Change of fluvial sediment transport rates after a high magnitude debris flow event in a drainage basin in the Northern Limestone Alps, Germany

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Abstract This paper deals with the influence of debris flows on fluvial sediment transport in a drainage basin in the Northern Limestone Alps, Germany. A high magnitude rainstorm event in the year 2002 triggered several debris flows on slopes and in channels. Weekly quantification of the sediment transport in small channels in the study area Lahnenwiesgraben since the year 2000, show a drastic increase in sediment yield after the debris flow event due to extremely high sediment mobilization in the channel beds. The investigations show that erosion and deposition by debris flows also affect the long-term fluvial sediment budget. Debris flows change the state of the fluvial geomorphic system and induce prolonged high fluvial sediment transport. The composition of the transported sediment (organic content, granulometry) may also be modified. The interaction of geomorphic processes is an important issue in modelling sediment budgets and landform development.

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

INTRODUCTION

Debris flows are a common geomorphic process in mountainous geosystems. In spite of long recurrence intervals (low frequency–high magnitude events), they greatly contribute to the development of landforms (Zimmermann *et al.*, 1997) due to their high sediment yield.

A great deal of research has been undertaken to understand and model debris flows as a geomorphic process (e.g. Becht, 1995; Zimmermann *et al.*, 1997; Rieger, 1999; Hagg & Becht, 2000; Wichmann & Becht, 2003, 2004a,b), while their influence on fluvial processes, and thus the sediment budget of alpine drainage basins, has not yet been quantified. The significance of debris flows has been pointed out by various studies (e.g. Dietrich & Dunne, 1978; Caine & Swanson, 1989; Lehre 1981; Becht 1995), but a quantification of the changes to the sediment budget beyond short-term assessment has not been undertaken.

Within the scope of our research on fluvial and slope aquatic erosion processes in alpine geosystems, the amount of change caused to the fluvial system by debris flow events in the year 2002 has been investigated (mapping, quantification, modelling).

The investigation of the fluvial erosion processes forms part of the project *Sediment Cascades in Alpine Geosystems* (SEDAG), which aims at quantifying and modelling the sediment budget of mountain drainage basins. For this purpose, detailed studies of several geomorphic and hydrologic processes including soil creep, rockfall, landslides, debris flows, avalanches, aquatic and fluvial processes and the corresponding sediment storages are in progress (Heckmann *et al.*, 2002; Keller & Moser, 2002; Unbenannt, 2002; Schrott *et al.*, 2003; Wichmann & Becht, 2003).

STUDY AREA

The Lahnenwiesgraben drainage basin (16.7 km^2) is located in the Northern Limestone Alps ("Ammergebirge"; Bavaria) northwest of Garmisch-Partenkirchen (Fig. 1). It is drained by the Lahnenwiesgraben creek, which is tributary to the River Loisach. The "Hoher Kramer" in the southeast of the drainage basin is the highest peak with an elevation of 1985 m a.s.l. The maximum vertical distance in the drainage basin is 1279 m. Its geology consists of Triassic ("Hauptdolomit", "Plattenkalk" limestone, "Kössener" marls) and Jurassic series ("Aptychen" limestone and marls). The presence of glaciers during the last glaciations is indicated by several moraine deposits.

Most of the area is covered by vegetation consisting of forest (coniferous, mixed and *Pinus mug*; 75% of the drainage basin) and alpine meadows (18%).

METHOD

Fluvial and erosion processes on the slopes have been measured since the summer of 2000 using denudation gauges and sediment traps. Precipitation has been measured by two writing

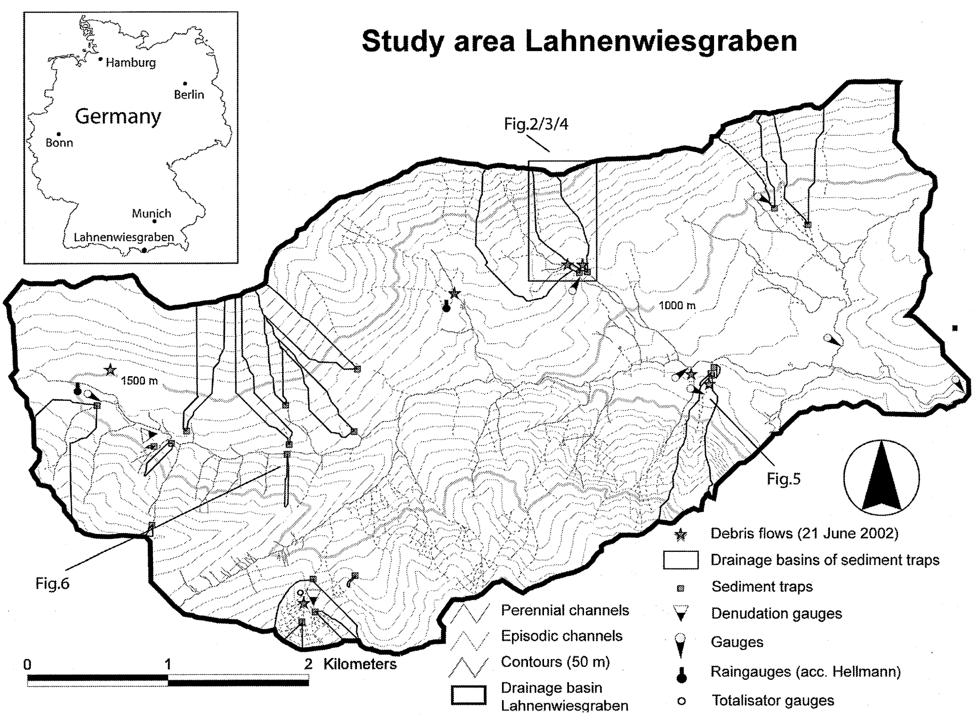

Fig. 1 Study area Lahnenwiesgraben.

raingauges (acc. Hellmann) and a totalisator gauge. In addition, runoff has been monitored by gauges in six creeks within the study area (Fig. 1).

Plastic troughs with a volume of 65 l installed in small channels are being used as sediment traps (Becht, 1995). Twenty-one sub-basins in the study area have been equipped with these sediment traps that are emptied weekly (Fig. 1). The sediment samples taken from the traps are weighed and analysed in the laboratory (granulometry and organic content).

The sub-basins have areas of between 1100 and 443 000 m^2 (determined by means of GIS analysis and mapping/terrestrial surveying). They have been chosen in order to represent a sufficient number of geofactor combinations (vegetation, geology, slope etc.) of the study area. On the basis of measured sediment transport rates and the geofactor combinations of the sub-basins, a regionalization of slope erosion for the whole study area is performed in order to establish a spatially distributed model.

The debris flow deposits of the year 2002 (see next section) that affected some sub-basins have been mapped and surveyed in order to determine process pathways and sediment yield.

HIGH MAGNITUDE RAINSTORM EVENT AND CONSEQUENCES

On 21 June 2002, two intense rainstorm events occurred in the Lahnenwiesgraben study area. The first event at 08:00 h with 46 mm/30 min precipitation triggered only slope type debris flows. The second event at 14:00 h with about 70 mm h^{-1} precipitation triggered several debris flows in channels all over the drainage basin (see Fig. 1).

The forest road and numerous installations (sediment traps, gauges) were destroyed by these channel-type debris flows. In one sub-basin ("Herrentischgraben"), a debris flow ran over a sediment trap and deposited a large quantity of sediment on the forest road below (Fig. 2). This event caused the mobilization and deposition of 300 t of sediment in the sub-basin, which corresponds to 1500 times the mass of the sediment transported by fluvial processes within the period July 2000–June 2002.

The sediment trap destroyed by the debris flow was reinstalled later. As fluvial transport was measured before the event, and measurement has been continued since then, the change of fluvial sediment transport rates caused by the debris flow can be quantified.

RESULTS

Figure 3 shows that fluvial sediment yield within the sub-basin "Herrentischgraben" has greatly increased after the debris flow, as soil and vegetation cover (shrubs and scrub) have been destroyed by the event. The debris flow incised the channel, leading to lateral erosion and local bank failure. This led to the mobilization of a great amount of sediment (Pleistocene deposits and weathered bedrock). In addition, the debris flow created deposits (debris flow cones, levées) now delivering material to fluvial erosion processes. These observations are corroborated by analyses of organic content and granulometry of the transported material. Figure 4 shows a remarkable coarsening after 21 June, which can be explained by the fact that the debris flow has exposed deeper and coarser layers of hillslope sediments to fluvial erosion.

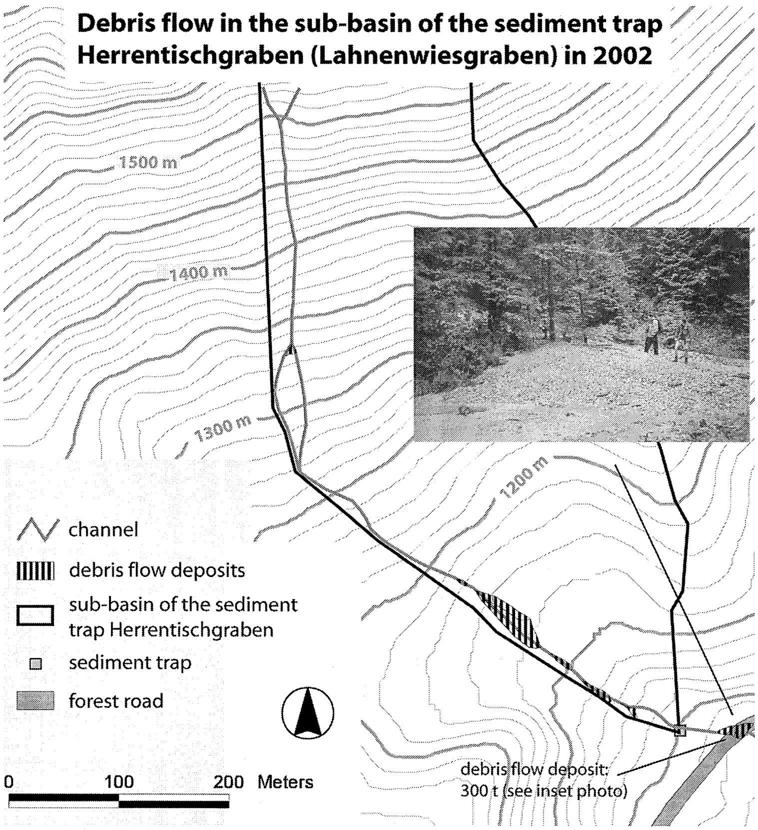

Fig. 2 Debris flow in the sub-basin of the sediment trap "Herrentischgraben" (Photo: V. Wichmann).

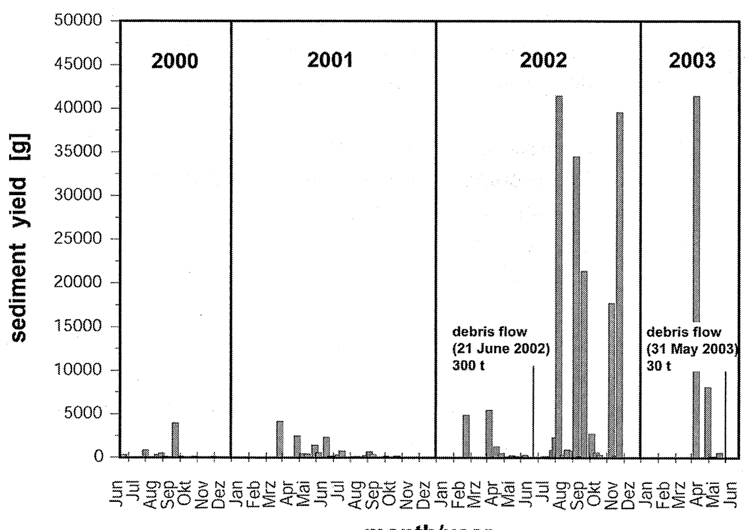

Fig. 3 Sediment yield of the sub-basin "Herrentischgraben" (weekly data).

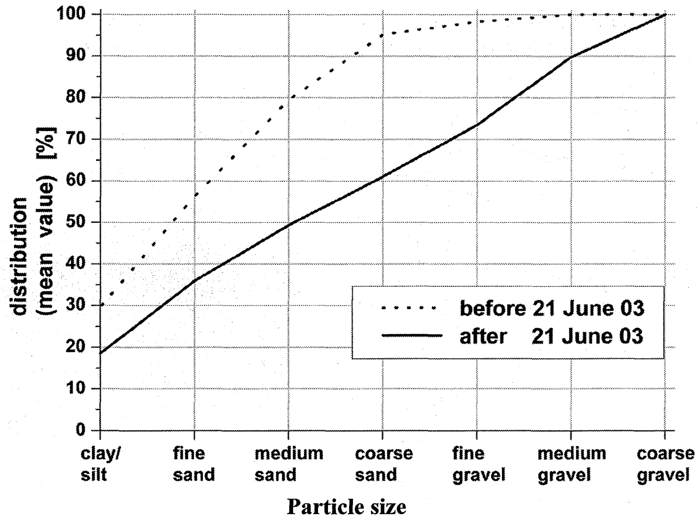

Fig. 4 Particle size distribution (mean value) of the transported material before and after the debris flow (Atterberg scale DIN4022; Leser, 1977).

The organic content of the sediment samples decreased from 15% before the event to about 8% after the event. This is due to the destruction and removal of vegetation cover and organic soil horizons from the surface.

The fact that important properties of the system have been changed by the debris flow not only led to increased fluvial sediment yield, but also influenced further debris flow activity. An event on 31 May 2003 in the same sub-basin was triggered by a precipitation event (45 mm/90 min) that would not have initiated (and did not initiate) a debris flow before the 2002 event. The sediment yield of the 2003 event (30 t), however, was an order of magnitude below the 2002 event.

Similar observations could be made in the "Königsstand" sub-basin, where an increase in fluvial sediment transport after a debris flow in 2002 could be measured too (Fig. 5). Contrary to the "Herrentischgraben" sub-basin, transport rates had started to decrease again soon (at the end of the year 2002), until another debris flow occurred on 31 May 2003.

The main difference between the two sub-basins is the channel size. The channel in the "Königsstand" sub-basin has a comparatively large cross section, while the cross section of the channel in the "Herrentischgraben" sub-basin is smaller and thus it is reacting more profoundly to debris flows (lateral erosion, bank failure, destruction of vegetation and/or soil cover). Increased sediment yield in the "Königsstand" sub-basin is mainly derived from sediments supplied to the channel by bank failure and levees. These sediment sources obviously are depleted after comparatively short time intervals. In the "Herrentischgraben" sub-basin, the profound change in the system has led to longer-reaching changes.

Sub-basins not affected by debris flows have been observed to react differently. For example, the sub-basin "Sulzgraben 2" showed increased fluvial transport (bed load) during the two rainstorms in 2002 and 2003, but no evidence of continued higher transport rates was found afterwards. This may corroborate our observation that long-term increased sediment yield in the sub-basins "Herrentischgraben" and "Königsstand" has indeed been caused by the debris flow events of 21 June 2002.

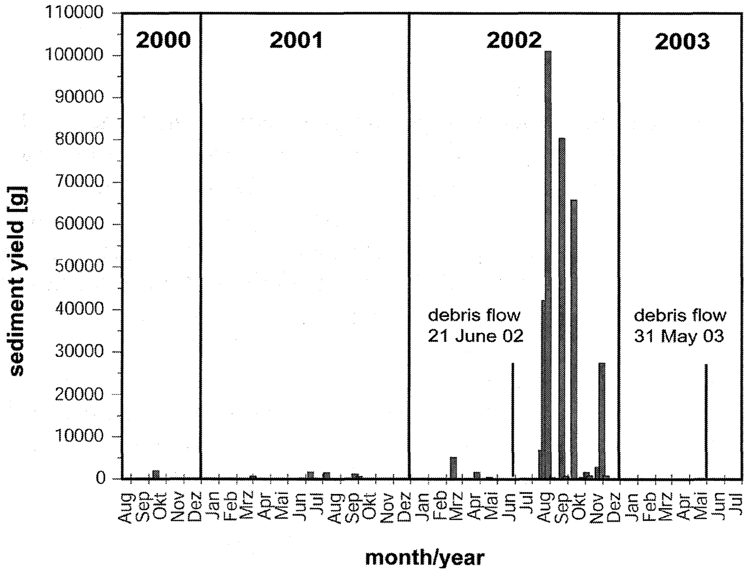

Fig. 5 Sediment yield of the sub-basin "Königsstand" (weekly data).

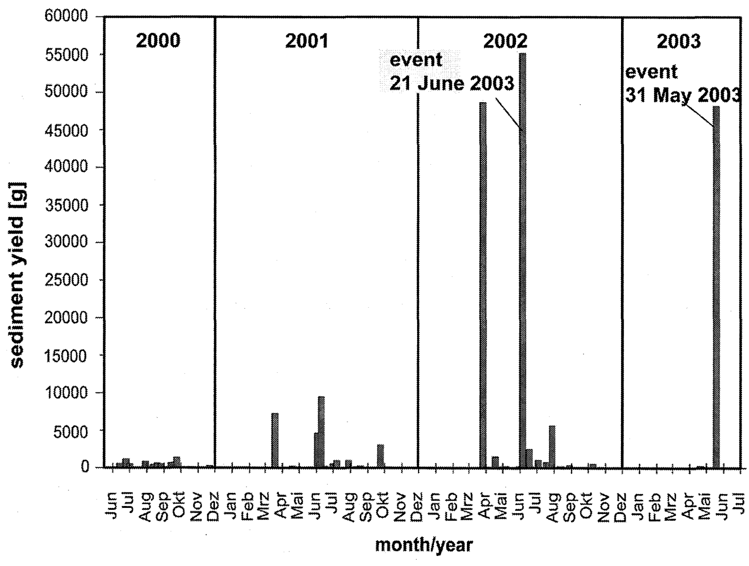

Fig. 6 Sediment yield of the sub-basin "Sulzgraben 2" (weekly data).

CONCLUSION

The results clearly indicate that debris flows are a very important geomorphic process contributing greatly to the sediment budget (Dietrich & Dunne, 1978; Lehre, 1981; Zimmermann *et al.*, 1997), especially to the fluvial sediment budget. According to our measurements, they can have a significant impact on drainage basins beyond the time of their occurrence, causing a change in the system that may lead to increased fluvial erosion and transport for years. Increased sediment availability also results in lower precipitation thresholds for the initiation of new debris flows.

At this stage, a period of increased geomorphic activity due to debris flows is observed in some sub-basins of the study area, the duration of which can not be readily assessed. In order to model sediment yield of fluvial processes and landform development, the influence of such low frequency–high magnitude events has to be taken into account. If debris flows are not taken into account, the long-term contribution of fluvial processes to the sediment budget may be greatly underestimated. Moreover, deriving transport rates from short-term observations is prone to errors and long-term observations are necessary for a better understanding of sediment budgets in alpine drainage basins.

The investigations described above are being continued within the SEDAG project in order to allow conclusions on future behaviour and the relaxation time of the system after debris flow impacts. The considerations concerning the interaction of geomorphic processes are incorporated in our approach to modelling landform development in the Lahnenwiesgraben study area.

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