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Estimation of debris flood magnitudes based on dendrogeomorphic data and semi-empirical relationships

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ABSTRACT

Magnitude estimations of hydrogeomorphic processes contain crucial information for hazard assessments and for the understanding of longer term landscape evolution. In this study, we reconstruct magnitudes of debris floods for a torrential catchment in Tyrol by combining dendrogeomorphic time series of events with semi-empirical equations used to predict event volumes. Reconstructed debris flood magnitudes cover eight decades (A.D. 1930–2008) and vary from 2900 to 45,900 m^3. We illustrate that magnitude estimates derived from tree-ring data and semi-empirical equations represent a valuable contribution to the documentation and understanding of hydrogeomorphic processes and that they can complement fragmentary time series in small watersheds for periods covering decades up to centuries. Limitations of the approach are mainly inherent to the age and spatial distribution of sampled trees and may thus influence reconstructed event magnitudes as one goes back in time.

1. Introduction

Hydrogeomorphic processes are a key driver of sediment transfer in mountain watersheds (Stoffel and Wilford, 2012). As a result, definition of recurrence intervals or total sediment volume is a crucial parameter for hazard assessment, for land use planning, or for the design of torrent control measures (Rickenmann, 1999; Mao et al., 2009). Data on frequency–magnitude relations of hydrogeomorphic processes are also important for an improved understanding of long-term landscape evolution (Stock and Dietrich, 2006). In the recent past, several authors have derived magnitude–frequency relations for debris flows (see Stoffel, 2010 and references therein), whereas such data is much scarcer for debris floods. Past work was based primarily on dating techniques, such as stratigraphic (Blair and McPherson, 1998; Blair, 1999) or lichenometric methods (Innes, 1985; Helsen et al., 2002). Other approaches used included the analysis of aerial photography and laser scan analysis (Jordan, 1994; Jakob and Podor, 1995; Scheidl et al., 2008) or the application of empirical models (e.g., Takei, 1984; D'Agostino, 1996; Bianco and Franzi, 2000; Marchi and D'Agostino, 2003). Eaton et al. (2003) and Hungr et al. (2005) estimated event magnitudes by balancing debris material along the flow channel. However, several sources of uncertainty exist in such approaches, and the obtained magnitude–frequency curves typically suffer from a significant range of uncertainty.

The analysis of tree-ring series allows the reconstruction of event frequencies and provides indications on the frequency and spread of past hydrogeomorphic activity (e.g., Bollschweiler and Stoffel, 2007; Stoffel et al., 2008, 2012; Procter et al., 2012). Based on the position of impact scars on trees, several authors have also derived peak discharges for torrential floods (Gottesfeld and Gottesfeld, 1990; Yanosky and Jarrett, 2002; Ballesteros et al., 2011a,b; Ruiz-Villanueva et al., in press).

By contrast, comparably few studies have addressed event volumes of debris flows and debris floods with dendrogeomorphic records. Jakob and Bovis (1996), for instance, assessed debris-flow frequencies with dendrogeomorphic techniques and estimated volumes through surveys of deposited material and empirical methods. Wilkerson and Schmid (2003) monitored debris flows by combining dendrogeomorphic and lichenometric approaches, repeat photography, plant succession, and stratigraphic analyses. Stoffel (2010) determined magnitude–frequency relations of debris flows by coupling tree-ring records with morphometric characteristics of dated deposits and meteorological data.

In this study we combine dendrogeomorphic techniques with semi-empirical equations, used to predict event volumes, to estimate time series of debris-flood magnitudes for a torrent in Tyrol, Austria (Mayer et al., 2010). Following a brief overview of the study site and a review of reconstructed flow events, we (i) introduce a semi-empirical approach used for magnitude estimation, (ii) reconstruct a time-series of debris flood magnitudes, and (iii) discuss the potential and limitations of tree-ring and semi-empirical approaches for the reconstruction of frequency–magnitude analyses of debris floods.

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2. Study site

The Gratzental (47°27′N, 11°38′E) is located northeast of Innsbruck (Tyrol, Austria; Fig. 1) and is drained by the Gratzentalbach, an ephemeral channel where runoff occurs only after precipitation events of long duration or high intensity. The watershed occupies a glacially shaped valley ranging from 2106 m asl at Mondscheinspitze to 1166 m asl at the confluence with the Pletzach River; it has a catchment area of ~2.5 km^2. Average fan slope is 5°, whereas the inclination reaches its maximum at 35° above the fan apex. The watershed is dominated by late Triassic grey-brown dolomite (*Hauptdolomit*) and local Pleistocene moraines (Geologische Bundesanstalt, 2008). Mean grain size of the material deposited on the fan is 29 mm (d_m) using the surface sampling method (Mayer et al., 2010). Humid climatic conditions with cool summers and mild winters are characteristic and annual rainfall varies between 1300 and 2500 mm with a mean of 1526 mm for the period A.D. 1895–2008 (Hübl et al., 2002; Skolaut et al., 2004). The fan of the Gratzentalbach is dominated by Norway spruce (*Picea abies* (L.) Karst), European larch (*Larix decidua* Mill.), and Scots pine (*Pinus sylvestris* L.). Mountain pines (*Pinus mugo* T.) dominate the higher parts of the catchment. On the westernmost segments of the fan, the forest stand is subject to regular timber harvesting, cattle pasture, and extensive browsing by deer. Based on field investigations, Mayer et al. (2010) concluded that debris floods are the dominating process delivering sediment to the fan, referring to the flow type classification of Hungr et al. (2001).

Archival records from the Austrian Service for Torrent and Avalanche Control contains data on two debris floods in the Gratzentalbach in 2005 and 2007 (Mayer et al., 2010), without any indication on event volumes.

A total of 37 events were reconstructed for the Gratzentalbach (Mayer et al., 2010), of which 24 were based on a very large number of growth disturbances (GD). For the remaining 13 events, tree-ring data was less readily available because of (i) local differences in the age structure of the forest under investigation or (ii) the small number and/or weak intensity of GD in trees. The mean return period of debris floods at Gratzentalbach was 5.6 years between A.D. 1800 and 2008 (4.2 years if analysis is limited to the period A.D. 1900–2008).

3. Methods

3.1. Assessment of equivalent deposition areas

Deposition areas of past debris floods (B_{mapped}) were determined using a combination of tree-ring records and geomorphic mapping as described in Stoffel and Bollschweiler (2008, 2009). In a second step, we estimated equivalent deposition areas (B_{sector}) following the approach proposed by Rickenmann and Scheidl (2012), which takes account of the circular sector of radius L_f and angle Ψ of the planar deposition area (Fig. 2).

$$B_{sector} = {L_f}^2 \pi \Psi \frac{1}{360^\circ}. \tag{1}$$

This approximation is based on the assumption of geometric similarity of deposits and is limited to fans where deposition is not influenced by obstacles (e.g., technical mitigation measures) or distinct channels. The approach further assumes that the cross section or the conveyance of the channel in the proximity of initiation of deposition is small in relation to the peak discharge of the event (Rickenmann and Scheidl, 2012). We therefore determined the angle Ψ and radius L_f of the circular segment by using the position of the outermost trees affected by an event. Volume estimates were performed for 16 debris floods for which sample size and the spatial distribution of sampled trees were not limiting factors.

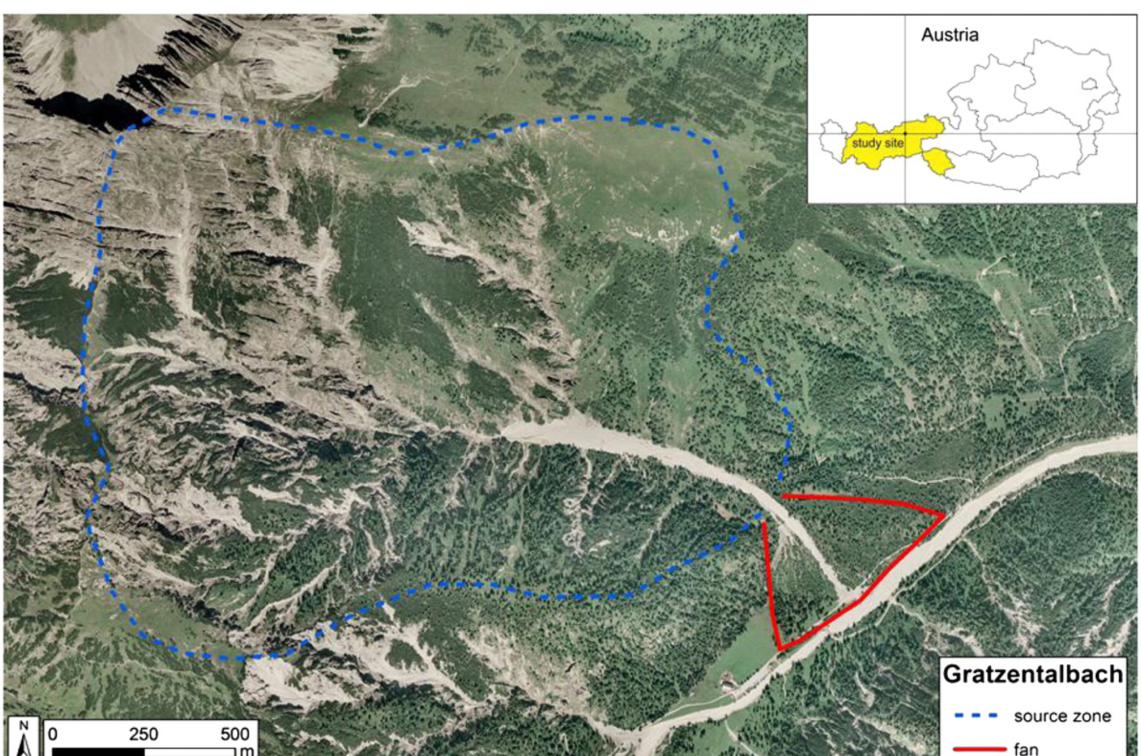

Fig. 1. The Gratzentalbach is located in the Gratzental (Tyrol, Austria). The catchment area is indicated with a blue dotted line; the red line shows the fan.