Geomorphology 201 (2013) 80–85

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

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

Klaus Schraml [a,*], Barbara Kogelnig [a], Christian Scheidl [a], Markus Stoffel [b,c], Roland Kaitna [a]

[a] Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Peter Jordanstrasse 82, A-1190 Vienna, Austria
[b] Laboratory of Dendrogeomorphology, Institute of Geological Sciences, University of Berne, Baltzerstrasse 1+3, CH-3012 Berne, Switzerland
[c] Institute for Environmental Sciences, University of Geneva, 7 chemin de Drize, CH-1227 Carouge, Geneva, Switzerland

ARTICLE INFO

Article history:
Received 13 September 2012
Received in revised form 6 June 2013
Accepted 10 June 2013
Available online 21 June 2013

Keywords:
Debris flood
Magnitude estimation
Dendrogeomorphology
Time series

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.

* Corresponding author. Tel.: +43 1 47654 4356; fax: +43 1 47654 4390.
E-mail address: klaus.schraml@boku.ac.at (K. Schraml).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.06.009

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).

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

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.

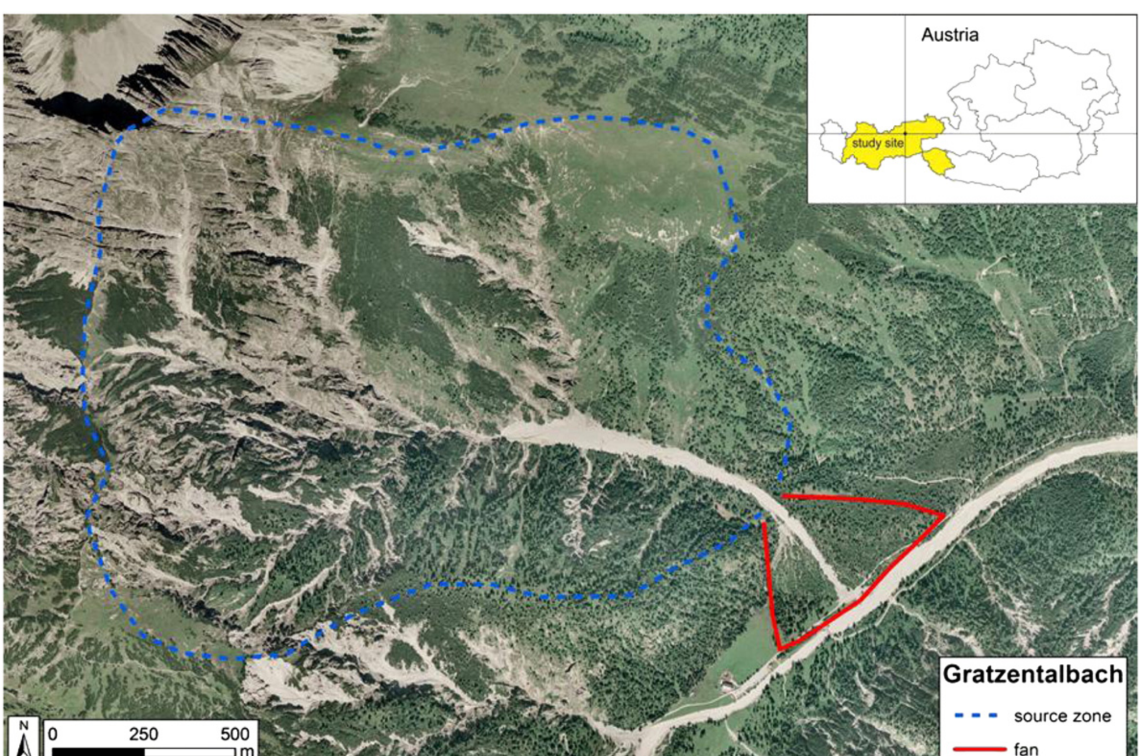

Fig. 1. The Gratzentalbach is located in the Gratzental (Tyrol, Austria). The catchment area is indicated with a blue dotted line; the red line shows the fan.

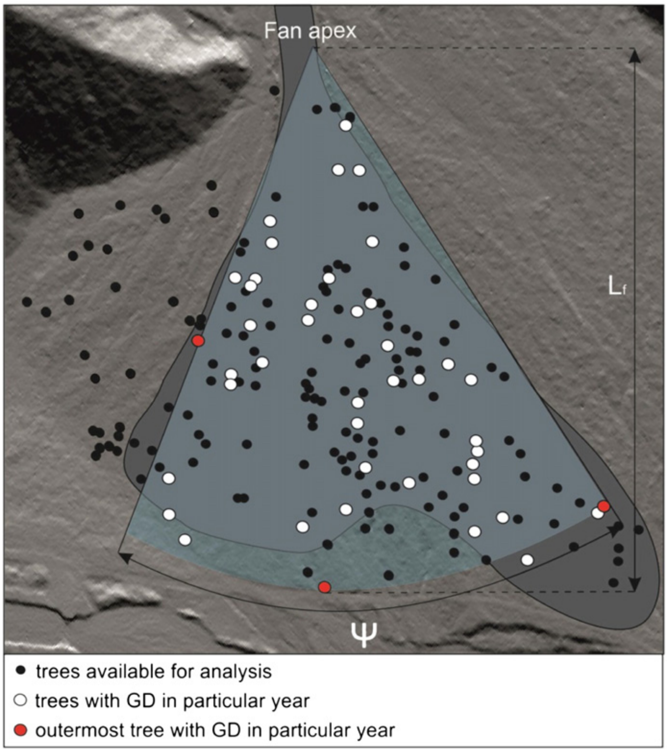

Fig. 2. Determination of the planimetric deposition area is based on the assumption of a circular sector under undisturbed, natural conditions (bright area). The area of the circular sector is assumed to be equal to the observed area (darker area). Tree-ring data serve for the determination of radius L_f and angle Ψ of the circular segment. Positions of the outermost trees affected by a particular event (red dots) are taken into consideration (modified after Kogelnig, 2012).

3.2. Estimation of event magnitudes

The estimation of event magnitudes is based on the approach of Iverson et al. (1998) who used a semi-empirical relationship between the planimetric deposition area (B) and the deposited volume (V) by assuming geometric similarity:

$$B = k_B\, V^{(2/3)} \quad (2)$$

where k_B is a dimensionless, empirically derived mobility coefficient. Rearranging Eq. (2) and combining it with the assessment of an equivalent deposition area (B_{sector}), the magnitude of a debris flood (V_{sector}) can then be estimated:

$$V_{\,sector} = B^{3/2}_{sector} k_B^{-3/2}. \quad (3)$$

Based on 126 past events from Austria, Italy, and Switzerland, Scheidl and Rickenmann (2010) proposed that an empirical relation k_B is linked with topographic catchment parameters:

$$k_B = 5.07 S_f^{-0.1} S_c^{-1.68} \quad (4)$$

where S_f represents the average fan slope and S_c the average channel slope. In this study, the average fan slope is determined between the fan apex (corresponding to the location of first deposition outside of the channel) and the confluence with the receiving river. The average channel slope is determined between the fan apex and the uppermost channelized stream point as determined on a 1:25,000 topographic map (see Scheidl and Rickenmann, 2010, for details).

Results obtained for the Gratzentalbach are then compared with similar empirical approaches (Rickenmann and Zimmermann, 1993; Rickenmann, 1995, in combination with Zeller, 1985, for high intense bedload carrying; D'Agostino, 1996; D'Agostino and Marchi, 2001), in which event volumes are derived from morphometric parameters (Table 2).

4. Results

4.1. Estimation of deposition areas

Estimated deposition areas range between 6000 m^2 for an event in A.D. 1934 and 38,000 m^2 for an event in 2000 (Table 1). The deposition area of the 2007 debris flood was 35,600 m^2 when determined by geomorphic mapping and 34,200 m^2 using the circular sector approach based on dendrogeomorphic input data. The very small differences (<4%) between mapped and reconstructed spatial patterns of the 2007 debris flood deposits are given in Fig. 3. Visual similarity between the surfaces is confirmed by the estimated deposition areas B_{sector} and B_{mapped}. Direct comparison was not possible for the other events, as geomorphic evidence of older activity was mostly missing because of the overriding and/or erosion of deposits by more recent activity (but signs of disturbance are still visible in the tree-ring records).

4.2. Magnitude estimation

After area estimations, volumes were calculated using Eq. (3) with a k_B value of 30. The mobility coefficient was defined using Eq. (4) using a channel slope $S_c = 0.40$ and a fan slope $S_f = 0.09$. Calculated magnitudes range from 2900 m^3 (A.D. 1934) to 45,900 m^3 (A.D. 2000), and the reconstructed time series covers almost eight decades. Fig. 4 also illustrates that for the 12 most recent debris floods, >98% of the trees sampled for analysis were in fact living and evenly distributed over the fan. For the events reconstructed between A.D. 1934 and A.D. 1955, in contrast, the sample size varied between 69 and 78%, and trees were not distributed evenly over the fan. Fig. 4 also illustrates that reconstructed volumes are quite small for these events.

5. Discussion

In this study we present the reconstruction of debris flood magnitudes at Gratzentalbach based on a combination of dendrogeomorphic data with empirical equations. The assessment of areas affected by past debris floods was based on a dendrogeomorphic reconstruction of 227 trees, which resulted in a frequency time series of 37 events

Table 1
Sectoral areas affected (B_{sector}), mapped area (B_{mapped}) for the last event and the difference (ΔB), angle Ψ, and radius L of the circular segment and sectoral event magnitudes (V_{sector}) of past debris floods at Gratzental (grey values represent reconstructed event volumes based on <98% of trees alive, whereas black values result from at least 98% of trees available and represent a complete time series for three decades).

Year	B_{sector} [m^2]	B_{mapped} [m^2]	ΔB [%]	Ψ [°]	L [m]	V_{sector} [m^3]
1934	6,000	–	–	73	97	2,900
1946	9,700	–	–	28	199	5,900
1950	8,100	–	–	25	193	4,500
1955	8,500	–	–	20	221	4,900
1979	8,900	–	–	29	188	5,200
1980	18,500	–	–	86	157	15,600
1983	20,000	–	–	47	221	17,600
1987	6,000	–	–	19	191	2,900
1989	20,700	–	–	95	158	18,400
1992	21,700	–	–	47	230	19,800
1995	27,400	–	–	62	225	28,100
1996	25,600	–	–	57	227	25,400
2000	38,000	–	–	54	284	45,900
2004	6,700	–	–	14	235	3,400
2005	16,700	–	–	29	257	13,400
2007	34,200	35,600	4	55	267	39,200

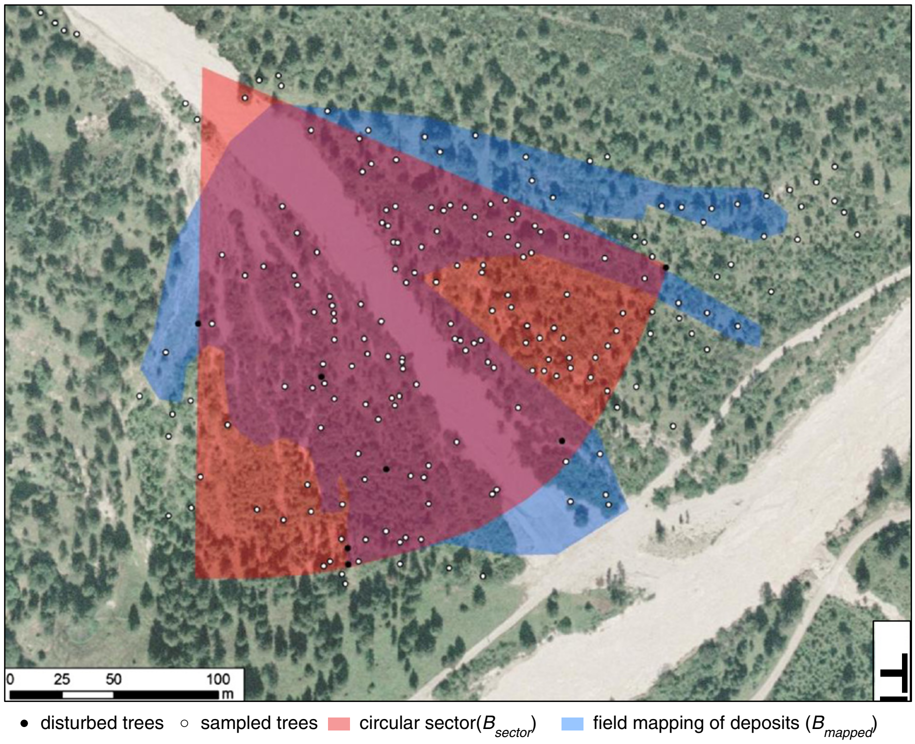

Fig. 3. Comparison of areas affected by the event in A.D. 2007 at Gratzentalbach. The circular sector (red surface) was calculated following Eq. (1), whereas the blue area was obtained using geomorphic mapping techniques in the field (mapping scale 1:1000).

covering the period A.D. 1800–2008 (Mayer et al., 2010). As a result of the uneven spatial distribution of old trees on the fan (reflecting differences in the age of the forest stand), reliable estimates of magnitudes could only be obtained for a subset of the events reconstructed with dendrogeomorphic techniques. In fact, reconstruction of magnitudes was limited to one-third of the frequency record for which >98% of all trees sampled were available for analysis (i.e., 12 debris floods for the period A.D. 1979–2008). For these events, areas affected by debris floods could be determined with high certainty, and the availability of recording trees was not a limiting factor.

In the case of the four older debris floods given in Fig. 4, which occurred between A.D. 1934 and 1955, the smaller sample size (i.e., 69–78% of its current size, i.e., 227 trees) and increasingly larger unevenness in tree distribution over the fan result in smaller reconstructed debris flood volumes, despite the fact that these events still leave a reasonable number of GD in the tree-ring records. In this sense, the approach described here seems to underestimate volumes as soon as an adequate distribution of recording trees over the fan is no longer available.

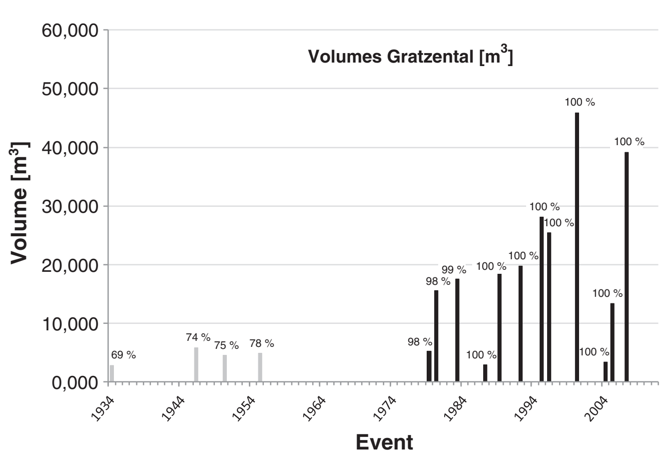

Fig. 4. Estimated magnitudes for debris floods at Gratzentalbach between A.D. 1934 and 2008. Percentages of sampled trees available are illustrated for each event.

Decreasing event volumes for debris floods prior to A.D. 1979 is possibly also influenced by the approach selected for analysis, as (i) geometric similarity is assumed between deposition area and a circular sector (Rickenmann and Scheidl, 2012), (ii) such similarity can only be achieved with an equal distribution of sampled trees over the fan, and (iii) the approach is limited to areas that are not influenced by any obstacles or distinct channels. Comparison of mapped deposition area (B_{mapped}) and circular sector approach (B_{sector}) is in good agreement for the most recent event in 2007, for which both data sets are available and for which results differ by <4% (Fig. 3).

In the past, volumes of debris flows and debris floods were based on empirical relations and used rainfall conditions, basic geomorphic dispositions within the catchment, lithological factors, or process coefficients (Rickenmann and Zimmermann, 1993; Rickenmann, 1995, with Zeller, 1985; D'Agostino, 1996; D'Agostino and Marchi, 2001). Most approaches are aimed at providing maximum volumes (magnitudes; e.g., Rickenmann and Zimmermann, 1993; Rickenmann, 1995 with Zeller, 1985; D'Agostino, 1996), whereas the approach suggested by D'Agostino and Marchi (2001) provided indications on low magnitude–high frequency events in basins with unlimited sediment supply. As a consequence, volumes obtained with the different approaches vary between 19,700 and 167,500 m^3 for the catchment under investigation (Table 2) and are therefore quite different from the values obtained in this study for obvious reasons. Almost a perfect match can be observed between the reconstructed volume of the largest debris flood at Gratzentalbach and values suggested by the approaches of Rickenmann (1995) with Zeller (1985) or D'Agostino (1996). As a consequence and despite existing temporal limitations of volume reconstructions based on dendrogeomorphic techniques, we observe

Table 2
Estimated event magnitudes of debris floods for the Gratzentalbach based on empirical equations of different approaches as well as our estimated minimum and maximum volumes (L_c represents the length of the channel, and J_f is described as the inclination of the fan in the approach after Rickenmann and Zimmermann (1993) (Eq. (5))). The catchment area A_c is to be used in Eqs. (6)–(8), whereas a geological index I_G and the mean channel slope J_c are additional parameters in Eq. (8) proposed by D'Agostino and Marchi (2001).

	Equation	Volume [m^3]	Study
(5)	$V = L_c(110 - 250\,J_f)$	167,500	Rickenmann and Zimmermann (1993)
(6)	$V = 27,000\,A_c^{0.78}$	55,200	Rickenmann (1995) in combination with Zeller (1985)
(7)	$V = 29,100\,A_c^{0.67}$	53,800	D'Agostino (1996)
(8)	$V = 70\,A_c\,I_G\,J_c^{1.28}$	19,700	D'Agostino and Marchi (2001)
(3)	$V_{sector} = B_{sector}^{3/2}\,k_B^{-3/2}$	2900	Minimum magnitude of our approach in A.D. 1934
(3)	$V_{sector} = B_{sector}^{3/2}\,k_B^{-3/2}$	45,900	Maximum magnitude of our approach in A.D. 2000

that reconstructed magnitudes are within the range of classical approaches based on rainfall conditions, geomorphic disposition, lithological factors, or process coefficients. Tree-ring series, when coupled with semi-empirical approaches, can be used to determine order of magnitudes of debris floods for the recent past, indications on the recurrence interval of different event magnitudes, as well as for the reconstruction of extreme events. At the same time, we also realise that the reconstructed values remain well below those of Rickenmann and Zimmermann (1993), which in turn seem to overestimate the magnitude of extreme debris floods at Gratzentalbach.

6. Conclusion

This study combines spatiotemporal, dendrogeomorphic data of past debris floods with semi-empirical equations, thereby transforming deposition area to deposition volume. The approach thus allows an approximation of event frequency and magnitude of past torrential events in the Gratzentalbach (Tyrol, Austria). As data on event frequency and volumes are typically scarce in small alpine watersheds, the coupling of tree-ring with empirical data represents an innovative and valuable means for a more realistic estimation of magnitudes of past debris flows and debris floods. Results certainly contribute to a better understanding of torrential activity in small watersheds and thus constitute a useful tool for engineering purposes as well as for hazard and risk assessments, despite the limitations inherent to dendrogeomorphic studies (age limitations, spatial distribution of trees sampled) and their influence on event magnitude.

Acknowledgements

This project receives financial support from the Climate and Energy Fund and is carried out within the framework of the 'ACRP' Programme.

References

Ballesteros, J.A., Bodoque, J.M., Díez, A., Sánchez, M., Stoffel, M., 2011a. Calibration of floodplain roughness and estimation of palaeoflood discharge based on tree-ring evidence and hydraulic modeling. Journal of Hydrology 403, 103–115.
Ballesteros, J.A., Eguibar, M., Bodoque, J.M., Díez, A., Stoffel, M., Gutiérrez, I., 2011b. Estimating flash flood discharge in an ungauged mountain catchment with 2D hydraulic models and dendrogeomorphic paleostage indicators. Hydrological Processes 25, 970–979.
Bianco, G., Franzi, L., 2000. Estimation of debris flow volumes from storm events. In: Wieczorek, G.F., Naeser, N.D. (Eds.), Debris-flow Hazards Mitigation: Mechanics, Prediction and Assessment. Balkema, Rotterdam, The Netherlands, pp. 441–448.
Blair, T.C., 1999. Sedimentology of the debris-flow dominated Warm Spring Canyon alluvial fan, Death Valley, California. Sedimentology 46, 941–957.
Blair, T.C., McPherson, J.G., 1998. Recent debris-flow processes and resultant form and facies of the dolomite alluvial fans, Owens Valley, California. Journal of Sedimentary Research 68, 800–818.
Bollschweiler, M., Stoffel, M., 2007. Debris flows on forested cones-reconstruction and comparison of frequencies in two catchments in Val Ferret, Switzerland. Natural Hazards and Earth System Sciences 7, 207–218.
D'Agostino, V., 1996. Analisi quantitativa e qualitative del trasporto solido torrentizio nei bacini montani del Trentino Orientale. Scrittidedicati a Giovanni Tournon. Associazione Italiana di Ingegneria Agraria — Associazione Idrotecnica Italiana, Novara (Italy), pp. 111–123 (in Italian).
D'Agostino, V., Marchi, L., 2001. Debris flow magnitude in the eastern Italian Alps: data collection and analysis. Physics and Chemistry of the Earth 26, 657–663.
Eaton, L.S., Morgan, B.A., Kochel, R.C., Howard, A.D., 2003. Quaternary deposits and landscape evolution of the central Blue Ridge of Virginia. Geomorphology 56, 139–154.
Geologische Bundesanstalt, 2008. Zusammenstellung ausgewählter Archivunterlagen er Geologischen Bundesanstalt Nr 119 – Schwaz. Ausgabe 2008/11.
Gottesfeld, A.S., Gottesfeld, L.M.J., 1990. Floodplain dynamics of a wandering river, dendrochronology of the Morice River, British Columbia, Canada. Geomorphology 3, 159–179.
Helsen, M.M., Koop, P.J., Van Steijn, H., 2002. Magnitude–frequency relationship for debris flows on the fan of the Chalance torrent Valgaudemar (French Alps). Earth Surface Processes and Landforms 27 (12), 1299–1307.
Hübl, J., Loiskandl, W., Feiersinger, R., Gruber, H., Holzinger, G., Kraus, D., Pichler, A., Strauss-Sieberth, A., Zott, F., 2002. Hochwasserschutz durch Reaktivierung von Überflutungsräumen – Evaluierung des Systmenverhaltens im Verbauungsprojekt "Pertisauer Wildbäche": Modellaufbau und Methodik. WLS Report 76, Band 1. Institut für Alpine Naturgefahren und Forstliches Ingenieurwesen, Universität für Boodenkultur Wien.
Hungr, O., Evans, S.G., Bovis, M.J., Hutchinson, J.N., 2001. A review of the classification of landslides of the flow type. Environmental and Engineering Geoscience VII (3), 221–238.
Hungr, O., McDougall, S., Bovis, M., 2005. Entrainment of material by debris flows. In: Jakob, M., Hungr, O. (Eds.), Debris-flow Hazards and Related Phenomena. Praxis, Springer, Berlin Heidelberg New York, pp. 135–155.
Innes, J.L., 1985. Magnitude–frequency relations of debris flows in northwest Europe. Geografiska Annaler 67A, 519–524.
Iverson, R.M., Schilling, S.P., Vallance, J.W., 1998. Objective delineation of lahar inundation hazard zones. Geological Society of America Bulletin 110 (8), 972–984.
Jakob, M., Bovis, M.J., 1996. Morphometrical and geotechnical controls of debris flow activity, southern Coast Mountains, British Columbia, Canada. Zeitschrift für Geomorphologie Supplementband 104, 13–26.
Jakob, M., Podor, A., 1995. Frequency and magnitude of debris flows. Canadian Geotechnical Conference, Vancouver, BC. , vol. 1, pp. 491–498.
Jordan, P., 1994. Debris Flows in the Southern Coast Mountains, British Columbia: Dynamic Behaviour and Physical Properties. Ph.D. Thesis The University of British Columbia, Vancouver.
Kogelnig, B., 2012. Tree Rings and Torrential Activity: Tree Disturbances and Event Histories. Ph.D. Thesis University of Natural Resources and Life Sciences, Vienna, Austria.
Mao, L., Cavalli, M., Comiti, F., Marchi, L., Lenzi, M.A., Arattano, M., 2009. Sediment transfer processes in two Alpine catchments of contrasting morphological settings. Journal of Hydrology 364, 88–98.
Marchi, L., D'Agostino, 2003. Estimation of debris-flow magnitude in the eastern Italian Alps. Earth Surfaces Processes and Landforms 29 (2), 207–220.
Mayer, B., Stoffel, M., Bollschweiler, M., Hübl, J., Rudolf-Miklau, F., 2010. Frequency and spread of debris floods on fans: a dendrogeomorphic case study from a dolomite catchment in the Austrian Alps. Geomorphology 118, 199–206.
Procter, E., Stoffel, M., Schneuwly-Bollschweiler, M., Neumann, M., 2012. Exploring debris-flow history and process dynamics using an integrative approach on a dolomitic cone in western Austria. Earth Surface Processes and Landforms 37, 913–922.
Rickenmann, D., 1995. Beurteilung von Murgängen. Schweizer Ingenieur und Architekt 48, 1104–1108.
Rickenmann, D., 1999. Empirical relationships of debris flows. Natural Hazards 19, 47–77.
Rickenmann, D., Scheidl, C., 2012. Debris-flow runout and deposition on the fan. In: Schneuwly-Bollschweiler, M., Stoffel, M., Rudolf-Miklau, F. (Eds.), Dating Torrential Processes on Fans and Cones, Methods and Their Application for Hazard and Risk Assessment. Advances in Global Change Research, vol. 47. Springer, Berlin Heidelberg New York. http://dx.doi.org/10.1007/978-94-007-4336-6 5.
Rickenmann, D., Zimmermann, M., 1993. The 1987 debris flows in Switzerland: documentation and analysis. Geomorphology 8, 175–189.
Ruiz-Villanueva, V., Díez-Herrero, A., Bodoque, J.M., Ballesteros, J.A., Stoffel, M., 2013. Characterization of flash floods in small ungauged mountain basins of central Spain using an integrated approach. Catena (in press).
Scheidl, C., Rickenmann, D., 2010. Empirical prediction of debris-flow mobility and deposition on fans. Earth Surface Processes and Landforms 35, 157–173.
Scheidl, C., Rickenmann, D., Chiari, M., 2008. The use of airborne LiDAR data for the analysis of debris flow events in Switzerland. Natural Hazards and Earth System Sciences 8, 1113–1127.
Skolaut, C., Hübl, J., Gruber, H., 2004. Reaktivierung von ehemaligen Überflutungsflächen am Beispiel des Projektes Pertisau Wildbäche, Gemeinde Eben am Achensee, Bezirk Schwaz, Tirol (Österreich). Proceedings 10th Interprävent Congress 2004, 24–27 May, Riva del Garda, Trient, Italy, vol. 3, pp. 313–324.

Stock, J.D., Dietrich, W.E., 2006. Erosion of steepland valleys by debris flows. Geological Society of America Bulletin 118 (9–10), 1125–1148.

Stoffel, M., 2010. Magnitude–frequency relationships of debris flows — a case study based on field surveys and tree ring records. Geomorphology 116, 67–76.

Stoffel, M., Bollschweiler, M., 2008. Tree-ring analysis in natural hazards research — an overview. Natural Hazards and Earth System Sciences 8, 187–202.

Stoffel, M., Bollschweiler, M., 2009. What tree rings can tell about earth-surface processes: teaching the principle of dendrogeomorphology. Geography Compass 3, 113–137.

Stoffel, M., Wilford, D.J., 2012. Hydrogeomorphic processes and vegetation: disturbance, process histories, dependencies and interactions. Earth Surface Processes and Landforms 37, 9–22.

Stoffel, M., Conus, D., Grichting, M.A., Lièvre, I., Maître, G., 2008. Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: chronology, environment and implications for the future. Global and Planetary Change 60, 222–234.

Stoffel, M., Casteller, A., Luckman, B.H., Villalba, R., 2012. Spatiotemporal analysis of channel wall erosion in ephemeral torrents using tree roots — an example from the Patagonian Andes. Geology 40 (3), 247–250.

Takei, A., 1984. Interdependence of sediment budget between individual torrents and a river-system. International Symposium Interpraevent 1984: Villach (Austria), vol. 2, pp. 35–48.

Wilkerson, F.D., Schmid, G.L., 2003. Debris flows in Glacier National Park, Montana: geomorphology and hazards. Geomorphology 55, 317–328.

Yanosky, T.M., Jarrett, R.D., 2002. Dendrochronologic evidence for the frequency and magnitude of paleofloods. In: House, P.K., Levish, D.R., Webb, R.H., Baker, V.R. (Eds.), Paleoflood Hydrology. American Geophysical Union Water Science and Application Series, 5, pp. 77–89.

Zeller, J., 1985. Feststoffmessung in kleinen Gebirgseinzugsgebieten. Wasser, Energie, Luft 77 (7/8), 246–251.