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A CONTRIBUTION TO A BETTER UNDERSTANDING OF THE METEOROLOGICAL TRIGGERING CONDITIONS OF PAST DEBRIS FLOWS

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ABSTRACT

An unusually dense and highly resolved database on periglacial debris flows is linked here with meteorological records dating back to AD 1864 to reconstruct ~150 yr of rainfalls triggering debris flows at high-elevation sites (source area elevations ranging from 2000 to 4545 m asl) in the Swiss Alps. Results show that the debris-flow season currently lasts from May to October as compared to late 19th century when activity was restricted to June – September. Debris flows early in the season are generally triggered with lower rainfall totals (<20 mm in 1 day) than those occurring late in the season as snow melt adds considerable amounts of water to the system and therefore facilitates debris-flow release. Debris flows in May, June, July and August are primarily triggered by short-duration high-intensity rainfalls (local thunderstorms) whereas the occurrence of debris flows late in the season is more often related to longer-lasting advective rainfalls.

Keywords: debris flow, precipitation, triggering, permafrost

INTRODUCTION

Through their unpredictable and sudden occurrence, debris flows represent a major hazard in many mountainous regions all over the world. The understanding of the triggering factors of such events is crucial for hazard assessment, forecasting of events and for early warning systems. In the recent past, many studies have been published on rainfall conditions, minimum thresholds, duration-intensity relationships or on antecedent moisture conditions leading to debris-flow triggering (e.g. Brandet al., 1984; De Vitaet al., 1998; Guzzettiet al., 2008). However, these studies were normally based on archival records or directly observed events and therefore often had a rather limited temporal coverage. This contribution is, in contrast, based on an unusually long (~150 yr) and dense database composed of archival data and tree-ring reconstructions and on meteorological records dating back to AD 1864. The focus of this paper is on rainfall-initiated debris flows in torrential catchments with source areas in periglacial environments. We explore the (i) timing and duration of past debris flow events, (ii) amount of rainfall needed to trigger debris flows and (iii) the percentage of events over fixed rainfall thresholds leading to the release of a debris flow.

STUDY SITE

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.; Fig. 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).

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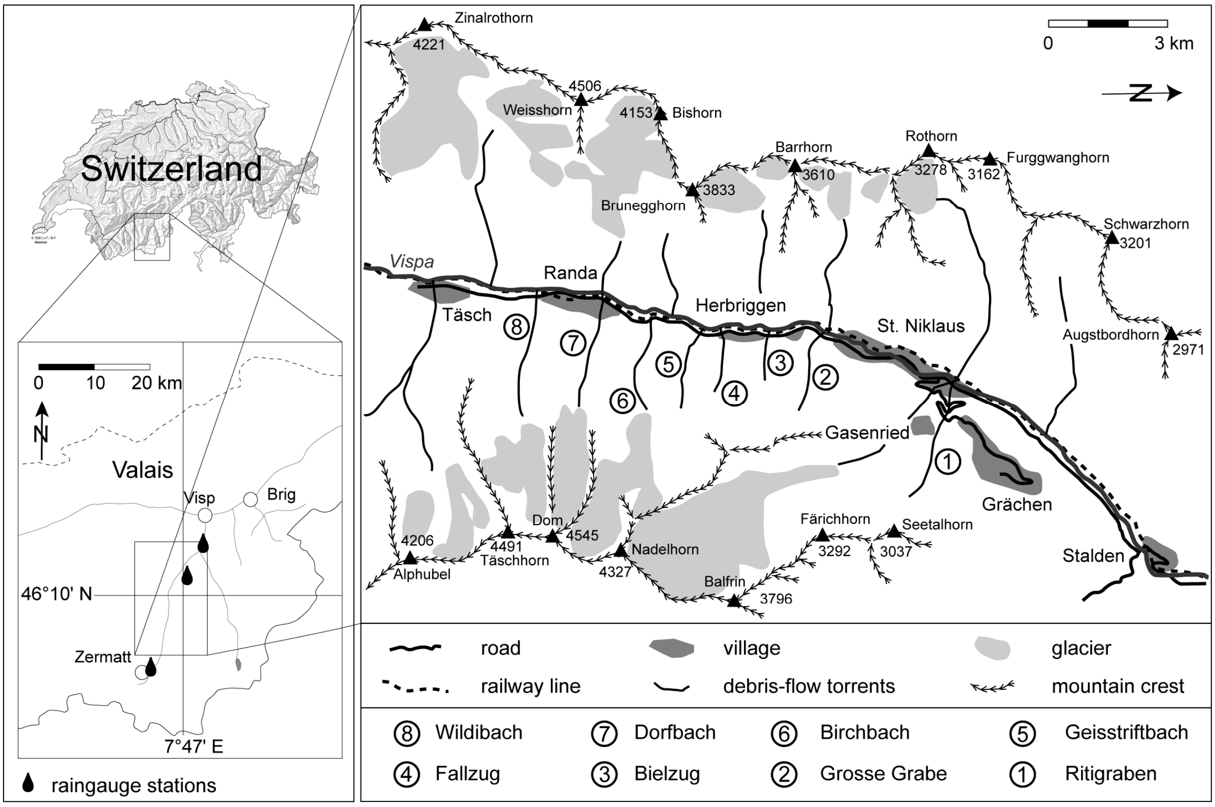

Fig. 1 Location of the eight torrents in the Zermatt valley where the debris-flow occurrence and triggering conditions have been investigated.

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 (BAFU, 2006; PERMOS, 2009). In three cases, the uppermost reaches of the catchment are glacierized. The catchments reach elevations of up to ~4500 m asl and the initiation zones of debris flows are located between 2000 and 3000 m asl.

Climatic conditions in the study area are characterized by low temperature, snow precipitation and high annual and day-time thermal ranges. These harsh climatic conditions favor 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. As material availability is unlimited, the input of water controls the triggering of debris flows. 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 (Stoffel, 2008).

Tab. 1 Geomorphic properties of the investigated catchments.

	Riti-graben	Grosse Graben	Bielzug	Fallzug	Geisstrift-bach	Birchbach	Dorfbach	Wildibach
Glacier					(x)	x	x	x
glaciated area (km2)	0	0	0	0	0.08	3.4	2.1	2.4
periglacial processes	x	x	x	x	x	x	x	x
min elevation catch-ment area (m asl)	2600	1900	2100	1900	2100	2000	2000	2100
max elevation catchment area	3136	3178	3192	3350	4035	4545	4479	4545
exposition	west	west	west	west	west	west	west	west
rock	gneiss	gneiss	gneiss	gneiss	gneiss	gneiss	gneiss	gneiss
catchment area (km2)	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 asl)	1460-1800	1200-1560	1230-1320	1250-1420	1260-1360	1300-1440	1400-1590	1420-1540

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.). The regional climate is typically dry and cool with average annual precipitation of 533 mm in Ackersand (1961–2008), 570 mm in Grächen (1864–2008) and 690 mm in Zermatt (1900–2008). Mean annual temperature amounts to 4.8°C in Grächen (1864–2008) and 3.9°C in Zermatt (1959–1971 and 1981–2008; no temperature data available for Ackersand). January through April are generally the driest months with 30–40 mm on average whereas October is commonly wettest with 63 (±52) mm of precipitation (MeteoSwiss, 2010).

METHODS

This study is based on a total of 116 debris flows between 1864 and 2008 gathered from archival records and tree-ring analysis. The oldest meteorological station in the valley is located in Grächen (46° 11' N, 7°49' E; 1,619 m a.s.l.) and operational since December 1863 (MeteoSwiss, 2010). The station has a continuous daily precipitation and temperature record from December 1863 to December 1886 and from January 1891 to the current day. The Zermatt station (46°01' N, 7°45' E; 1638 m a.s.l.) has been operational since January 1900 and recorded daily rainfall for the entire period, hourly resolved rainfall data for 1981–2008 and temperature data for 1959–1971 and 1981–2008. The northernmost meteorological station of the study area, Ackersand (46°14' N, 7°52' E; 700 m a.s.l.), has been operational since 1961 and only records precipitation.

Archival records indicating the day of the event were available for 22 (19%) debris flows. For the 94 (71%) other events, the possible time window of events was assessed via the intra-annual position of debris-flow injuries and/or tangential rows of traumatic resin ducts (TRD) in the growth series of trees growing on the debris-flow cones (Bollschweile ret al., 2008; Schneuwly et al., 2009; Stoffel et al., 2005). The intra-annual position of injuries and TRD allows event dating with up to monthly precision. Rainfall data from the three meteorological stations where then examined within the temporal range suggested by the tree-ring records so as to identify the rainfall events which would have triggered debris flows. We excluded rainy days with maximum temperatures below 5°C as precipitation was likely in the form of snow in these cases in the source area of debris flows. Events recorded in archives which occurred without any precipitation were disregarded from further analysis as these were likely released by triggers other than meteorological (e.g., sudden release of water from glaciers). Results report on precipitation totals of rainfall episodes (either 1, 2 or 3 days) as the approach used did not normally allow determination of the exact hour of debris-flow occurrences. However, the exact duration of triggering storms is not crucial for this study either as we do not aim at defining intensity-duration relations with sub-daily resolution. While it is true that the meteorological stations are not located in the source area of debris flows and rainfall totals may not therefore be reflective of the exact amount of rainfall in the source area, they are, nevertheless, located within the same valley and in relative proximity of all torrents (min 2 km, mean 12 km).

The timing, duration (with daily resolution) and total amount of rainfall was then assessed for each of the 116 debris flows. We also analyzed antecedent rainfall conditions for the 5, 10, 15 and 30 days preceding debris flows. Boxplots and standard statistical variables (mean, median, minimum, maximum, stdev) were used to analyze and illustrate rainfall totals (1-, 2- and 3-day events) involved in the triggering of debris flows and separated into rainfalls causing debris flows locally (one torrent) or at the regional scale (several torrents). We assessed the number of rainfall events over fixed rainfall thresholds (e.g., 20 mm in 1 day) and the percentage of effective triggering events.

RESULTS

We analyzed a total of 116 rainfall events that triggered periglacial debris flows in the Zermatt valley since 1864 and defined their intra-seasonal timing and duration. With the exception of three rainfall events which only affected the southernmost segment of the study area (i.e. only precipitation at Zermatt), all triggering rainfalls were recorded by the Grächen station (i.e. 113 out of 116 events, or 97%). Zermatt registered 96% of the rainfalls triggering debris flows between 1900 and 2008 and Ackersand 91% of effective storms 1961 and 2008.

Results show that debris flows from these high-elevation sites are released between mid-May (earliest event: 18 May 1960) to late October (latest event: 29 October 1913) with a mean on 3 August. Over the past ~150 yr, most debris flows were released in July and August (60.2% of all events at Grächen; Figure 2), but were also common in June and September (18% and 12%, respectively). Events were, in contrast, rather scarce very early and very late in the debris-flow season with 3% and 7% in May and October, respectively.

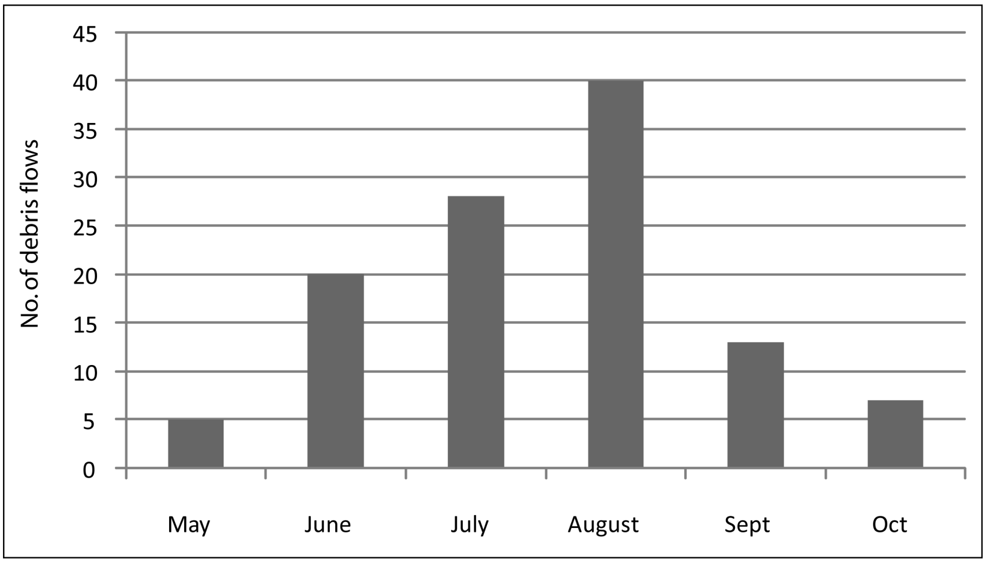

Fig. 2 Temporal occurrence of the 116 debris-flow events occurring in the Zermatt valley between 1864 and 2008. A majority of events occurred in July and August.

A subdivision of the intra-annual occurrence of triggering rainfalls with subsequent debris flows into four equally long time segments (1864–1899, 1900–1935, 1936–1971 and 1972–2008) is provided in Fig. 3 and clearly illustrates that the seasonality of events has shifted over the investigated time period. Between 1864 and 1899, a vast majority of debris flows was triggered in July and August (76% in total) and no debris flows occurred in May and October. The first debris flow in May is recorded for 1923 and the first in October for 1911. During the most recent time interval (1972–2008), debris flows become more frequent early (May) and late (October) in the season with 17% of all events, whereas debris flows have become less abundant in July and August (51%).

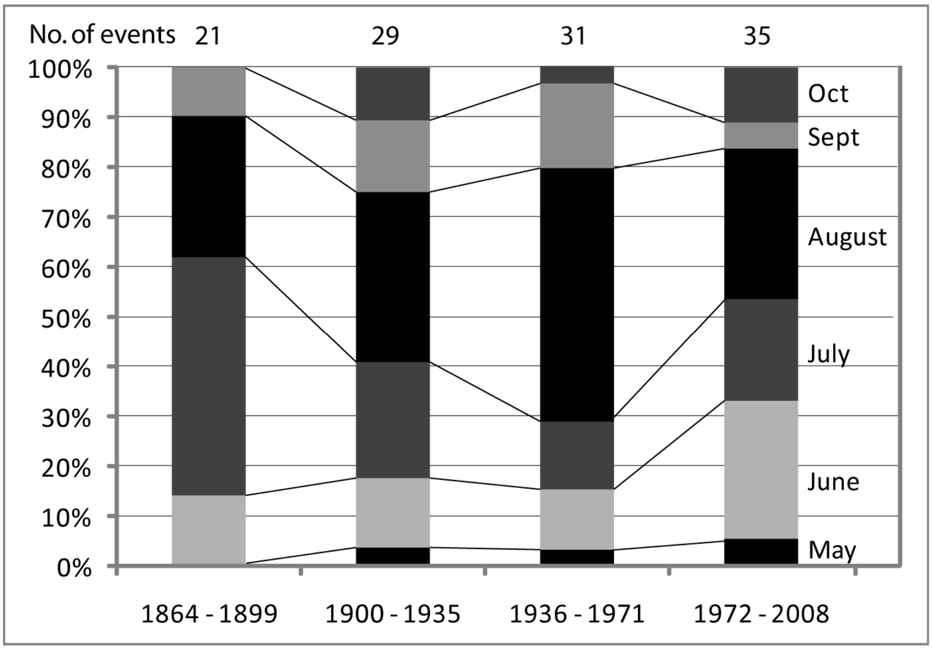

Fig. 3: Evolution of the temporal occurrence of debris flows between 1864 and 2008. Each bar represents and equally long time interval (35 years; 36 for 1972-2008) and the percentage of debris flows occurring per month (May – October). Total number of events per period is given on top of the bars. Whereas no events occurred in May and October between 1864 and the end of the 19th century, 18 % of all debris flows now occur very early (May) or late (October) in the season.

A majority of debris flows was released by short-lived rainfalls (≤1day; Figure 4). This is particularly true for May / June and July / August when 50–60% of all events fall into this category. Longer-lasting precipitation events (3-day events) were rather scarce in general and especially during the initial months of the debris-flow season and in summer (May to August). In July and August, less than 10% of all events were triggered by 3-day rainfalls. Longer-lasting rainfalls are more crucial in September and October when they are responsible for the release of one-third of the debris flows.

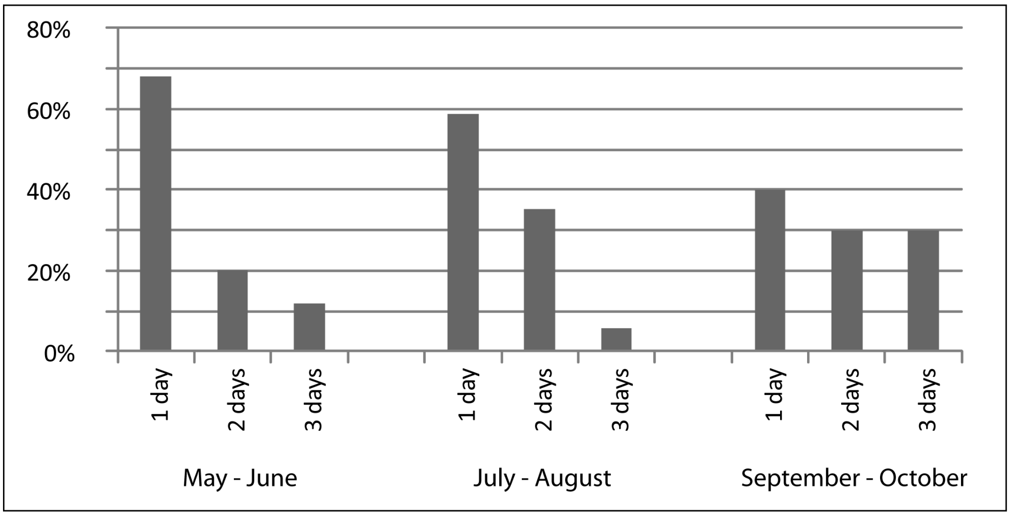

Fig. 4: Temporal occurrence and duration of triggering rainfall events. Early in the season, 1day intense rainfalls represent the most important triggering characteristic while the importance of longer-lasting rainfalls is more crucial in September and October.

Statistical data on the rainfall sums involved in the triggering of debris flows is provided in the form of boxplots in Figure 5. Mean rainfall totals of debris-flow triggering storms are comparable for the three meteorological stations and vary between about 33 (Ackersand) and 40 mm (Zermatt), with the slight increase in mean rainfall totals toward the south being in concert with higher annual precipitation recorded in Zermatt as compared to Ackersand. An increase in mean rainfall totals is also observed toward the end of the debris-flow season. While debris flows in May / June and July / August were generally triggered by storms with ~30 mm (1-, 2- and 3-day events combined), significantly higher mean, minimum and maximum precipitation totals are recorded for effective storms in September / October (means are ~45 mm and ~60 mm for Ackersand and Grächen, respectively).

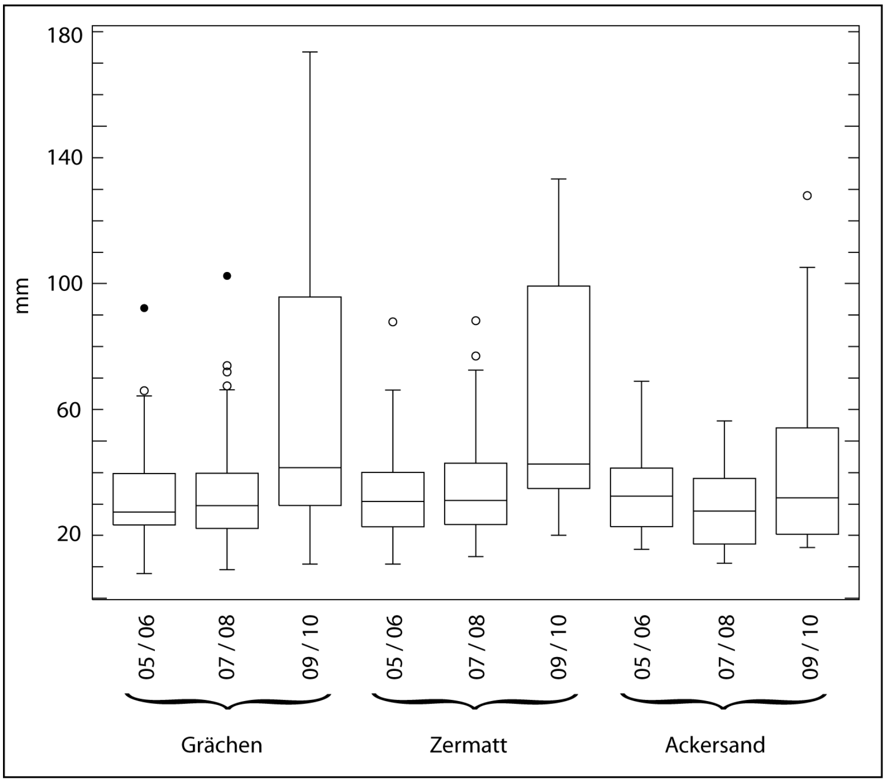

Fig. 5: Boxplots for the total amount of rainfall involved in the triggering of debris flows in May–June, July–August, and September–October). Circles indicate suspected outliers in the dataset.

This increase in the mean may partly be explained through the presence of different precipitation types. In May / June, debris flows were triggered by rather short-lived rainfalls (≤1 day), whereas long-lasting rainfalls (≤3 day) were more frequently releasing debris flows in September / October. Nevertheless, the range of rainfall sums increases disproportionally with increasing duration as shown by the standard deviations; they are rather low for the 1- and 2-day events with and 18 mm and raises to 31 (Zermatt) and 47 mm (Grächen) for the 3-day events.

The number of rainfall event over a fixed threshold (10 to 50 mm for 1- to 3-day intervals) triggering debris flows is given in Table 2. Threshold exceedences caused debris flows in 10% of the cases if the limit was set at 10 mm (1 day), and to events in 44% of the cases for 40 mm (1 day). Most interestingly, the percentage of effective rainfalls did remain below 35% for 50 mm in 3 days.

Tab. 2 Percentage of triggering rainfall events over fixed thresholds.

		Grächen			Zermatt			Ackersand		
		No. of rainfalls	No. of debris flows	% triggering	No. of rainfalls	No. of debris flows	% triggering	No. of rainfalls	No. of debris flows	% triggering
1 day	> 10 mm	1038	106	10.2%	881	86	9.8%	240	37	15.4%
	> 20 mm	301	84	27.9%	243	67	27.6%	84	27	32.1%
	> 30 mm	106	37	34.9%	99	36	36.4%	32	13	40.6%
	> 40 mm	45	20	44.4%	38	17	44.7%	10	3	30.0%
	> 50 mm	21	8	38.1%	15	6	40.0%	7	2	28.6%
2 days	> 20 mm	467	96	20.6%	410	80	19.5%	109	32	29.4%
	> 30 mm	192	60	31.3%	182	57	31.3%	59	18	30.5%
	> 40 mm	47	15	31.9%	75	28	37.3%	29	10	34.5%
	> 50 mm	47	17	36.2%	32	20	46.9%	14	5	35.7%
3 days	> 20 mm	559	96	17.2%	493	82	16.6%	133	35	26.3%
	> 30 mm	263	75	28.5%	252	66	26.2%	77	25	32.5%
	> 40 mm	133	40	30.1%	119	41	34.5%	36	12	33.3%
	> 50 mm	75	19	25.3%	58	20	34.5%	22	6	27.3%

DISCUSSION AND CONCLUSION

In this study, we analyzed hydrometeorological triggers of past debris flows originating from periglacial environments. Material availability is not normally a limiting factor for debris-flow occurrence in the area and water inputs (mainly during storms) can therefore be seen as the main element controlling the release of debris flows. We assessed dates of past debris-flow activity based on tree-ring records, as well as data from meteorological. The study is based on an unusually long, continuous and almost complete record of past debris-flow activity originating from high-elevation, permafrost environments. We assumed that reconstructed debris flows were triggered by the largest rainfall recorded during the period suggested by the tree-ring data. Possibly, debris flows triggered by localized short duration–high intensity thunderstorms were not always detected fully in the meteorological data and rainfall totals recorded at the station may deviate from those in the source area of debris flows (Buchanan and Savigny, 1990).The inclusion of three rainfall stations located within the same valley, however, considerably reduces the risk of faulty storms being considered as triggers of specific debris flows. In addition, the horizontal (min. 2km, mean 7km) and vertical (400 m) distances between source areas of debris flows and meteorological stations is very low as compared to most other studies analyzing linkages between debris-flow occurrence and rainfalls. Nevertheless, archival records contained information on 17 debris flows released during sunny days without precipitation recorded. These events were likely the result of the sudden release of water from glaciers (as is often suggested in the archival records).

Debris flows currently occur between May and October with a peak in activity in July and August. A majority of events is apparently triggered by short-duration, localized rainfalls, mainly in the form of summer thunderstorms (Staley and Wasklewicz, 2011). The number of longer lasting (>48h) rainfalls with subsequent debris flows in several catchments clearly increases in September and October when persistent low-pressure systems in the Mediterranean cause advective precipitation events in the Alps (Schmidli and Frei, 2005).

Temperature trends for the last century exhibit strong warming tendencies, both in mean and maximum temperature (Beniston, 2005; Beniston, 2009); precipitation data shows a tendency towards more intense rainfall events in autumn (Schmidli and Frei, 2005). These changes in temperature and precipitation regimes also resulted in a seasonal shift of debris-flow activity towards more events early (May / June) and late (September / October) in the season since the beginning of the 20th century. As a result, the debris-flow season has become longer as compared to the late 19th century when events were not apparently triggered in May and October. We speculate that this shift reflects impacts of climate change at high-elevation sites with reduced snow cover duration, earlier storms in spring, later rainfalls in fall as well as enhanced active-layer thawing of the permafrost bodies in the source areas of debris flows. Permafrost temperature has been reported to have warmed by about 0.5 to 0.8°C in the upper tens of meters in the 20th century and the lower permafrost limit has been estimated to have risen vertically by about 1m yr–1 (Harriset al., 2003) since the 1850s.

The assessment of rainfall totals involved in the triggering of debris flows is certainly restricted by the absence of rain gauges in the source area of debris flows, the coarse resolution of the record (24h) and by the fact that the exact moment of triggering within a precipitation events is unknown. Nevertheless, this study provided valuable insights into how debris-flow occurrences depend on rainfalls and how rainfall totals leading to the release of debris flows may change during the season. For instance, our data shows that storms with recorded rainfall totals <20 mm might be enough to trigger a debris flow in May / June (mean rainfall recorded during May / June events was ~30 mm), and that larger rainfall inputs (>25 mm; mean: 55 mm) are needed to release debris flows in September / October. These differences in minimum and mean values can be explained by the influence of snow melt during early season events which will add additional water to the system and therefore favor the release of debris flows even at rather low rainfall totals. This was, for instance, the case of the May 2011 Dorfbach debris flow which occurred after as little as 16 mm of rainfall recorded by a rain gauge which has been installed recently in its source area (personal communication Christoph Graf, WSL Birmensdorf). In addition to snow melt, the presence of ice (and a thin active layer) will likely result in concentrated runoff in the permafrost bodies (Krainer and Mostler, 2002) and thereby facilitate the release of debris flows. The low rainfall totals in July / August are reflective of short lived (minutes – hours) but high intensity thunderstorms which are only poorly represented in daily resolved precipitation records. The large precipitation totals recorded during late-season debris flows (September / October) are the result of more frequent long-duration rainfalls. In addition, it is possible that the higher thresholds observed in September / October would be reflective of thicker active layers in the permafrost bodies at the end of the summer (Akerman and Johansson, 2008; Wrightet al., 2009) allowing for more water to be absorbed without producing a debris flow.

Based on our data, however, there is scope and reason to believe that the risk for a debris flow to occur considerably increases as soon as rainfall sums exceed 20 mm in one day, 30 mm in two days or 40 mm in three days. These values therefore are well below the envelope proposed in regional studies (Caine, 1980; Guzzetti,Peruccacci,Rossi and Stark, 2008) but are in concert with data from Spitsbergen(Larsson, 1982; Rapp, 1960) where comparably low thresholds have been reported for debris flows originating from permafrost bodies. The absence of a maximum threshold in our dataset might be due partly through the exclusion of rainfalls with a temperature ≤5°C (measured at 1600 m a.s.l.). Runoff will be limited in these cases as snow in the upper catchments will likely inhibit the liquefaction of loose material and therefore prevent the occurrence of debris flows.

Antecedent rainfall and soil moisture conditions have been reported to considerably impact the triggering of debris flows or shallow landslides (Corominas and Moya, 1999; Gladeet al., 2000; Wieczorek, 1987). Antecedent moisture certainly plays a crucial role in forested areas and in catchments with thick soils (Jakob and Weatherly, 2003; Johnson and Sitar, 1989), but is less important or even negligible in regions without a soil cover and/or high permeability of the uppermost layers (Brand, 1995). The same holds true for our data where we tested the influence of antecedent rainfall 5, 10, 15, and 30 days prior to the event, but where we could not find an influence at all on the triggering of debris flows. The complete absence of soil and the coarse grain-size distribution in the source areas of the debris-flow torrents results in a very limited storing capacity for water and instantaneous runoff. Coe et al. (2008) also state that high antecedent moisture levels are not a prerequisite for the initiation of debris flows in periglacial environments as runoff would start immediately and as sediment along the channel would become quickly saturated.

Results obtained in this study are of importance for the understanding of debris-flow occurrence in periglacial environments. High-intensity precipitation in summer may release a debris flow at rainfall totals below 20mm. Rainfall totals and the duration of precipitation events increase in September and October when persistent (>48 h) advective rainfalls with lower intensities represent the main cause of debris flows. Debris flows early in the season are generally triggered by lower rainfall totals than late in the season as snow melt contributes to runoff in the catchment area and therefore facilitates their release. The general increase of mean and maximum temperatures in the Swiss Alps since the early 20th century has resulted in an extension of the debris-flow season. Subdaily rainfall data would help to further refine the reconstruction and rainfall totals responsible for the triggering of debris flows. More research is needed on the timing of past occurrence and related rainfall totals as such data may help the evaluation and improve our understanding of situations which could lead to the triggering of debris flows in a future greenhouse climate. Through the systematic analysis of such data with downscaled projections of future precipitations, it would be possible to check for rainfalls over a specific threshold even more for areas where material availability is not currently and will not in the future be a limiting factor for the occurrence of debris flows.

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