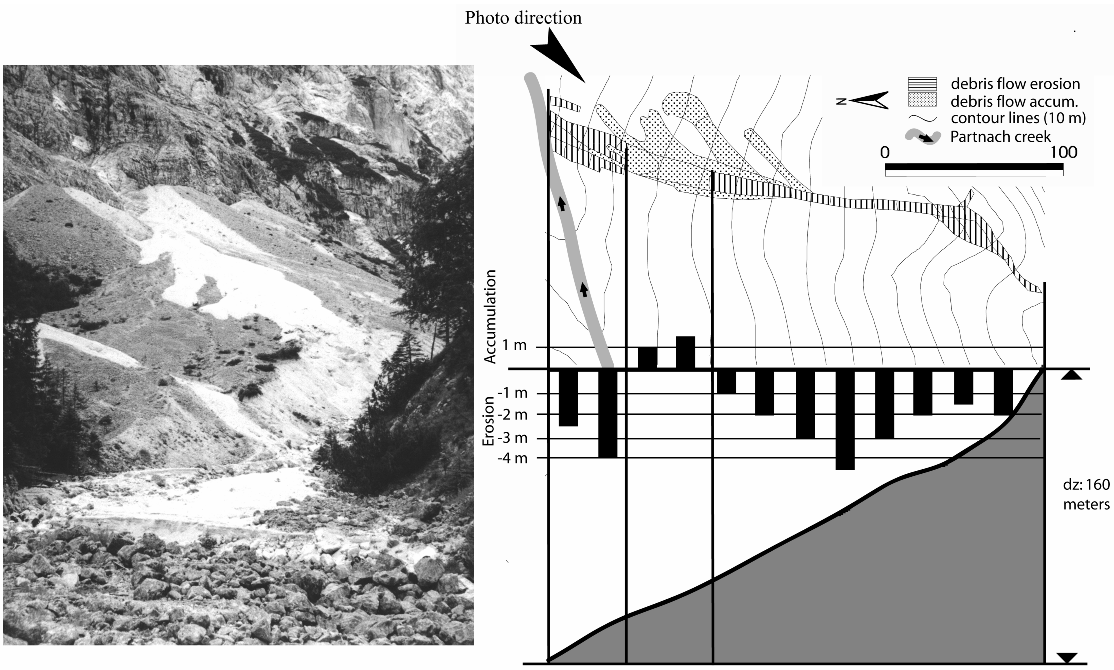

Fig. 2 Erosional and depositional zones of the debris flow on the talus cone "Vordere Blaue Gumpe" (photograph: V. Wichmann).

described in this paper. Surveying of the erosional and depositional zones on the talus (Fig. 2) yielded an estimate of 12 540 t of eroded sediment, part of which (5530 t) was deposited further downslope on the talus cone. The rest of the eroded sediment (7010 t) was transported out of the sub-basin and into the River Partnach.

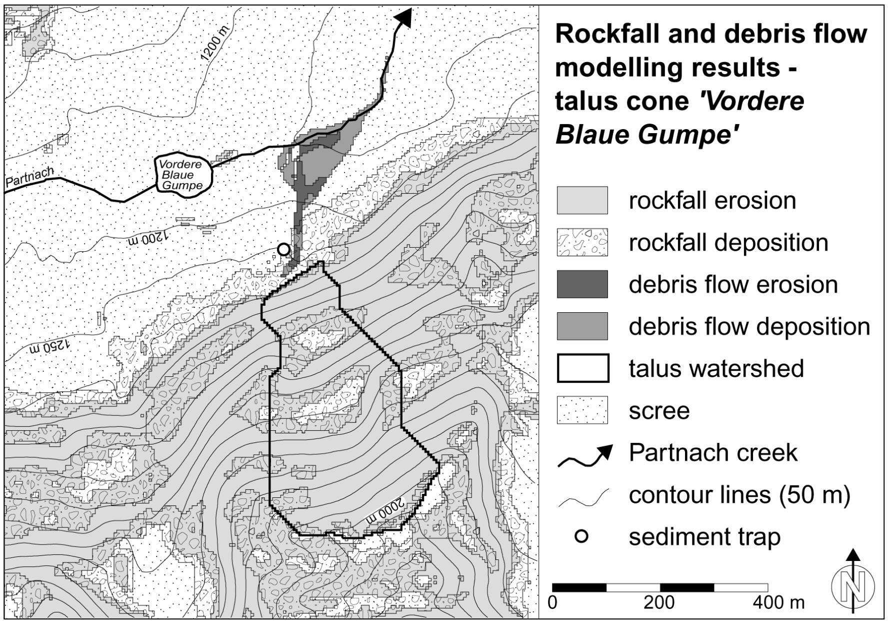

Fig. 3 Map of modelling results on the talus cone "Vordere Blaue Gumpe" / Reintal.

Heavy precipitation not only caused the debris flows, but also triggered increased rockfall activity delivering 40 t (Krautblatter, personal communication) of sediment onto the talus cone. On the flanks of the path of the debris flow, increased fluvial sediment transport occurred during the precipitation event. More than 130 kg of sediment were caught in the sediment trap installed there (Fig. 3), which represents approximately 13 t delivered from the total slope area to the debris flow channel.

The results clearly show that the talus cones are being dissected by debris flows, with only small sediment inputs by rockfalls—64 t year^{-1}, estimated on the basis of four years of field measurements with two extreme events, (Krautblatter, personal communication). The erosional activity of one debris flow is equivalent to 320 times the mean annual sediment yield of the fluvial processes (39 t year^{-1}) and 200 times the mean annual sediment yield of the rockfalls. These facts clearly corroborate the interpretation of debris flows as a major component of alpine sediment budgets (Dietrich & Dunne, 1978; Haas *et al*., 2004). On the talus cone presented in this study, debris flows are the only process to transport sediment out of the sub-basin, while the other processes deliver or redistribute sediments on the cone. This is the case particularly with fluvial processes, that only occur where fine, compact material is exposed, due to the very high infiltration rates measured elsewhere on the cone surface.

MODELLING OF PROCESS DOMAINS

Potential starting zones for rockfalls are controlled by local slope (van Dijke & van Westen, 1990; Dorren & Seijmonsbergen, 2003). Most starting zones are steeper than a threshold of 40°, whereas the talus below the rockwalls has a considerably lower slope (20–40°). The pathway of the process (downslope and sideways) is modelled using Monte Carlo simulation of random walks (Gamma, 2000) that can be adjusted to different processes via three parameters. The slope threshold determines the slope gradient above which no lateral dispersion may take place (in this case, only the direction of steepest descent applies). As the descent of a rock fragment is modelled as free fall, until the slope gradient falls below 65°, this value is also taken as the slope threshold. This threshold and two other parameters (controlling the tendency towards lateral dispersion and towards the retention of the last direction of movement) allow for adjustments to reflect different patterns of movement (Wichmann & Becht, 2003). The random walk is coupled with a friction model (Scheidegger, 1975) to calculate the development of velocity and the runout distance for each simulation. After detachment of a rock fragment from the wall, free fall is modelled until the slope gradient of the process pathway falls below 65° (without taking into account air resistance). The fragment loses 75% of its energy upon impact with the talus (Broilli, 1974; Scheidegger, 1975), where the subsequent movement is modelled by a one-parameter friction model (Scheidegger, 1975). The friction parameter is chosen to simulate a sliding movement of the rock fragment over the talus, assuming that all types of movement (bouncing, rolling, sliding) can be approximated by simulating a sliding movement over rough terrain (Kirkby & Statham, 1975). The dynamic angle of friction can be estimated using the ratio of the diameter of falling fragments and talus sediment (Kirkby & Statham 1975).

In the case of the Reintal, the talus slopes are covered with coarse sediments (about 10–30 cm). As it is intended to model continuous rockfall deposition of smaller fragments (debris shower deposition; Kotarba & Strömquist, 1984), the friction parameter μ has to be set to considerably high values (2.5 on talus slopes, 1.25 for bare rock), in order to calibrate the model to fit the observed runout distances. Among other outputs, the model generates maps indicating the stopping position of fragments and their maximum velocity. It is thus possible to identify zones of erosion and deposition within the overall process domain.

Using the certainty factor method (Binaghi *et al*., 1998; Heckmann *et al*., 2004), a statistical approach has been chosen to model the potential starting zones of slope-type debris flows. The model is calibrated using the mapped starting points of known events on the basis of classified raster datasets (slope gradient, flow accumulation, vegetation, distribution of bedrock and talus). The result is a raster map, containing the combined certainty factors CF^+ [–1;1]. Values close to 1 signify an increase in certainty that the raster cell is susceptible to debris flow initiation, 0 means that the geofactor combination present does not influence susceptibility, and a –1 value decreases the certainty. From this raster map, potential starting cells are identified where the CF^+ exceeds 0.98. To reduce the number of adjoining cells, a flow direction filter is applied. The process pathway is delineated using the same approach as the rockfall model (for parameter settings see Table 1). Unlike the rockfall model, the debris flow model uses a two-parameter friction model (Perla *et al.,* 1980) to determine flow velocities and the runout distance. This model contains two friction parameters, the mass-to-drag ratio (M/D) and the coefficient of dry friction (μ). The M/D ratio is held constant along the pathway, μ is determined for each model step using an estimation function of local flow accumulation a (Gamma, 2000). Using simple threshold functions of slope and/or flow velocity (Wichmann & Becht, 2004), it is possible to assess where the modelled debris flow is eroding and depositing sediment.

Table 1 Model parameters.

	Rockfall	Debris flow
Disposition	Slope > 40°	$CF^+ > 0.98$ and filter
Random walk:		
Slope threshold	65°	35°
Dispersion exponent	2	2
Persistence factor	1	1.5
Friction model:		
Fall threshold	65°	–
Energy reduction (impact)	75%	–
Friction coefficient μ	2.5 (scree) / 1.25 (bare rock)	$\mu = 0.13 \times a \quad [km^2]^{-0.25}$
M/D	–	75 m
Iterations (model runs)	1000	1000
Zonation	Disposition / stopping position	Velocity threshold

All necessary input data are prepared as raster grids with a resolution of 5 m. The modelling results are shown in Fig. 3. Rockfall erosion occurs mostly along the steep rock faces, except for some rock ledges. In these small areas, rockfall material from up-slope is deposited and this can be remobilized later, mostly by runoff following heavy precipitation. The bulk of the small rock fragments is deposited on the talus within a short distance of the foot of the rockwall, as observed in the field (Krautblatter, 2004).

In Fig. 3, only the debris flow contributing to the local sediment budget is depicted. The initiation cell of the debris flow chosen by the disposition model is situated directly at the apex of the talus cone, which can be confirmed by field observation. The process model has been calibrated in such a way that it yields the potential process domain and not only the 2003 event. That is why the modelled process domain covers the whole talus cone.

The modelled zones of erosion and deposition closely match the zones mapped in 2003 (see Fig. 2). In the upper part of the pathway, small deposition zones are predicted by the model, due to the lower gradient and lower flow velocity. In this area, debris flow deposits from smaller events are found. The dissecting activity of debris flows in the lower part, where the talus cone is truncated by the River Partnach, is also correctly modelled. Potential process pathways include the next approx. 100 m of the River Partnach. In the field, fluvially reworked debris flow deposits can be observed in this area.

The superposition of debris flow and rockfall modelling results permits an analysis of the local sediment cascade. In the example shown in Fig. 3, there is a clear overlap of rockfall deposition and erosion by debris flows.

CONCLUSION

The available results show that the SEDAG approach permits a fairly accurate assessment and zonation of geomorphic process domains. As the results of process simulations can be superimposed, a detailed analysis of sediment cascades on individual slopes and in the whole study area is possible. In our opinion, this is an important step towards accurate sediment budgeting, because accurate modelling of process domains may facilitate a more accurate regionalization of measured process rates without the need for time-consuming area-wide geomorphic mapping. Coupling the measured sediment transport rates with the modelled process domains, however, remains a challenging problem and is subject to further research.

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