Estimating Magnitude-Frequency Relationships for Debris Flows on Forested Cones — Working Concept and Preliminary Results

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Abstract

Signatures in century-old trees were used to assess past activity on a debris-flow cone, providing an unusually complete record on the frequency and deposition processes of debris-flow material and channel incision events on a cone in the central Swiss Alps. The study of 2450 tree-ring series sampled from 1204 *Larix decidua*, *Picea abies* and *Pinus cembra* trees allowed reconstruction of 123 debris-flow events since A.D. 1570. Currently, individual deposits are dated and the material left on the cone during particular events quantified. These data will be used — in combination with other field approaches — to assess frequency-magnitude relationships of debris flows. In this paper, first results are shown on the deposits identified on the cone and the frequency of events.

Keywords: it debris flow; tree-ring analysis; dendrogeomorphology, frequency; magnitude; Swiss Alps

Introduction

Debris flows represent a major threat in the Swiss Alps, where their repeated and, quite often, unexpected occurrence regularly causes fatalities or major damage to infrastructure and transportation corridors. Data on the frequency and volume of debris flows, therefore, are of crucial importance for the assessment of hazards and risks as well as for the design of e.g., torrent control works or retention basins (Rickenmann 1999). As a result, a great deal of attention has been directed toward the analysis and documentation of processes in the aftermath of the widespread flooding and debris-flow events in 1987 (Rickenmann & Zimmermann 1993), 1993 (Röthlisberger 1994), 2000 (BWG 2002) and 2005 (Beniston 2006), affecting large parts of the Swiss Alps.

There is, thus, an important lack of torrents and gullies having been monitored over sufficiently long periods of the past and fragmentary archival records on former debris-flow events. Only little information generally exists on volumes or return periods of debris flows in mountainous basins, despite recognition that individual events possess much greater erosive and hazard potential than flood processes.

Several estimation procedures have been applied in the past to assess magnitudes and frequencies of former debris-flow events, including stratigraphic methods (Blair 1999), dating of lichens on debris-flow deposits (Helsen *et al.* 2002), volumes derived from aerial photography (Jakob & Podor 1995) or the assessment of volumes triggered from the source area and material entrained along the flow path (Hungr *et al.* 2005).

Similarly, tree-ring records have repeatedly been used in the past to obtain information on past events (Strunk 1997, Baumann & Kaiser 1999, Stoffel *et al.* 2006), to gain knowledge on spatio-temporal patterns of debris flow on cones or their activity in currently abandoned flow channels (Bollschweiler *et al.* 2006), to assess the seasonality of past debris-flow events (Stoffel & Beniston 2006) or to investigate synoptic weather situations triggering individual events (Stoffel *et al.* 2005a).

However, data from tree-ring records have only exceptionally been coupled with data from ground survey for the analysis of volumes left on the cone during particular events so far. It is therefore the purpose of this study to shed light on magnitude-frequency aspects of debris flows on a forested cone in the Southern Alps of Switzerland, and their variability in time by coupling tree-ring with ground survey data. The specific objectives of this study are (i) to date former events; (ii) to quantify volumes deposited on the cone during past events with tree-ring data; (iii) to quantify the volumes of unconsolidated material available for future events, before (iv) an estimation of magnitude-frequency relationships will be done for the investigated torrent.

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Study site

The site investigated within this study is the debris-flow producing Ritigraben torrent (Valais, Swiss Alps). In the source area of the torrent (2,600–3,214m a.s.l.), contemporary permafrost was prospected with geophysical soundings and BTS measurements. In addition, ice lenses were observed after the release of debris-flow surges in 1994 (Lugon & Monbaron 1998). On its way down to the confluence with the receiving Mattervispa river, the torrent passes a forested cone on a structural terrace (1,500–1,800m a.s.l.), where debris-flow material frequently affects trees within an old-growth stand composed of European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) Karst.) and Swiss stone pine (*Pinus cembra* ssp. sibirica).

Figure 1 provides an overview of the catchment and the intermediate cone. Previous investigations have shown that debris-flow activity in the torrent is restricted to June through September (Stoffel *et al.* 2003) and that the largest event ever would have occurred in 1993 with eleven surges and an estimated volume of ca. 60,000 m^3 (see Zimmermann *et al.* 1997). As a result of these surges, the debris-flow channel was deeply incised on the intermediate cone. Thereafter, events remained comparably small with "only" 5000m^3 mobilized in 1994 (Dikau *et al.* 1996) and 3000m^3 transported in 2002.

Methods

Geomorphic mapping of debris-flow forms and deposits

Analysis of past debris-flow activity started with geomorphic mapping of all forms and deposits associated with past events, such as lobes, levees or abandoned flow paths. In addition, forms originating from other geomorphic processes or anthropogenic activity were indicated as well on the map in a scale of 1:1000. Due to the presence of a relatively dense forest cover, GPS devices could not be used, reason why the mapping had to be realized with a tape, inclinometer and compass.

Sampling design and dating of growth disturbances in trees

Based on the map and on an inspection of the stem surface, trees that have been disturbed by debris flows (i.e. tilted stems, partial burying of the stem, destruction of root mass or erosion, scars) were sampled with increment borers. In addition to the disturbed trees sampled on the cone, undisturbed reference trees were selected from a stand located southwest of the cone. Sample analysis included surface preparation, a visual inspection of the tree rings as well as ring-width measurements using a digital positioning table connected to a stereomicroscope and TSAP 3.0 software (Rinntech 2006).

Growth curves of the disturbed samples were then crossdated with the corresponding reference chronology so as to separate insect infestations or climatically driven fluctuations in tree growth from growth disturbances (GD) caused by debris flows (Cook & Kairiukstis 1990). Ring-width data were used to determine the initiation of abrupt growth reductions or recovery (Schweingruber 2001). In the case of tilted stems, the appearance of the cells (i.e. structure of reaction wood cells) and the growth curve data were analyzed (Fantucci & Sorriso-Valvo, 1999). Finally, the cores were visually inspected so as to identify further signs of past debris-flow activity in the form of callus tissue overgrowing abrasion scars or tangential rows of traumatic resin ducts formed after cambium damage (Stoffel *et al.* 2005b, Stoffel 2006).

Preliminary results

Geomorphic mapping of debris-flow channels and deposits

Geomorphic mapping permitted identification of more than 760 forms related to past debris-flow activity on the intermediate cone of the Ritigraben torrent. The forms and deposits inventoried in the study site covering 32 ha are illustrated in Figure 2.

The most common geomorphic feature identified on the intermediate debris-flow cone was lateral levees. The lengths of the 465 levees varied between a few to several dozens of meters. While some of these levees may appear quite isolated on the current cone surface, some others can easily be attributed to one of the twelve channels being currently abandoned. Most of the former flow tracks are still clearly visible over large parts of the cone, although major parts of the channel walls have already collapsed and the channel beds filled with material and mostly small vegetation. In addition, 291 lobes were mapped, mostly representing terminal lobes.

Fig. 1. Study site Ritigraben (Valais, Swiss Alps) with its departure zone at 2,600 m a.s.l. and its intermediate debris-flow cone.

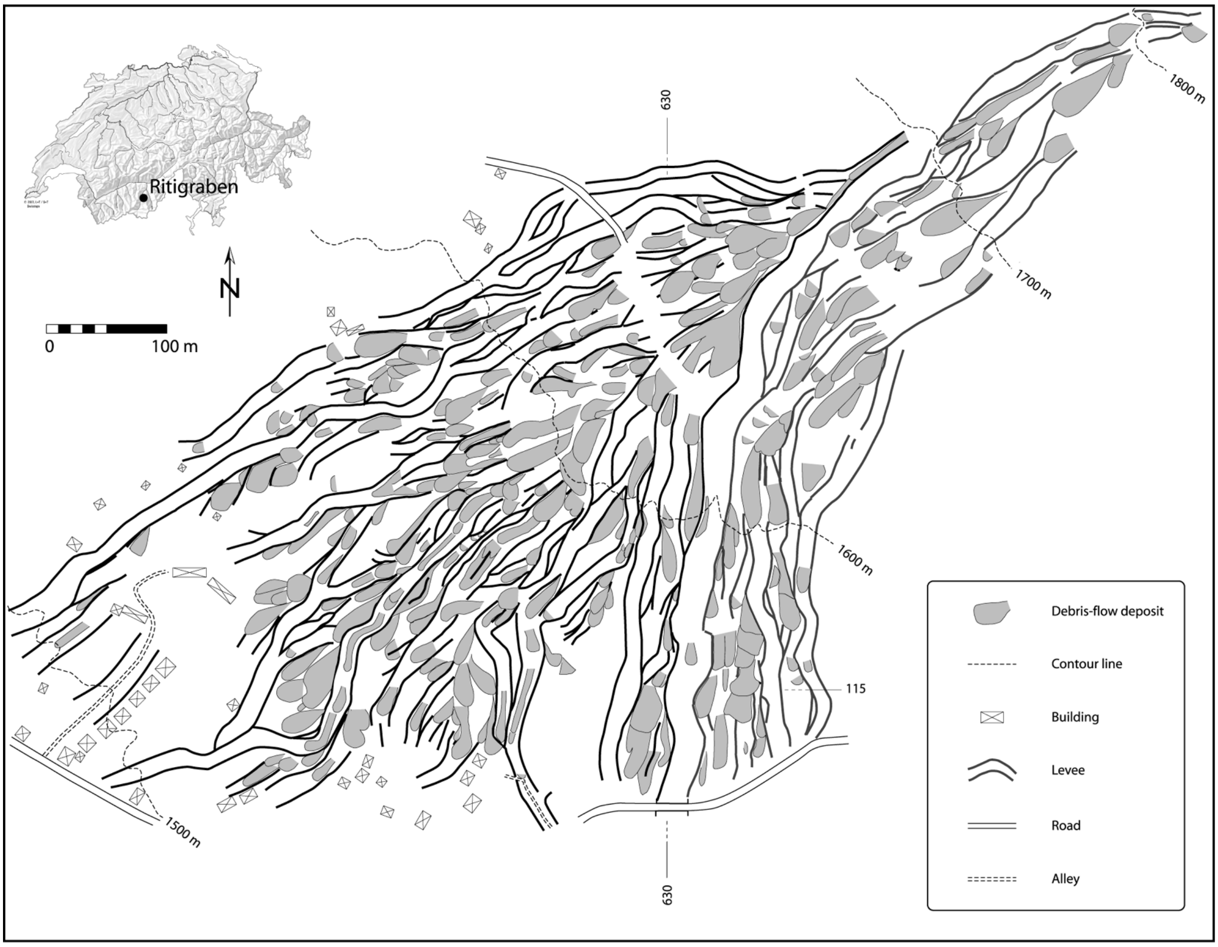

Fig. 2. Geomorphological map of the intermediate debris-flow cone with (terminal) lobes, levees and channels.

Debris flows and growth disturbances in trees

In total, 1204 trees were sampled (2450 increment cores): 539 Larix decidua, 429 Picea abies and 134 Pinus cembra trees (2246 cores) from the debris-flow cone and 102 trees (204 cores) from the undisturbed reference sites. Analysis of the disturbed trees allowed reconstruction of 2263 characteristic growth disturbances caused by passing debris-flow surges or the deposition of material on the cone. Signatures of past events were mainly identified on the increment cores via tangential rows of traumatic resin ducts (43.6%) or reaction wood (32.1%). Abrupt growth reductions or recovery could only occasionally be found in the tree-ring series and wounds or overgrowing callus tissue were rarely present on the cores. In total, the analysis of signatures occurring simultaneously in different trees on the cone allowed reconstruction of 123 debris-flow events covering the last 440 years. Figure 3 gives the reconstructed frequency of debris flows between AD 1566 and 2005.

The age of trees sampled on the cone largely varied, with innermost rings of living trees dated to between AD 1962 and 1492. On average, the 1204 conifer trees analyzed show more than 300 tree rings at sampling height and old trees were quite evenly spread over the cone. It can, thus, be assumed that the samples used for the reconstruction registered signatures of most events of at least the last 300 years.

Figure 4 breaks the reconstructed frequency down into 10-yr periods, with bars representing variations from the mean decadal frequency of debris flows for the period 1706–2005 (i.e. 3.26 events decade^{-1}). Results illustrate that decadal frequencies generally remained well below average during most of the "Little Ice Age" (*c.* AD 1570–1900; see Matthews & Briffa 2005) and periods with considerable above-average debris-flow activity only start to emerge from the data after the 1860s. Largely increased activity continued well into the early 20th century and culminated in two 10-yr periods between 1916 and 1935, when seven events each were derived from the tree-ring series. Results further show that this episode of important activity was followed by a rather sharp decrease in the 10-yr frequencies. In a similar way, very low activity can be observed for the last 10-yr segment (1996–2005) with only one debris-flow event recorded on August 27, 2002. Along with the periods of 1706–1715 and 1796–1805, the most recent ten years would have seen the least important debris-flow activity

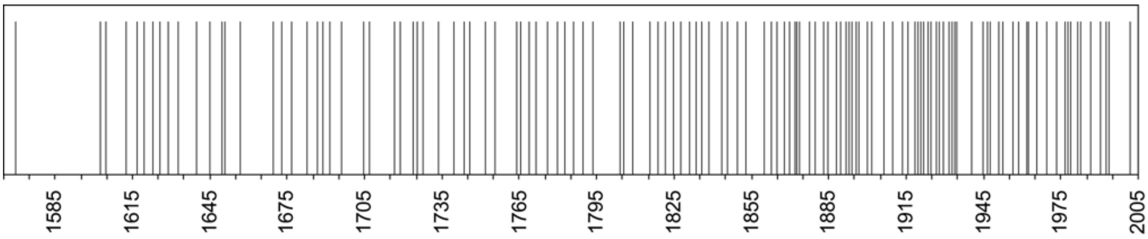

Fig. 3. Tree-ring based reconstruction of debris flow activity at Ritigraben between AD 1566 and 2005.

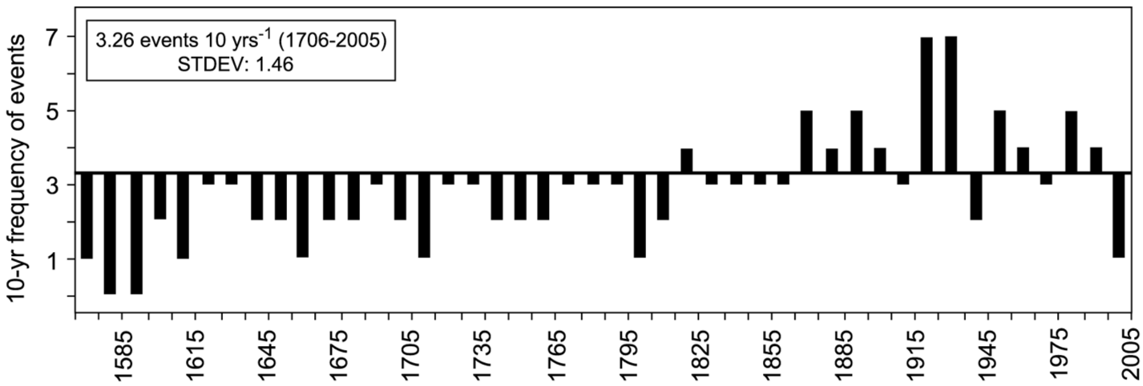

Fig. 4. Reconstructed 10-yr frequencies of debris-flow events between AD 1566 and 2005. Data are presented as variations from the mean decadal frequency of debris flows of the last 300 years (AD 1706-2005), corresponding to the mean age of trees sampled.

for the last 300 years.

Ongoing research

After the dating of growth anomalies on the increment cores, the spatial distribution of trees that have been affected during particular events of the past is currently being analyzed. Within this investigation, an attribution of an anomaly to a specific deposit is only done if (i) a partially buried tree with abrupt growth reduction is identified within the lobe or if (ii) a tilted tree with eccentric growth rings and the presence of reaction wood is located in the snout of a terminal lobe. In a subsequent step, the volume of those lobes being deposited during the same events will be quantified.

The reconstruction of past events and the analysis of those deposits being currently on the surface of the intermediate cone are supposed to furnish valuable data on the past behavior of the torrent. They will, however, not provide a sufficiently complete image on frequency-magnitude relationships for the Ritigraben catchment, (i) as only part of the material is left on the intermediate cone while some is transported further down to the confluence and subsequently eroded by the Mattervispa; (ii) as only some of the material being deposited over the last centuries is still on the cone surface today and not covered with more recent deposits; (iii) as deposits of past events might have been remobilized; (iv) as the volumes triggered during past events and the sediment sources of the past might no longer be available today.

In this sense, the analysis of past debris-flow events forms an important element for a better understanding of locally predominant processes, but magnitude estimates imperatively need to be completed with detailed investigations in the entire catchment in order to identify as well as quantify present-day sediment sources and the volumes they may contribute to individual events in the future (for further details, see Bovis & Jakob (2005) or Frick *et al.* (2006)).

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