Research paper

The Holocene
20(6) 907–916

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DOI: 10.1177/0959683610365942
http://hol.sagepub.com
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Changes and trends in debris-flow frequency since AD 1850: Results from the Swiss Alps

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Abstract

Although studies have repeatedly focused on feedbacks and impacts of climate change on mass movements in the past, the inter-relations between climatic variables and debris-flow occurrence remain widely unclear and ambiguous to date. Most studies on past debris-flow occurrence remained rather isolated reconstructions for single torrents or they were restricted to short time periods. It is therefore the aim of this study to provide a regional chronology of past debris-flow events for the Zermatt Valley (Swiss Alps) and to go beyond the simple dating of events. Based on tree-ring reconstructed debris-flow histories of eight torrents, we shed light on changes and trends in debris-flow occurrence, climatic conditions prevailing during events and on potential evolutions in a future climate. Based on the analysis of tree-ring records of 2467 conifers (mainly *Larix decidua* and *Picea abies*), 417 events between AD 1600 and 2009 were assessed. Decadal frequencies suggest peaks in debris-flow activity after the end of the 'Little Ice Age' and for the period 1920–1929. In contrast, activity was rather low during the most recent part of the record (2000–2009), which is in concert with the observed decrease in the number of triggering rainfall events. Long-term trends in debris-flow occurrence were analysed for three time intervals of the period 1850-2009 with Student's *t*-tests. For the debris-flow frequency of the entire valley, no significant trends can be observed over the last 150 years. We conclude that the occurrence of debris flows would depend on short-term changes in triggering rainfall rather than on long-term climatic changes.

Keywords

climate change, debris flow, frequency, Swiss Alps, tree rings, trends

Introduction

The unpredictable occurrence of debris flows in steep channels represents an important hazard in mountainous regions all over the world. Debris flows have repeatedly caused severe damage to communication routes, infrastructure or even loss of life (Jakob and Hungr, 2005; Pasuto and Soldati, 2004). Therefore, a detailed understanding of the temporal and spatial occurrence of past events is essential for a realistic appraisal of potential hazards associated with debris-flow processes. As debris flows are usually triggered by meteorological events such as short duration-high intensity (i.e. convective storms; e.g. Butler and Malanson, 1996) or as low intensity-long duration events (i.e. advective storms; e.g. Caine, 1980; Guzzetti *et al*., 2008), they are of special interest to studies of climatic control of rapid mass movements (Innes, 1997).

Currently, there is much debate about the impacts of global climate change on debris-flow frequency and magnitude (Bollschweiler and Stoffel, 2010; Jakob and Friele, 2010; Kotarba, 1992; Matthews *et al*., 2009; Stoffel, 2010). Some studies suggest that the current global warming might increase the frequency of extreme precipitation events (e.g. Easterling *et al*., 2000; Fowler and Hennessy, 1995; Fowler and Kilsby, 2003) and therefore enhance the occurrence of mass-movement processes. Others state that there is no such increase in debris-flow activity (Blijenberg, 1998; Stoffel *et al*., 2008; Van Steijn, 1996). Jomelli *et al*. (2004, 2007) even report a significant decrease in the number of small, low-elevation debris flows since the 1980s in the Ecrins massif, French Alps.

Even though a large number of studies focused on the interrelation between climate and debris-flow occurrence, knowledge on changes in frequency and magnitude or on triggering mechanisms remain widely defective. This is partly because previous work was either limited to individual study sites (Schneider *et al*., 2010; Stoffel *et al*., 2008) or rather restricted in time (Jomelli *et al*., 2003, 2007). The general lack of records on former debris-flow activity is a widespread and notorious problem in debris-flow research, as available data sets do not normally cover more than a few decades and as the temporal and spatial resolution of data remain very low (Matthews *et al*., 1997; Soldati *et al*., 2004).

This paper therefore aims at providing detailed insights into the temporal and spatial debris-flow occurrence in eight torrents located in an inner-alpine valley of the Swiss Alps. The study is based on a uniquely large spatial and temporal data set of past events obtained from tree-ring series of conifers influenced by debris-flow activity. We shed light on the frequency of debris

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Received 20 November 2009; revised manuscript accepted 15 February 2010

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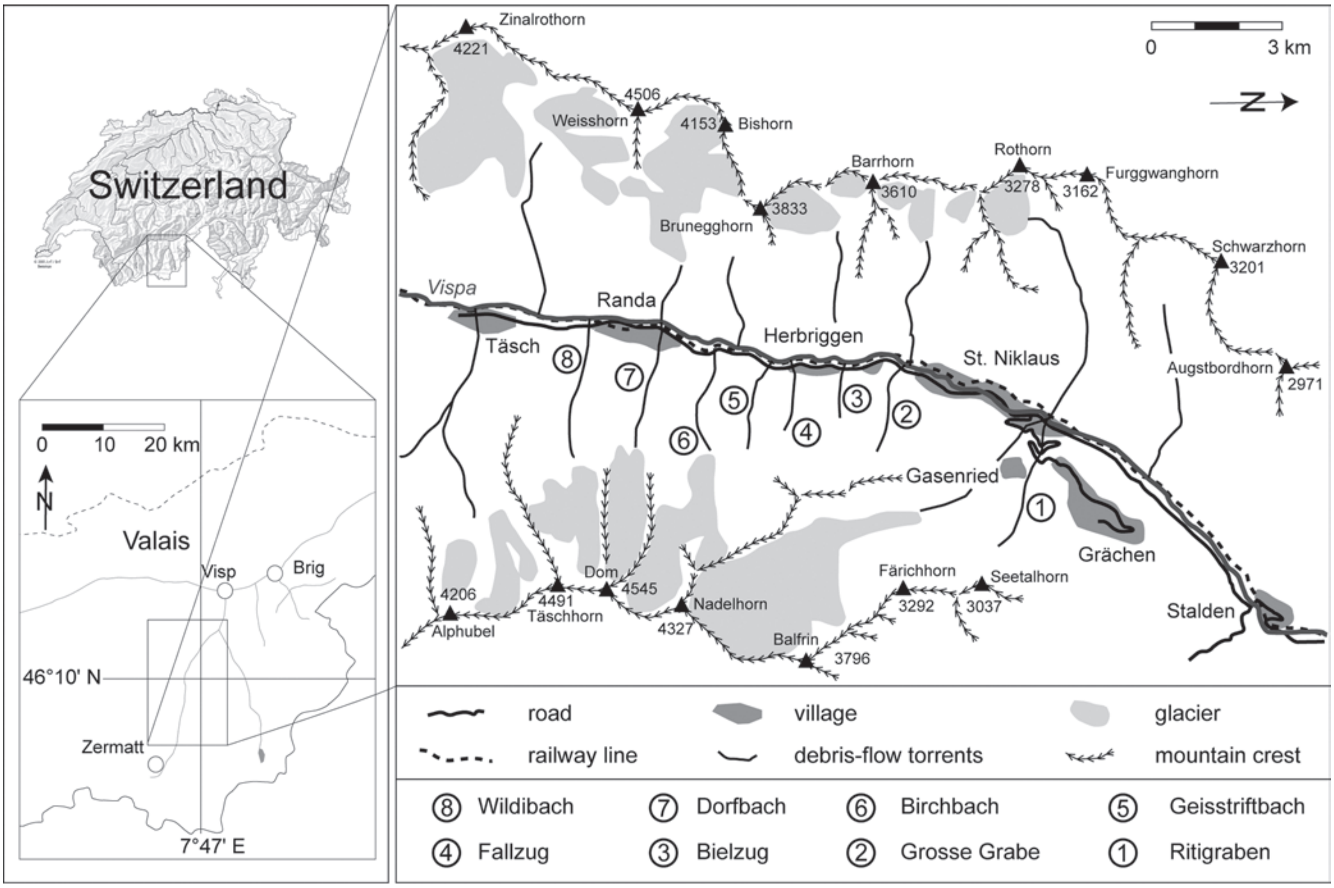

Figure 1. The study region is located in the southern Swiss Alps, where eight torrents on the west-facing slopes of the Zermatt Valley were investigated

flows since AD 1600, with a clear focus on the period 1850–2009. The specific aims of this study are to (i) illustrate debris-flow frequencies in eight catchments of the Valais Alps (Switzerland); (ii) depict similarities in the occurrence of events in the different torrents; and (iii) investigate changes in recurrence intervals over the reconstructed time period.

Regional setting

The case-study area chosen for the analysis of past debris-flow frequencies is the Zermatt valley, a dry inner-alpine valley of the Valais Alps (Switzerland, central coordinates 46°10′N/47°7′E; Figure 1), where eight torrents have been investigated (i.e. Ritigraben, Grosse Grabe, Bielzug, Fallzug, Geisstriftbach, Birchbach, Dorfbach, Wildibach). Geology is dominated by gneissic lithologies belonging to the crystalline Mischabel unit (Labhart, 2004; Pfiffner, 2009). Table 1 illustrates that all torrents reveal similar geomorphic settings and that periglacial processes and permafrost are present in all source areas of debris flows (Bundesamt für Umwelt (BAFU), 2006; PERMOS, 2009). In three cases, the uppermost reaches of the catchment are glacierized. The catchments reach elevations of up to ~4500 m a.s.l. and the initiation zones of debris flows are located between 2000 and 3000 m a.s.l. Climatic conditions in the study area are characterized by low temperature, snow precipitation and high annual and daytime thermal ranges. These harsh climatic conditions favour morphogenetic processes related to cycles of freezing and thawing and therefore regolith production. Moraine deposits form another source of sediment supply. Triggering of debris flows is normally related to a sudden input of large quantities of water, mainly through intense or persistent rainfall. Debris-flow material usually bypasses the steep channels with mean slope angles of 22–33° (mean 27.6°) and is deposited on the debris-flow cones in the valley floor. The Ritigraben presents a different geomorphic setting, as its cone is situated on a structural terrace located 500 m above the valley floor (see Stoffel *et al*., 2008). All cones are covered with forests primarily composed of European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) Karst.) and Cembran pine (*Pinus cembra* L.). Since the 1980s, the channel walls of most torrents have been reinforced and material is being evacuated after events at the level of the cones. However, there are no large deflection dams along the torrents.

Material and methods

Debris-flow frequencies for the eight torrents investigated in this study were obtained from tree-ring series of affected conifers and complemented, where available, with data from local archives. As trees record external disturbances – such as mass-movement processes – with at least yearly precision in their increment ring, they represent a very valuable and one of the most accurate natural archives (e.g. Bollschweiler *et al*., 2007; Schweingruber, 1996; Stoffel and Perret, 2006). For the reconstruction of past frequencies, 2467 trees obviously influenced by past debris-flow activity were sampled with 4491 increment cores and cross-sections on the cones and along the channels of the eight torrents. The frequency of past events was assessed for each torrent using standard dendrogeomorphic methods including surface preparation of the samples, measuring of the ring-width series with an accuracy of 1 μm, correction of faulty tree-ring series with a reference chronology and assessment of growth disturbances. The definition of event years was based on

Table 1. Geomorphological properties and data availability of the investigated torrents

	Ritigraben	Grosse Grabe	Bielzug	Fallzug	Geisstriftbach	Birchbach	Dorfbach	Wildibach
Geomorphology								
Glacier					(x)	x	x	x
Glaciated area (km^2)	0	0	0	0	0.08	3.4	2.1	2.4
Periglacial processes	x	x	x	x	x	x	x	x
Elevation catchment area (m a.s.l.)	3136–2600	3178–1900	3192–2100	3350–1900	4035–2100	4545–2000	4479–2000	4545–2100
Exposition	west	west	west	west	west	west	west	west
Rock	gneiss	gneiss	gneiss	gneiss	gneiss	gneiss	gneiss	gneiss
Catchment area (km^2)	0.8	1.5	1.5	2.1	4.3	7.1	5.6	7.7
Size cone (ha)	47	48	3.7	26	13	27	63	46
Elevation cone (m a.s.l.)	1460–1800	1200–1560	1230–1320	1250–1420	1260–1360	1300–1440	1400–1590	1420–1540
Anthropogenic interventions	no	yes	yes	yes	yes	yes	yes	yes
Data availability								
Time period	1600–2009	1780–2009	1840–2009	1900–2009	1735–2009	1750–2009	1890–2009	1600–2009
No. of sampled trees	1102	144	16	34	252	211	21	414
No. of debris-flow events	126	50	16	12	54	52	20	87
25% of all trees present since	1581	1826	1841	1897	1896	1841	1942	1765
50% of all trees present since	1613	1873	1878	1948	1923	1930	1947	1838
Data sources	1	2	3	3	4, 5	6	3, 7	3

Data sources: 1, Stoffel *et al.* (2008); 2, Bollschweiler *et al.* (2008); 3, this study; 4, Sorg *et al.* (2010); 5, Stoffel *et al.* (2010); 6, Bollschweiler and Stoffel (2010); 7, Graf and McArdell (2005).

the concept of replication meaning that only years with several intense growth disturbances were considered events. In addition, we carefully assessed the spatial distribution of trees with strong growth disturbances to determine past events. Details on the different working steps mentioned can be found in Stoffel and Bollschweiler (2008, 2009). In this study, we include previously published data on debris-flow frequencies from the Ritigraben, Grosse Grabe, Geisstriftbach and Birchbach (for details see Bollschweiler and Stoffel, 2010; Bollschweiler *et al*., 2008; Sorg *et al*., 2010; Stoffel *et al*., 2008, 2010) and previously unpublished material from the Bielzug, Fallzug, Dorfbach and Wildibach. In addition, the reconstructed series were complemented with 21 events noted in archives (Graf and McArdell, 2005; Rickenmann *et al*., 2001; Service des Routes et des Cours d'Eau (SRCE), 2007).

Table 1 provides an overview on the data sets available for this study. The longest records exist for the Ritigraben and the Wildibach, where tree-ring reconstructions extend back to the late sixteenth century. In other torrents, debris-flow reconstructions only reach the late nineteenth century. Analysis therefore focused on the period 1850–2009, when most sites start to exhibit adequate sample depths (i.e. when > 25% of the trees sampled are available for analysis). In addition, for reasons of limited cone size or restricted forest cover, tree-ring analysis had to be performed with a more limited number of samples in the case of the Bielzug, Fallzug and Dorfbach and debris-flow reconstructions do not, therefore, reach back as far in time as for the other torrents.

In a first analytical step, debris-flow frequencies were reconstructed for individual torrents and for the study area, before decadal frequencies were calculated. The coincidence in debris-flow occurrence in the different torrents was investigated with conditional probabilities so as to analyse simultaneity in debris-flow occurrence between a specific torrent and each of the other torrents. The presence of an event in a torrent in a particular year was noted with a 'Y' in the data base, years with no events were registered with 'N'. Conditional probabilities were calculated for 'Y/Y' and 'Y/N' couples but disregarded for 'N/Y' combinations. Calculations were performed for all torrents for the period 1900–2009. In addition, the period 1850–1899 was analysed for the five torrents with sufficient data availability before AD 1900 (i.e. Ritigraben, Grosse Grabe, Geisstriftbach, Birchbach and Wildibach).

Afterwards, statistical analysis of long-term trends and changes in debris-flow frequency were performed with FHX2, a software designed for frequency analysis of data sets obtained from tree-ring records (Grissino-Mayer, 2001). Analyses were based on the intervals between the occurrences of debris flows and minimum, maximum, mean and Weibull median debris-flow recurrence intervals were calculated for each torrent. In the following, statistical analyses were performed for the entire time period (1600–2009) and for the subperiods 1850–1899, 1900–1949 and 1950–2009. A Student's *t*-test was finally applied to test changes in mean debris-flow recurrence intervals between the investigated periods for significance.

Results

Debris-flow frequencies

Figure 2 illustrates the debris-flow frequencies for the individual torrents and the overall frequency for the entire valley. In total, 417 debris-flow events were recorded in 226 different event years between AD 1600 and 2009. Since 1850, 296 events and 134 event years are registered in the tree-ring series collected in the eight torrents. Figure 2 also shows clearly that debris flows were common in the torrents analysed for the entire period of the record. The highest frequency is observed at Ritigraben with a total of 126 events. In contrast, only 12 events could be reconstructed from the tree-ring series for the Fallzug.

In Figure 3, the debris-flow frequency reconstructed for each of the eight different torrents is summarized in ten-year periods with bars representing variations from the mean decadal frequency of debris flows for the period 1850–2009. The number of trees available for the reconstruction is represented with a solid line above the

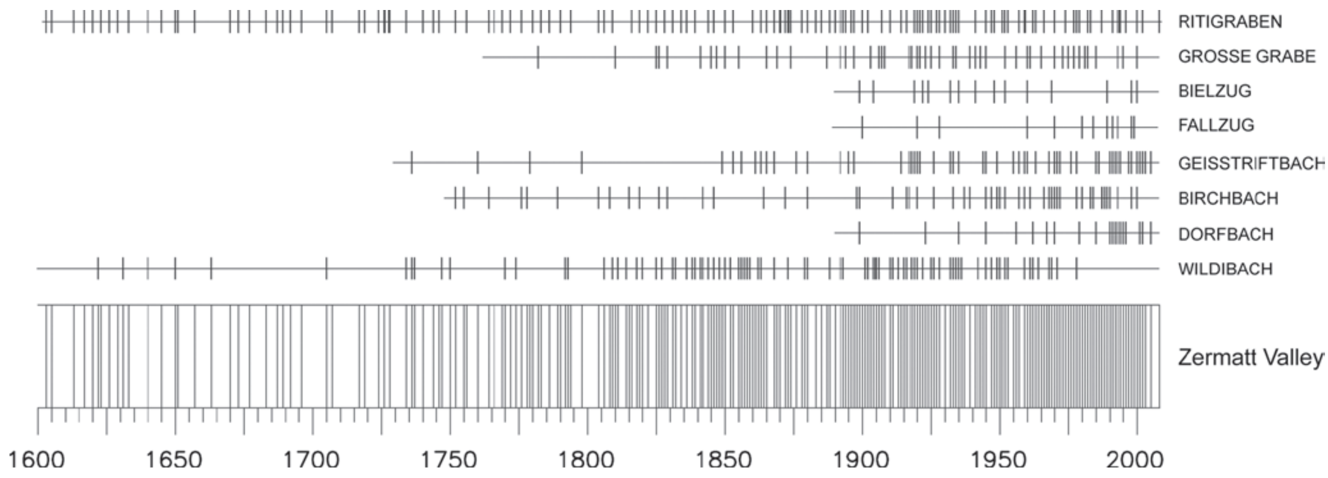

Figure 2. Debris-flow frequencies for the eight torrents and the composite for the valley-wide reconstruction. Each vertical bar represents an event in one torrent

frequency bars. While sample depth does not influence the number of reconstructed events over the reconstructed time period in the Wildibach and Ritigraben, a strong dependence of the number of reconstructed events with sample depth exists for the Birchbach and Dorfbach. Even though there are differences in the number of events and the decadal frequencies between the torrents, we realize that debris flows became more frequent in all eight torrents after the end of the 'Little Ice Age' at around 1900. Remarkably, the last ten-year period (2000–2009) was characterized by a reduced number or even complete absence of events in torrents of the Zermatt valley.

The overall decadal frequency of past debris-flow occurrence in the Zermatt valley is given in Figure 4. On average, 18.6 events per 10 years were identified in the tree-ring series over the time period covered by the reconstruction. A slight trend towards more debris-flow events is observed in the more recent ten-year periods but is at least partly explained by the increasing sample depth in some of the torrents. Differences in debris-flow activity are clearly visible and we identify a decade with largely increased occurrences between 1920 and 1929 (i.e. 27 events recorded in the eight torrents) or from 1990 to 1999 (i.e. 28 events). For the two periods 1960 to 1979, 23 and 24 events, respectively, were reconstructed per decade which makes them rather active periods as well. Very low activity can, in contrast, be observed between 2000 and 2009 with only 13 events, rendering the most recent past the period with the lowest number of events since the late nineteenth century.

Valley-wide event years

In a subsequent step, years with at least 50% of the torrents showing signs of activity were considered as being valley-wide event years (see Table 4). Between 1600 and 2009, 30 valley-wide event years could be reconstructed with the most recent dated to AD 2000. For the twentieth century, 16 valley-wide event years were dated from the tree-ring series. Their number decreases to eight and six events, respectively, for the nineteenth and eighteenth centuries. Event years with activity in all eight torrents could not be identified and tree-ring records did not allow for an identification of simultaneous events in more than six torrents, as was the case in 1993, 1970, 1945 and 1920. For the nineteenth century, we reconstruct two events with activity in four out of the six torrents, namely in 1880 and 1846. As sample depth becomes even more limited for the eighteenth century, only 1734 and 1705 could be identified as valley-wide event years in the two torrents extending back to AD 1600 (i.e. Ritigraben and Wildibach).

Coincidence of event years

The probability of having an event in a specific torrent with simultaneous activity in another torrent was assessed with conditional probabilities. Analysis was restricted to the period 1900–2009 and results are listed in Table 2. Notably, the probability of having an event in the Ritigraben is high if there is an event recorded in any of the other torrents (e.g. p=0.64 if there is an event in the Bielzug; p=0.51 on average). Similarly, probabilities are increased to identify a reconstructed debris-flow occurrence in the Geisstriftbach and Wildibach if there was an event in any of the other torrents (p=0.45 on average). In contrast, small torrents with a lower number of reconstructed events (e.g. Bielzug, Fallzug) reveal rather low conditional probabilities (p=0.18 and 0.15, respectively) when compared with the other torrents.

As the quantity and, therefore, quality of data was limited by the availability of affected trees for some torrents in the nineteenth century, conditional probabilities for the period 1850–1899 were only computed for the torrents with sufficient data. As can be seen from Table 2, the Ritigraben was again the torrent showing the best accordance with other torrents (p=0.55 on average). It is also striking to see that, in contrast to the twentieth century, the probability of recording an event at Grosse Grabe or Birchbach during activity in any of the other torrents drop from average values of p=0.33 and p=0.38, respectively, to p=0.06 during the second half of the nineteenth century.

Long-term changes in debris-flow occurrence

For each torrent, minimum, maximum, Weibull median and mean intervals of debris flows are given in Table 3. The minimum interval between two debris-flow events generally remained between one and two years. In the valley-wide chronology, debris flows represent a very common geomorphic process with a total of 225 intervals between 1600 and 2009 and a mean recurrence interval of 1.78, meaning that more than one event occurred in one of the valley torrents every second year. Recurrence intervals vary considerably between the torrents, with the Ritigraben exhibiting the largest activity with a mean recurrence interval of 3.24 years over the

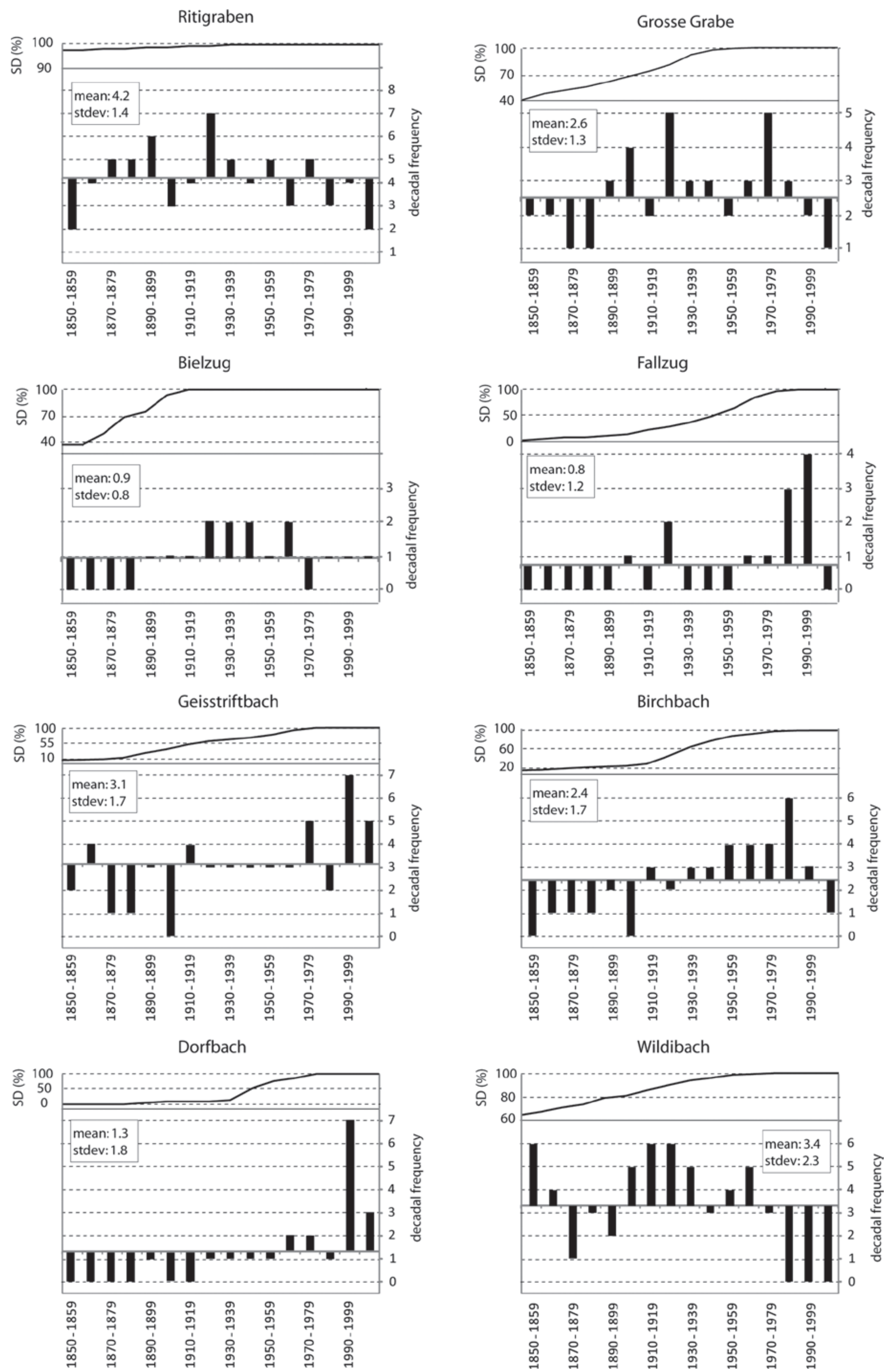

Figure 3. Debris-flow frequencies are depicted as decadal frequencies for all torrents for the period 1850–2009 represented as bars going up or down from the mean frequency. Sample depth (SD) per decade is indicated with a line above the decadal frequencies of each torrent

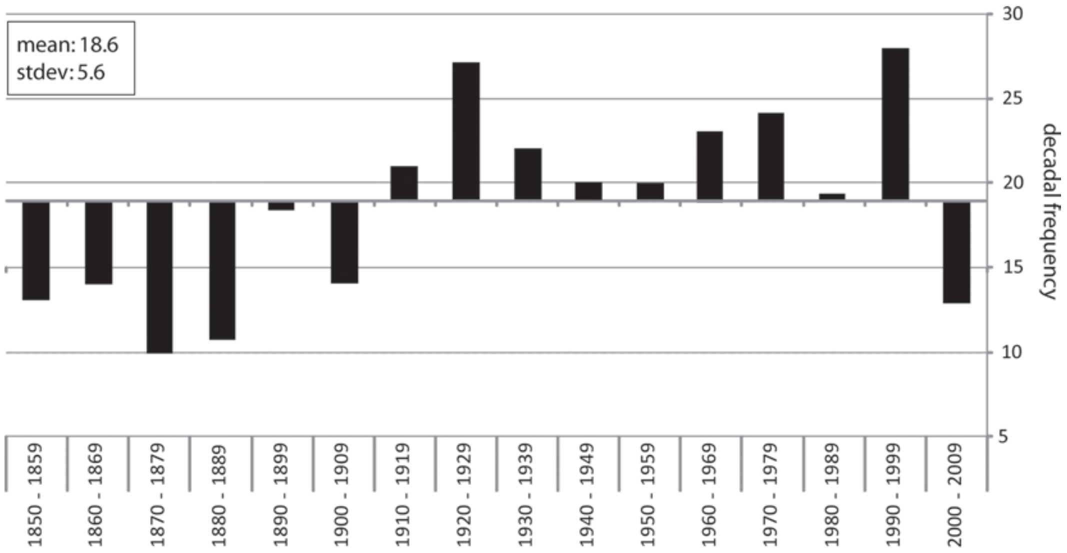

Figure 4. Decadal debris-flow frequency for the valley-wide reconstruction illustrated as variation from the mean (18.5 events per decade)

Table 2. Conditional probabilities of events between the different torrents for the period 1900–2009 and 1850–1900

	1 Ritigraben	2 Grosse Grabe	3 Bielzug	4 Fallzug	5 Geisstriftbach	6 Birchbach	7 Dorfbach	8 Wildibach
1900–2008								
1 Ritigraben	1	0.36	0.22	*0.13*	0.40	0.33	0.24	**0.42**
2 Grosse Grabe	**0.48**	1	*0.15*	0.15	**0.33**	0.30	0.27	0.30
3 Bielzug	**0.64**	0.29	1	0.21	0.43	0.36	*0.13*	0.47
4 Fallzug	0.50	0.42	0.25	1	0.50	**0.58**	0.25	*0.17*
5 Geisstriftbach	**0.47**	0.29	0.18	*0.16*	1	0.45	0.37	0.34
6 Birchbach	0.45	0.30	*0.15*	0.21	**0.52**	1	*0.15*	0.48
7 Dorfbach	0.50	0.41	*0.09*	0.14	**0.64**	0.23	1	0.23
8 Wildibach	**0.51**	0.27	0.19	*0.05*	0.35	0.43	0.14	1
Mean	**0.51**	0.33	0.18	*0.15*	0.45	0.38	0.22	0.45
1850–1900								
1 Ritigraben	1	0.29	–	–	0.33	*0.10*	–	**0.38**
2 Grosse Grabe	**0.67**	1	–	–	0.33	*0.00*	–	0.33
3 Bielzug	–	–	–	–	–	–	–	–
4 Fallzug	–	–	–	–	–	–	–	–
5 Geisstriftbach	**0.64**	0.27	–	–	1	*0.09*	–	0.45
6 Birchbach	**0.40**	0.00	–	–	0.20	1	–	0.20
7 Dorfbach	–	–	–	–	–	–	–	–
8 Wildibach	**0.50**	0.19	–	–	0.31	*0.06*	–	1
Mean	**0.55**	0.19			0.29	*0.06*		0.34

Maximum values per torrent are indicated in bold, minimum values in italic.

period 1600–2009. For the Bielzug and Fallzug and based on the tree-ring reconstructions, 7.21 (1840–2009) and 9 years (1890–2009), respectively, pass on average between two events.

Recurrence intervals were not only determined for the entire time series, but also for the episodes 1850–1899, 1900–1949 and 1950–2009. In addition, we used Student's *t*-test to check if changes in the temporal occurrence of debris flows are significant at a level of 0.125. In the case of the Ritigraben, we do not observe any significant changes in the occurrence of events between the three investigated time periods, as can be seen in Table 3. In contrast, some torrents (e.g. Birchbach) underwent significant changes in the number of reconstructed debris-flow events over the reconstructed time period. The slightly but constantly increasing number of events observed in the valley reconstruction results from sample depth limitations and is, in addition, not statistically significant.

Discussion

Tree-ring series from conifers disturbed by former debris-flow activity were used to assess the frequencies and changes in the temporal occurrence of events in eight torrents of the Zermatt valley (Valais Alps, Switzerland). A total of 417 events could be reconstructed for the period 1600–2009, with 296 of these events occurring after AD 1850.

The overall debris-flow frequency for the Zermatt valley suggests an increase in the number of events since AD 1850 in general and during the twentieth century in particular. This increase in debris-flow activity is, however, biased to a certain degree through the steadily growing number of trees available for the reconstruction and, at the same time, the rather limited data availability for several torrents prior to AD 1900 (Table 1). However as sample

Table 3. Debris-flow interval statistics for each torrent and the valley-wide reconstruction

	Time period	No. of intervals	Min	Max	Weibull Median	Mean interval	Student's *t*	*p* > *t*
1 - Ritigraben	entire series	125	1	13	2.94	3.24		
	1850–1899	20	1	7	2.19	2.35	0.65	0.52
	1900–1949	22	1	6	1.99	2.18		
	1900–1949	22	1	6	1.99	2.18	−1	0.32
	1950–2009	22	1	6	2.44	2.59		
2 - Grosse Grabe	entire series	49	1	28	3.48	4.45		
	1850–1899	8	2	13	5.45	5.88	3.11	0.005
	1900–1949	16	1	9	2.27	2.63		
	1900–1949	16	1	9	2.27	2.63	−1.18	0.24
	1950–2009	15	1	8	2.99	3.2		
3 - Bielzug	entire series	15	2	53	7.44	10.27		
	1900–1949	7	2	15	5.66	6.29	−0.91	0.38
	1950–2009	5	2	20	8.67	9.6		
4 - Fallzug	entire series	11	1	32	6.64	9		
	1900–1949	2	8	21	–	–	–	–
	1950–2009	8	1	10	4.29	4.88		
5 - Geisstriftbach	entire series	53	1	51	3.07	5.08		
	1850–1899	10	2	13	3.95	4.4	1.75	0.09
	1900–1949	12	1	9	2.36	2.92		
	1900–1949	12	1	9	2.36	2.92	0.76	0.45
	1950–2009	24	1	8	1.84	2.08		
6 - Birchbach	entire series	51	1	18	3.83	4.86		
	1850–1899	4	1	18	7.13	8.75	1.07	0.35
	1900–1949	10	1	7	3.59	3.8		
	1900–1949	10	1	7	3.59	3.8	2.05	0.05
	1950–2009	21	1	8	2.15	2.38		
7 - Dorfbach	entire series	19	1	24	4	5.58		
	1900–1949	2	4	12	–	–	–	–
	1950–2009	15	1	9	2.71	3.27		
8 - Wildibach	entire series	85	1	42	2.77	4.19		
	1850–1899	15	1	8	2.42	2.87	1.16	0.25
	1900–1949	25	1	6	1.76	1.92		
	1900–1949	25	1	6	1.76	1.92	−1.19	0.25
	1950–2009	10	1	30	2.45	2.8		
Zermatt Valley	entire series	225	1	10	1.55	1.78		
	1850–1899	36	1	3	1.33	1.36	1.62	0.03
	1900–1949	42	1	2	1.16	1.17		
	1900–1949	42	1	2	1.16	1.17	1.12	0.26
	1950–2009	53	1	3	1.07	1.09		

depth is no longer a limiting factor after 1900, we are convinced that fluctuations in the frequency of events in the twentieth century reflect the natural variance of debris-flow occurrence in the different torrents investigated. Notably, the debris-flow frequencies reported here represent minimum frequencies (i) as archival records are normally incomplete (see e.g. Marchi and Tecca, 2006) and (ii) as tree-ring reconstructions only provide data on events big enough to leave the channel and affect trees on the cone or to leave signs in the vegetation bordering the channel. Small events remaining inside the channel without affecting trees or stopping above the cone could not therefore be recorded using dendrogeomorphic methods.

The relatively low debris-flow activity at the end of the nineteenth century is not only the result of the sample depth but a phenomenon observed in torrents with sufficiently large data availability and rivers of the wider study region as well. We therefore believe that the reasons for the reduced activity need to be sought in the climatological and geomorphic conditions prevailing in the Zermatt valley at the end of the 'Little Ice Age' (LIA; 1570–1900, according to Grove, 2004). Cool summers with frequent snowfalls at higher elevations regularly prevented the release of debris flows during most of the LIA in the study region (Pfister, 1999), even towards the end of the nineteenth century. In addition, we believe that cooler temperatures have had a stabilizing effect on local permafrost bodies and that they would thus have limited debris mobilization. Besides, it is also feasible that the lower temperatures along with limited debris production rates would also have resulted in primarily smaller debris-flow events (Stoffel, 2010), which would have remained inside the channel without leaving clearly visible signs of disturbance in the trees growing on the cone (Hupp, 1984; Jakob, 1996).

The warming trend with greater precipitation totals in summer and autumn and warm-wet conditions (Pfister, 1999) resulted in a clustering of reconstructed debris-flow events in the Zermatt Valley between 1916 and 1935, and especially between 1920 and 1929. This increase in debris-flow frequency at the beginning of the twentieth century is in agreement with documented data on flooding in Alpine rivers where the frequency of events was rather limited during most of the LIA as well (Lütschg-Lötscher, 1926; Röthlisberger, 1991). However, in contrast with the debris-flow series, flooding activity in Swiss rivers started to increase after the mid-nineteenth century (Pfister, 1999). Again, the delayed occurrence of increased frequencies in the debris-flow torrents can be explained by the much higher elevation of the catchments, the

Table 4. Valley-wide debris-flow event years and data on flooding in neighbouring rivers and lakes

Year	Sample depth	Recorder[a]	%	Torrent no.								Events in other locations[b]
				1	2	3	4	5	6	7	8	
2000	8	5	63	×	×	×		×	×			Saltina, Lago Maggiore
1998	8	4	50			×	×	×	×			
1993	8	6	75	×	×		×	×	×	×		Saltina, Lago Maggiore
1991	8	4	50	×			×	×		×		Lago Maggiore
1978	8	4	50	×				×	×		×	Lago Maggiore
1970	8	6	75	×	×		×	×	×	×		
1960	8	4	50		×	×	×	×				Lago Maggiore
1959	8	4	50	×			×		×		×	
1952	8	5	63	×	×	×			×		×	
1945	8	6	75	×	×			×	×		×	
1935	8	5	63	×		×		×		×	×	Lago Maggiore
1933	8	5	63	×	×			×	×		×	other parts of CH
1932	8	4	50	×		×		×			×	Saltina, other parts of CH
1928	8	4	50	×	×		×				×	Lago Maggiore, other parts of CH
1920	8	6	75	×	×		×	×	×		×	Saltina, Lago Maggiore, Rhone
1919	8	4	50	×		×		×			×	
1892	7	4	57	×	×			×			×	Saltina, Lago Maggiore, Rhone, Vispa
1880	6	4	67	×				×	×		×	Lago Maggiore
1868	6	3	50	×				×			×	Saltina, Vispa, Saas Valley, Rhone, Lago Maggiore
1865	6	3	50	×	×			×				
1863	6	3	50	×				×			×	Vispa
1850	6	3	50	×	×						×	Saltina, Rhone, Vispa
1846	6	4	67	×		×			×		×	Lago Maggiore, Rhone, Saas Valley
1825	5	3	60	×	×						×	
1776	4	2	50	×					×			
1764	4	2	50	×					×			Rhone, Vispa
1752	4	2	50	×					×			Saltina, Rhone, Vispa
1736	3	2	67					×			×	
1734	2	2	100	×							×	Rhone
1705	2	2	100	×							×	Lago Maggiore
30				**27**	**13**	**7**	**8**	**19**	**15**	**4**	**20**	**18**

Grey bars illustrate time period with no data.

[a]'Recorders' indicates the number of torrents available for the reconstruction in the specific year.
[b]Data sources: Berchtold (2002); Imboden (1996); Jossen (1988); Lütschg-Lötscher (1926); Röthlisberger (1991); Ruppen *et al.* (1979); Spinedi *et al.* (1995); Stoffel *et al.* (2005).

buffering effects of snow during spring and autumn events and the stabilizing effect of permafrost in the source areas of events. Another period with enhanced debris-flow activity can be observed between 1960 and 1979, when summer and autumn precipitation totals are again characterized by positive anomalies. The concentration of debris-flow events between 1990 and 1999 cannot be explained with changes in total precipitation totals, and the large number of events rather represents the result of two exceptional event years, 1993 and 1994, when most torrents produced debris flows following intense rainfalls (Röthlisberger, 1994, 1995).

Results also contradict the widely accepted assumption that climatic changes will univocally lead to an increase in event frequency. In contrast, our records are in concert with data from Jomelli *et al.* (2007), indicating that the most recent past (2000–2009) represents the period with the lowest frequency of debris-flow events since AD 1900. While part of this decrease in debris-flow activity certainly results from the recent decrease in heavy summer rainfalls in the Swiss Alps (Schmidli and Frei, 2005), we also have to admit that the observed decrease may also partly reflect anthropogenic interventions in the torrent systems. In the case of the Wildibach, for example, protection measures have prevented events to affect the cone after 1978 and archival records do not exist for the last 30 years.

Long-term changes or significant increases in debris-flow frequency were only observed for the torrents where sample depth biased results for the intervals 1850–1899 and 1900–1949. A significant increase in frequency could not, in contrast, be observed for torrents with an appropriate sample depth over the entire period of the reconstruction. We therefore conclude that the increase in the number of events after the LIA, as observed by Stoffel *et al.* (2008) or Baumann and Kaiser (1999), was too much limited in time and therefore only visible in the reconstruction at the decadal but not the long-term level. In addition, our reconstruction clearly shows that geomorphic or climatic changes in the source areas of debris flows have not been important enough so far to significantly influence the long-term frequency of events triggered.

Over the last 400 years (1600–2009), reconstructions point to 30 years with events in at least 50% of the investigated torrents. When compared with data on flooding in neighboring rivers and lakes (Berchtold, 2002; Imboden, 1996; Jossen, 1988; Lütschg-Lötscher, 1926; Röthlisberger, 1991; Ruppen *et al.*, 1979; Spinedi *et al.*, 1995; Stoffel *et al.*, 2005), it becomes apparent that 18 out of the 30 valley-wide events (60%) were recorded in at least one of the other water bodies as well. Table 4 reveals that in 11 out of 18 cases, debris-flow events in the Zermatt valley are in concert with high water levels at

Lago Maggiore. As Lago Maggiore is located to the southeast of our study region and south of the Alps, we speculate that these 11 valley-wide events were released through a marked low-pressure system south of the Alps with persistent rainfall around the southern Alpine divide and inside the Zermatt valley. In case of debris-flow events recorded in the Zermatt valley but no signs of activity in the other water bodies, we would expect more isolated, convective rainfalls, such as thunderstorms, to be the trigger of events.

Conclusion

Based on tree-ring reconstruction, this paper addressed past debris-flow occurrence in eight torrents of the Zermatt valley since AD 1600 and 1850. Major differences and trends in debris-flow activity were identified at the decadal timescale with peaks in activity toward the end of the LIA and in the early twentieth century when warm-wet conditions prevailed during summers in the Swiss Alps. We also observe a considerable decrease in frequency over the past decades which result from a decrease in the frequency of triggering precipitation events. In contrast, we cannot identify any significant trends in the debris-flow series between 1850 and 2009 as soon as longer-term changes (i.e. changes in 50-year segments) are addressed. We therefore conclude that large-scale climatic conditions would not be the only limiting factor for debris-flow occurrences in the Zermatt valley but that the presence and timing of triggering events would represent a crucial element. Notably, the focus of future research should therefore be on alterations in the number, timing and intensity of rainfall events in a future greenhouse climate. Nevertheless, the specific geomorphic conditions in the source areas of debris flows should not be neglected either and we therefore suggest to integrate rock-glacier movements, grain-size distribution of debris-flow material and other sedimentological aspects into future analysis to foster the understanding of debris-flow triggering and changes in activity in Alpine catchments.

Acknowledgements

This publication has been supported by the FOEN-SFP-SRCE ‘RUFINE’ Project under Contract No. 0931030100RA/8253; SFP-SRCE, by the EU-FP7 ‘ACQWA’ Project (www.acqwa.ch) under Contract No. 212250 and by a post-doctoral grant from the AXA Research Fund.

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