Hydrometeorological triggers of periglacial debris flows in the Zermatt valley (Switzerland) since 1864

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[1] The triggering of debris flows depends on a critical combination of available unconsolidated material and water supply. In periglacial environments, debris flows are generally triggered by liquefaction of loose material in a channel, or by progressive erosion during a large release of water. Here, we link an unusually dense and highly resolved database on periglacial debris flows with meteorological records dating back to AD 1864 to reconstruct ~150 yr of rainstorms that triggered debris flows at high-elevation sites (source area elevations ranging from 2000 to 4545 m a.s.l.) in the Swiss Alps. Analysis is based on a tree ring-derived frequency series of debris flows from eight torrents, as well as on daily records from three meteorological stations and runoff data from four river gauging stations. Results show that the debris-flow season at these high-altitude sites now is much longer (May to October) than it used to be in the late nineteenth century when activity was limited to June–September. Debris flows early in the season are generally triggered by lower rainstorm totals (<20 mm/day) than those occurring later in the season because early season snowmelt adds considerable amounts of water to the system and therefore facilitates debris-flow formation. Debris flows in May, June, July, and August are triggered primarily by short-duration high-intensity rainstorms (local thunderstorms) whereas late season (September, October) debris flows are commonly related to longer-lasting advective rainstorms.

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1. Introduction

[2] Debris flows in high mountain areas are commonly initiated by the mobilization of sediment stored in channels or by shallow landslides through the sudden input of large amounts of water, such as intense or long-lasting rainstorms, sudden snowmelt, rain-on-snow events, or the sudden release of water from glaciers or (landslide) dammed lakes [e.g., *Iverson et al.*, 1997; *Sassa*, 1984; *Wieczorek and Glade*, 2005]. High-intensity, short-duration rainstorms or low-intensity, long-duration precipitation events are the most common triggers of debris flows and shallow landslides in alpine environments. A large body of literature exists on the identification of triggers and rainfall thresholds for debris flows and shallow landslides [e.g., *David-Novak et al.*, 2004; *Coe et al.*, 2008; *Godt et al.*, 2006; *Godt and Coe*, 2007; *Jakob and Weatherly*, 2003]. In some of the work, empirical thresholds have been used to represent triggering rainfall conditions, integrating the most common rainstorm parameters: duration, intensity, cumulative precipitation and antecedent precipitation. Triggering thresholds have been defined either by a critical cumulative rainfall [*Campbell*, 1974] or rainfall intensity [*Brand et al.*, 1984] and mostly based on the relation between rainstorm intensity and duration [*Caine*, 1980; *Guzzetti et al.*, 2008]. Empirical rainfall thresholds generally have been obtained from historical databases and have relied on observed correlations between rainfall and mass-movement occurrences [*Caine*, 1980; *Crozier and Glade*, 1999; *Godt and Coe*, 2007; *Guzzetti et al.*, 2008]. Physical thresholds are, in contrast, based mainly on numerical models that integrate rainfall, pore pressure and/or slope stability [*Borga et al.*, 2002; *Crosta*, 1998; *Crosta and Frattini*, 2003; *Terlien*, 1998; *Wilson and Wieczorek*, 1995]. More recently, models have been developed to demonstrate the influence of infiltration and pore pressure change in unsaturated layers on the occurrence of shallow landslides and debris flows [*Baum et al.*, 2008; 2010; *Brooks et al.*, 2004; *Salciarini et al.*, 2006]. Comprehensive reviews of rainstorm thresholds for shallow landslides and debris flows are provided by *De Vita et al.* [1998], *Wieczorek and Guzzetti* [2000] and *Guzzetti et al.* [2008].

[3] In most cases, definition of rainfall thresholds and debris-flow triggers was based on a limited number of

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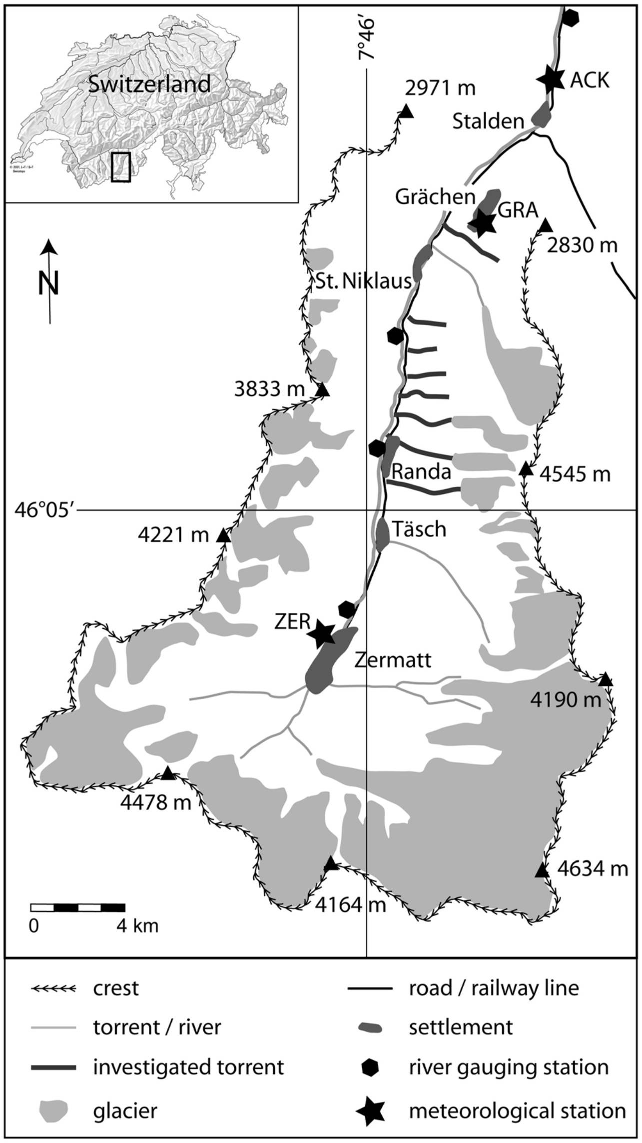

Figure 1. Location of the eight torrents investigated, river gauging stations and meteorological stations in the Zermatt Valley.

observations or on incidents reported in archival records that covered at most a few decades, and most of this past research has focused on catchments outside the range of permafrost occurrence. These studies contributed to the overall understanding of contemporary triggers, but cannot address possible changes in the seasonality of debris-flow occurrences or changes in triggering rainfall totals over time. *Stoffel et al.* [2011] coupled periglacial debris-flow data with more than a century of meteorological records (1864–2010) at a case-study site in the Swiss Alps to study changes in the seasonality of rainfall and debris flows. In this study, we focus not on a single catchment, but instead analyze debris-flow activity at a regional level using data from a unique and highly resolved archive of tree ring-derived debris-flow frequencies from eight torrents, as well as from daily records from three meteorological stations (1864–2008; 1900–2008; 1961–2008) and four river gauging stations (1900–2008). Debris-flow torrents are the main pathways of sediment transport from hillslopes to stream channels in alpine regions, and thug have distinct source (catchment), transport (channel), and depositional zones (cone) [*Sterling and Slaymaker*, 2007]. The focus of this paper is on rainfall–triggered debris flows in catchments with source areas in periglacial environments, where the frozen ground inhibits infiltration of water and therefore leads to direct runoff. Permafrost bodies have been demonstrated to be particularly sensitive to climate warming and prone to instability, as evidenced by the release of a number of recent, large-magnitude debris flows in the Alps beyond historical experience [*Stoffel and Huggel*, 2012]. Furthermore, we address the duration of rainstorms leading to debris flows, and analyze the occurrence of debris flows in the cases where rainfall sums exceed fixed thresholds of 10, 20, 30, 40 and 50 mm in 1, 2 or 3 days. The approach presented here covers an unusually long time period, addresses the triggering of past debris flows at the regional level and considers high-elevation, periglacial catchments where data have been largely missing so far.

2. Study Region

[4] The region chosen for the analysis to correlate rainfall with past debris-flow activity is the Zermatt valley, a dry inner-alpine valley of the Swiss Alps (central coordinates 46°10′N./47°7′E.; Figure 1). The valley has a north-south orientation and is bordered to the south by a high Alpine mountain range reaching up to 4634 m a.s.l. Geology is dominated by gneissic lithologies belonging to Penninic nappes [*Labhart*, 2004; *Pfiffner*, 2009]. Frequency data from eight debris-flow torrents were gathered from archives, or were reconstructed from tree rings [*Bollschweiler et al.*, 2008a; *Bollschweiler and Stoffel*, 2010b; *Sorg et al.*, 2010; *Stoffel et al.*, 2008, 2010]. All selected catchments studied have western exposure and very similar geomorphic settings (Table 1). Various permafrost features (i.e., rock glacier, moraine, push moraine, covered glacier, frozen deposits) are present in all source areas [*Delaloye et al.*, 2009; BAFU, Hinweiskarte Permafrost Schweiz, unpublished data, 2006, http://umweltzustand.admin.ch/?reset_session&initialState=permafrost&lang=de#], and the uppermost reaches of three torrents (Wildibach, Dorfbach, Birchbach) are glaciated. The catchments reach elevations of up to 4545 m a.s.l., and the initiation zones of debris flows are located between 2000 and 3000 m a.s.l. The principal sediment sources for periglacial debris flows are extensive moraine deposits, scree slopes and rock glaciers within permafrost environments. Debris-flow occurrence is typically restricted to late spring, summer, and early fall. High annual and daily thermal ranges favor weathering related to cycles of freezing and thawing as well as regolith production delivered to scree slopes [*Hall et al.*, 2002; *Hall and Thorn*, 2011]. Slope angles in the initiation zones reach 27–41° (mean 32.6°). Permafrost in the loose sediment of the eight catchments under investigation forms an impermeable layer which promotes drainage along preferential paths [*Krainer and Mostler*, 2002]. During rainstorms, water (and ice melt) is released to a torrent along the contact with the permafrost body. Rainstorms can trigger debris flows either through the wetting of material [*Griffiths et al.*, 1997] continuously delivered by a rock glacier to a

Table 1. Geomorphic Properties of the Investigated Torrents

	Ritigraben	Grosse Graben	Bielzug	Fallzug	Geisstriftbach	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
Elevation catchment area (m a.s.l.)	3136–2600	3178–1900	3192–2100	3350–1900	4035–2100	4545–2000	4479–2000	4545–2100
Aspect	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
Cone area (ha)	47	48	3.7	26	13	27	63	46
Cone elevation (m a.s.l.)	1460–1800	1200–1560	1230–1320	1250–1420	1260–1360	1300–1440	1400–1590	1420–1540

channel or by promoting failure of the rock glacier (snout) along an impermeable ice layer (i.e., active layer) during exceptional water input [*Larsson*, 1982; *Sattler et al.*, 2011]. In both cases, debris flows are thought to occur through a liquefaction mechanism similar to that described for shallow landslides [*Fleming et al.*, 1989; *Iverson et al.*, 1997; *Sassa*, 1984]. In addition to being triggered by rainfall, debris flows at high-elevation sites can also occur when sediment shear resistance is reduced by the melting of ice particles [*Arenson and Springman*, 2005] and by the delivery of fine-grained sediment formerly frozen in the ice matrix [*Rist*, 2001].

[5] Following initiation, debris flows in the torrents studied normally pass through steep channels having slope angles of 22–33° (mean 27.6°) and are either deposited on debris-flow cones located on the valley floor (1200–1400 m a.s.l.) or directly transported to the Vispa river. A slightly different setting exists for Ritigraben (Figure 1) because its cone is situated on a structural terrace located at 1460–1800 m [see *Stoffel et al.*, 2008] and not in the valley floor. The proportion of debris-flow sediment originating from the initiation zones commonly has been reported to be one order of magnitude smaller than the total debris-flow volume deposited on the cone [*Stoffel*, 2010]. However, where active-layer failures are the cause, up to one-third of the total debris-flow material is released from the rock glacier front [*Lugon and Stoffel*, 2010]. Channel erosion therefore adds considerable amounts of material to debris-flows volumes.

[6] All debris-flow cones are covered with old-growth forests composed primarily 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 is 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/month on average, whereas October is commonly wettest with 63 ± 52 mm of precipitation (MeteoSwiss, online database, 2010, http://www.meteoswiss.ch/en/).

3. Data and Methods

3.1. Data

[7] This study is based on a total of 118 debris flows between 1864 and 2008, gathered from archival records and tree ring analysis (Table 2). The oldest meteorological station in the valley is located in Grächen (46° 11′ N, 7°49′ E; 1,619 m a.s.l.), which has been operational since December 1863 (MeteoSwiss, online database, 2010). The station has a continuous daily precipitation and temperature record from December 1863 to December 1886 and from January 1891 to present. Daily data were homogenized to remove all non-climatic influences from the data [*Costa and Soares*, 2009] because the station was moved in the 1960s (M. Begert, oral communication, 2010). The Zermatt station (46°01′ N, 7°45′ E; 1638 m a.s.l.) has been operational since January 1900 and has recorded daily precipitation for the entire period, hourly precipitation from 1981 to 2008, and temperature from 1959 to 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 records only precipitation. In addition, we used data from four river gauging stations located within the study area [*BAFU*, 2011; *BUWAL*, 1977; *Ghezzi*, 1916; *Wasserwirtschaft*, 1916] to refine the quality of dating of storm-induced events. The locations of rainfall and river gauging stations are given in Figure 1.

3.2. Reconstruction of Rainstorms That Triggered Debris Flows

[8] The resolution of correlating rainfalls with debris flows varied with the assessment method. Archival records indicating the day of occurrence were available for 20 (17%)

Table 2. Data Availability for the Investigated Torrents[a]

	Ritigraben	Grosse Graben	Bielzug	Fallzug	Geisstriftbach	Birchbach	Dorfbach	Wildibach
Time period	1864–2008	1864–2008	1864–2008	1900–2008	1864–2008	1864–2008	1864–2008	1864–2008
No. of sampled trees	1102	144	16	34	252	211	21	414
No. of debris flows 1864–2008	62	39	13	14	44	33	24	28
Data sources	1	2	3	3	4, 5	6	3, 7	3

[a]Data sources: 1, *Stoffel et al.* [2008]; 2, *Bollschweiler et al.* [2008a]; 3, *Bollschweiler and Stoffel* [2010a]; 4, *Sorg et al.* [2010]; 5, *Stoffel et al.* [2010]; 6, *Bollschweiler and Stoffel* [2010b]; 7, (C. Graf and B. W. McArdell, Die Murgangbeobachstungsstation Randa, unpublished data, 2005, http://www.wsl.ch/forschung/forschungsprojekte/murgaenge/datenerhebung/randa_DE).

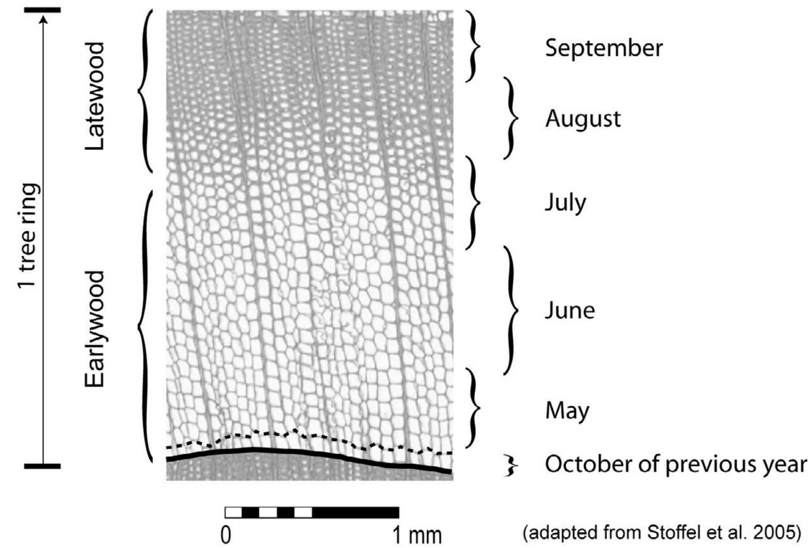

Figure 2. Schematic drawing of tree rings subdivided into earlywood and latewood. The location of an injury or tangential rows of traumatic resin ducts caused by debris flows in the tree ring allows dating of the damage with up to monthly precision [see *Stoffel et al.*, 2005].

debris flows. For the other 98 (83%) debris flows, timing was assessed using the intraannual position of debris-flow injuries and/or tangential rows of traumatic resin ducts (TRD) in the growth series of rings of trees growing on the debris-flow cones. Trees that showed obvious signs of the impact of past debris flows were sampled from along the active channel and in older deposits on the cone surfaces. Sampling was mainly done using increment borers. In addition, wedges from a limited number of injured trees were collected . In temperate climates, coniferous trees are characterized by a summer growing period and a winter dormant season. As illustrated in Figure 2, cambium starts to produce thin-walled earlywood cells at the beginning of the growth period (about mid-May at the study location) [*Stoffel et al.*, 2005]. In summer, cell formation gradually merges to thick-walled latewood cells, before cell growth slowly ceases in fall. The position of an injury caused by impact of rocks or woody debris can be used to identify the timing of the debris-flow occurrence which has caused damage. Furthermore, TRD are produced within a few days after impact and therefore provide an additional tool for constraining the date of past debris-flow occurrence [see *Bollschweiler et al.*, 2008b; *Schneuwly et al.*, 2009; *Stoffel*, 2008; *Stoffel et al.*, 2008]. The intraannual position of an injury and TRD therefore allows dating of the injury and therefore also the debris flow with up to monthly precision ($\sim\pm 2$ weeks). Rainfall data from the three meteorological stations and runoff data from the river gauging stations were then examined within the temporal range suggested by the tree ring records to identify likely rainfalls that could have triggered debris flows. We excluded rainy days with maximum temperatures below 5°C because precipitation likely fell as snow in the source area of debris flows. Because the study region is located in a dry alpine environment having few days between May and October with precipitation >10 mm and temperature $\geq$5°C (7.7 mm in Grächen), 9 in Zermatt and 6 in Ackersand, identification of possible triggering rainstorms within the monthly intervals suggested by tree rings was usually straightforward. River runoff data were used to cross-check the definition of triggering rainstorms. If river gauging stations showed a sudden increase in runoff, this supported our assumption that a debris flow could have occurred at that time. Intense precipitation with no increase in runoff suggests precipitation fell as snow in the upper parts of the catchment. Debris flows recorded in archives that occurred without any precipitation were disregarded because these were likely caused by triggers other than meteorological (e.g., a sudden release of water from a glacier). If a debris flow occurred in the northernmost torrent with no activity in the other torrents, and without rainfall recorded at the southernmost station (and vice versa), the data from the southernmost stations were disregarded from analysis to account for spatially limited rainstorms (i.e., localized thunderstorms). Probable correlations between rainfall and debris flows were linked to precipitation totals over 1 to 3 days duration, because the timing of debris flows using tree rings could not be linked to hourly intensities of rainfall.

[9] The methodological approach presented here has three substantial limitations with regard to linking debris flows with rainfall: (i) identification of triggering storms, (ii) imprecise quantification of storm duration (lacking hourly data for older rainstorms) and (iii) the distance of the meteorological stations from the source areas of debris flows. However, these limitations are not prohibitive. The limited number of possible triggering rainstorms during the monthly interval suggested by tree rings minimizes uncertainties and potential errors in choosing triggering rainstorms. In addition, sudden increases in discharge of the Vispa river helped define the timing of debris flows. The exact duration of triggering storms is not crucial for this study, as we do not aim to define intensity-duration relations with sub-daily resolution. Although the meteorological stations are not located in the source area of debris flows, and thus measured rainfall totals may not reflect precisely the amount of rainfall in the source area, the stations are, nevertheless, located within the

Table 3. Timing and Duration of Debris-Flow Triggering Rainstorms

		Grächen		Zermatt		Ackersand	
Duration	Months	Number	Percentage	Number	Percentage	Number	Percentage
all	all	112		93		42	
all	May	4	4%	4	4%	2	5%
all	June	19	17%	16	17%	10	24%
all	July	29	26%	18	19%	7	17%
all	August	40	36%	35	38%	16	38%
all	September	13	12%	12	13%	3	7%
all	October	7	6%	8	9%	4	10%
1 day	all	62	55%	49	53%	20	48%
2 days	all	36	32%	29	31%	16	38%
3 days	all	14	13%	15	16%	6	14%
1 day	May–June	14	61%	12	60%	6	50%
2 days	May–June	6	26%	4	20%	3	25%
3 days	May–June	3	13%	4	20%	3	25%
1 day	July–Aug	41	59%	31	58%	11	48%
2 days	July–Aug	24	35%	18	34%	11	48%
3 days	July–Aug	4	6%	4	8%	1	4%
1 day	Sept–Oct	7	35%	6	30%	3	43%
2 days	Sept–Oct	6	30%	7	35%	2	29%
3 days	Sept–Oct	7	35%	7	35%	2	29%

same valley and in relative proximity to all torrents (min 2 km, mean 12 km). All debris-flow dates, related rainfall sums, and the dating quality are provided in Table S1 of the auxiliary materal.[1]

3.3. Statistical Analysis

[10] The timing, duration (with daily resolution) and total rainfall was assessed for each of the 118 debris flows. We also analyzed antecedent rainfall conditions for 5, 10, 15 and 30 days preceding debris flows. Boxplots and standard statistical variables (mean, median, minimum, maximum, standard deviation) were used to analyze and illustrate rainstorm totals (1-, 2- and 3-day rainstorms) involved in the triggering of debris flows, and rainstorms were classified by those causing debris flows only locally (one torrent) or at the regional scale (several torrents). We assessed the number of rainstorms over several rainfall thresholds (e.g., 10, 20, 30 and 40 mm in 1, 2 or 3 days) and the number of rainstorms that triggered debris flows compared to those that did not. We then assessed minimum rainfall thresholds for the occurrence of debris flows based on daily precipitation data, but disregarded the lowermost percentile of rainstorms ($\sim$10% of all storms) to accommodate for the local effects and the distance between source areas and meteorological stations. Thresholds were defined for specific months (May–June, July–August, September–October) and for different rainstorm durations (1, 2, and 3 days). These threshold values were then used to define the number of rainstorms exceeding the threshold value. For the analysis and comparison of the characteristics of triggering and non-triggering rainstorms, available hourly rainfall values from Zermatt were used (1981–2008). All rainstorms between 1981 and 2008 with a minimum of 20 mm per day and temperature >5°C were considered and divided into debris-flow triggering and non-triggering rainstorms. Differences in the characteristics between the two groups (triggering and non-triggering) were tested for significance using Student's t and non-parametric Mann-Whitney U tests [*Deganutti et al.*, 2000].

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011JF002262.

4. Results

4.1. Timing and Duration of Debris-Flow Triggering Rainstorms

[11] We analyzed 118 rainstorms that triggered periglacial debris flows in the Zermatt valley since 1864, and defined their intraseasonal timing and duration (see Table S1). With the exception of six rainstorms that affected only the southernmost segment of the study area (i.e., only precipitation at Zermatt), all triggering rainstorms were recorded by the Grächen station (i.e., 112 out of 118 rainstorms, or 95%). Zermatt registered 96% of the rainstorms that triggered debris flows between 1900 and 2008, and Ackersand recorded 91% of the effective storms between 1961 and 2008.

[12] Results show that debris flows from high-elevation sites in Zermatt valley occur between mid-May (earliest debris flow: 18 May 1960 or Julian day 139) and late October (latest debris flow: 29 October 1913 or Julian day 302) with a mean in early August or Julian day 217. Over the past $\sim$150 yr, most debris flows were released in July and August (62% of all debris flows at Grächen; Table 3), but were also common in June and September (17% and 12%, respectively). In contrast, debris flows were rather scarce very early and very late in the debris-flow season with 4% and 6% occurring in May and October, respectively.

[13] Subdividing the intraannual rainstorms that triggered debris flows into four equally long time segments (1864–1899, 1900–1935, 1936–1971 and 1972–2008) illustrates that the seasonality of debris flows has shifted over time (Figure 3). Between 1864 and 1899, the majority of debris flows were triggered in July and August (80%) and no debris

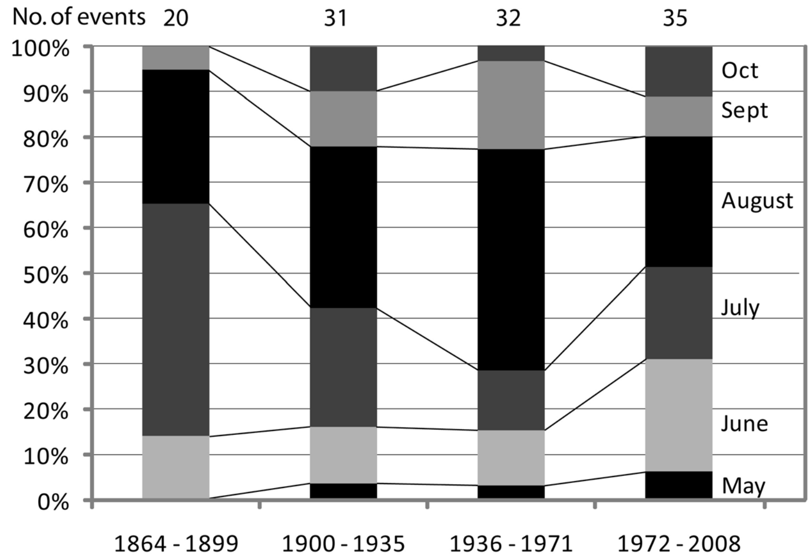

Figure 3. Evolution of the temporal occurrence of debris flows between 1864 and 2008 in the Zermatt valley. Each bar represents an equally long time interval (35 years; 36 for 1972–2008) and the percentage of debris flows occurring per month (May–October). Total number of debris flows per period is given on top of the bars. Whereas no debris flows 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 debris-flow season.

flows occurred in May and October. The first debris flow in May is recorded in 1923 and the first in October in 1911. During the most recent time interval (1972–2008), debris flows became more frequent early (May) and late (October) in the season (17% of all debris flows), whereas they became less abundant in July and August (51%).

[14] Most debris flows were triggered by short-duration rainstorms (≤1 day; Table 3). This is particularly true for May–June and July–August when 50–60% of all debris flows fall into this category. Long-lasting rainstorms (3-day rainstorms) were 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 debris flows were triggered by 3-day rainstorms. Long-lasting rainstorms are more crucial in September and October when they trigger about 30% of the debris flows that occur at this time.

4.2. Rainfall Sums Involved in the Triggering of Past Debris Flows

[15] Mean rainfall totals recorded for rainstorms that triggered debris flows are comparable for the three meteorological stations (Figure 4) and vary between about 33 (Ackersand) and 40 mm (Zermatt). The slight increase in mean rainstorm totals toward the south coincides with higher annual precipitation recorded in Zermatt as compared to Ackersand.

[16] An increase in mean rainfall totals that trigger debris flows is observed toward the end of the debris-flow season (Figure 5). Whereas debris flows in May–June and July–August were generally triggered by storms with ~30 mm over the full rainstorm duration, significantly higher mean, minimum and maximum precipitation totals are recorded for debris-flow triggering rainstorms in September–October (means are ~45 mm and ~60 mm for Ackersand and

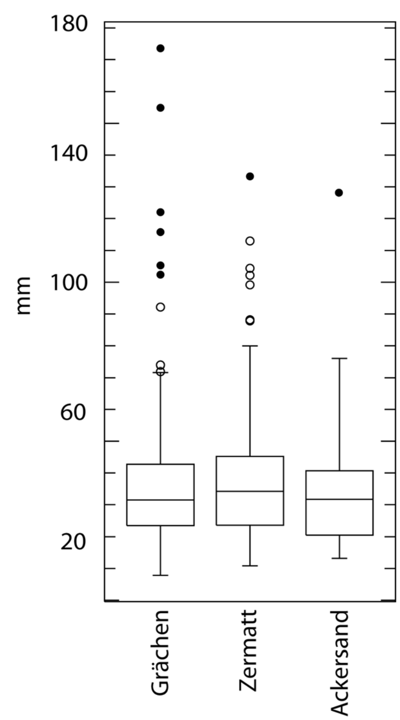

Figure 4. Boxplot for the total amount of rainfall during the rainstorm duration that triggered debris flows in all torrents in the Zermatt valley as recorded at the meteorological stations. The lower limit of the box shows the first quartile, the middle bar the median and the upper limit of the box the third quartile of the distribution. The whiskers represent the lower- und uppermost observations excluding values considered as outliers. Values are considered outliers (circles) if they lie 1.5 interquartile ranges above the third quartile.

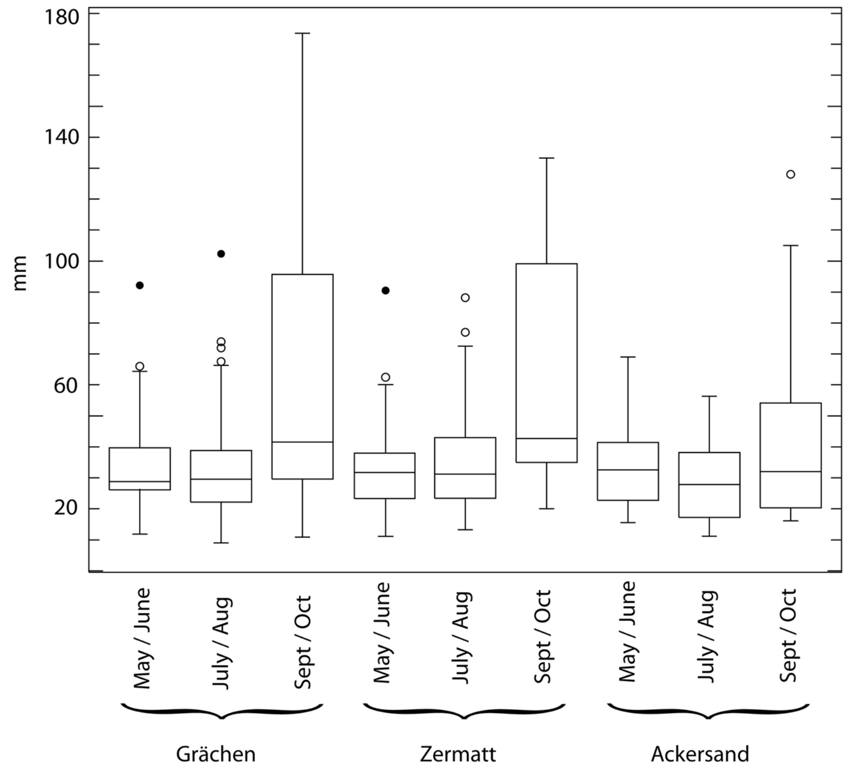

Figure 5. Boxplots for the total amount of rainfall that triggered debris flows in May–June, July–August, and September–October as recorded at the meteorological stations between 1864 and 2008.

Grächen, respectively) (Figure 5). This increase in the mean rainfall needed to trigger debris flows may partly be explained by the different precipitation types. In May–June, debris flows are triggered by short-duration rainstorms (≤1 day), whereas longer-lasting rainstorms (≤3 days) typically are needed to trigger debris flows in September–October. The range of rainfall sums increases disproportionally with increasing duration as shown by the standard deviations (Figure 6); they are low for the 1- and 2-day rainstorms with 10 and 18 mm and raises to 31 (Zermatt) and 47 mm (Grächen) for the 3-day rainstorms.

4.3. Rainstorms Triggering Localized and Regional Debris Flows

[17] Rainstorms that triggered debris flows only locally were separated from those that triggered debris flows regionally to see if the threshold values differ. Group binary 1 includes rainstorms that triggered debris flows in a single torrent, suggesting they were very localized rainstorms. Group binary 2 incorporates storms that triggered debris flows in several torrents suggesting the rainstorms affected a large region. Median rainfall totals are slightly lower for the binary 1 grouping as compared to the binary 2 grouping (Figure 7); however, differences are not statistically significant at $p < 0.05$. Debris flows in a single torrent are by far more frequent in the early months of the season (85% of all isolated debris flows occurred before September), whereas the simultaneous occurrence of debris flows in several torrents is more common toward the end of the debris-flow season (63% of all documented debris flows in August or later) (Figure 8).

4.4. Minimum Thresholds and Number of Debris-Flow Triggering Rainstorms Above Fixed Thresholds

[18] Periglacial debris flows can be triggered by comparably small rainfall inputs (Table 4). The smallest rainfall thresholds observed in the study region occurred in July and August with 12–14 mm in 1 day. The minimum thresholds needed to trigger a debris flow increase later in summer and early fall for both short- and long-duration rainstorms to about 20 mm for 1-day and around 50 mm for 3-day rainstorms.

[19] The percentage of rainstorms which exceed a fixed threshold and trigger a debris flow are given in Table 5. Debris flows were triggered by only 10% of the rainstorms if the threshold limit was set to 10 mm (1 day). This percentage increased with higher rainfall totals and reached almost 50% for 40 mm and 50 mm in 1 day. For the 2- and 3-day rainfall totals, the percentage of rainstorms triggering debris flow increased with higher rainfall totals as well but never exceeded ~50%.

5. Discussion

[20] In this study, we analyzed hydrometeorological triggers of debris flows originating from periglacial environments based on an unusually long and continuous record of debris-flow activity and meteorological data. In our reconstruction, we assumed that debris flows were triggered by the greatest rainfall (either high intensity-short duration or low intensity-long duration) recorded during the monthly interval suggested by tree ring records of debris-flow

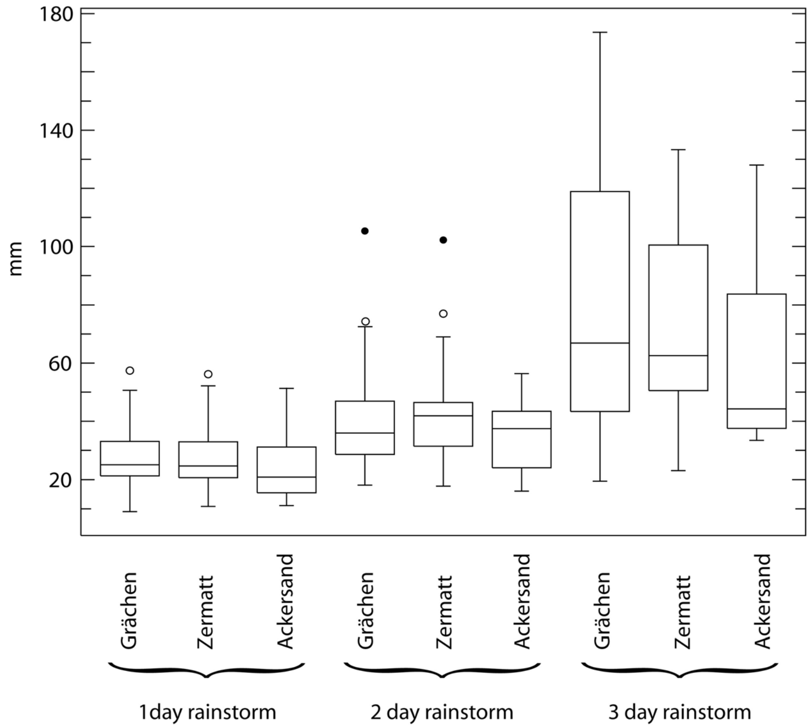

Figure 6. Boxplots for the total amount of rainfall for 1-day, 2-day, and 3-day duration rainstorms that triggered debris flows as recorded at the meteorological stations.

activity. Debris flows triggered by localized, short-duration high intensity thunderstorms were not always detected fully in the meteorological data, and rainfall totals recorded at a meteorological station may deviate from those in the debris-flow source area [*Buchanan et al.*, 1990]. The inclusion of three meteorological stations located within the same valley, however, considerably reduces the risk of misidentifying storms that triggered debris flows. In addition, the horizontal (min. 2 km, mean 12 km) and vertical (400 m) distances between source areas of debris flows and meteorological stations is very low compared to most other studies that have analyzed linkages between debris-flow occurrence and rainfall. Nevertheless, archival records contained information on 17 debris flows released during sunny days without any precipitation recorded. These debris flows were likely triggered by the sudden release of water from glaciers [*Chiarle et al.*, 2007; *Evans et al.*, 2009; *Walder and Driedger*, 1994].

[21] Debris flows presently occur between May and October, with a peak in activity in July and August. Most debris flows appear to be triggered by short-duration, localized rainstorms, mainly in the form of summer thunderstorms [*Stoffel et al.*, 2011]. The number of long lasting (>48 h) rainstorms associated with debris flows increases in September and October when persistent low-pressure systems in the Mediterranean cause advective rainstorms in the Alps [*Schmidli and Frei*, 2005].

[22] Temperature trends for the last century in the Alps exhibit strong warming, both in mean and maximum temperature [*Beniston*, 2005, 2009]; precipitation data show a tendency toward more intense rainstorms in autumn [*Schmidli and Frei*, 2005]. These changes in temperature and precipitation regimes have resulted in a seasonal shift of debris-flow activity, toward more debris flows early (May–June) and late (late September–October) in the season since the beginning of the 20th century. As a result, the debris-flow season has become longer compared to the late 19th

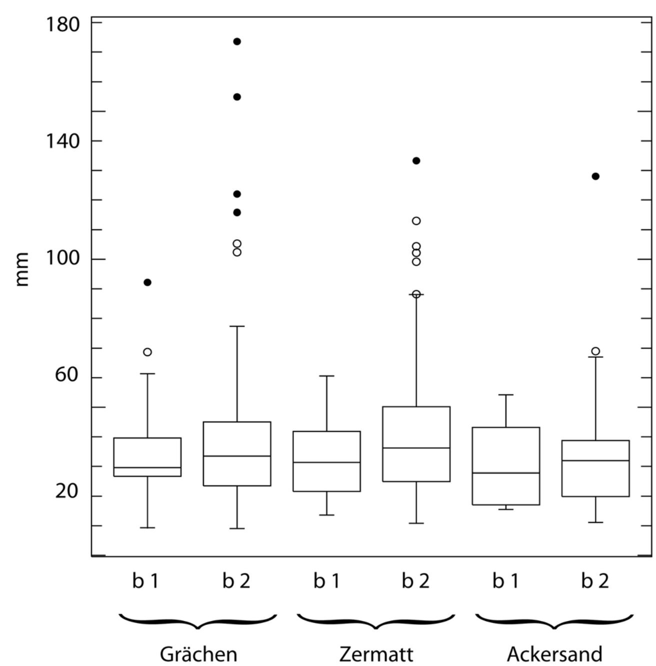

Figure 7. Boxplots for the total amount of rainfall that triggered debris flows subdivided by single-torrent and multitorrent debris flows (b1 = 1 torrent reacting, b2 ≥ 1 torrent reacting).

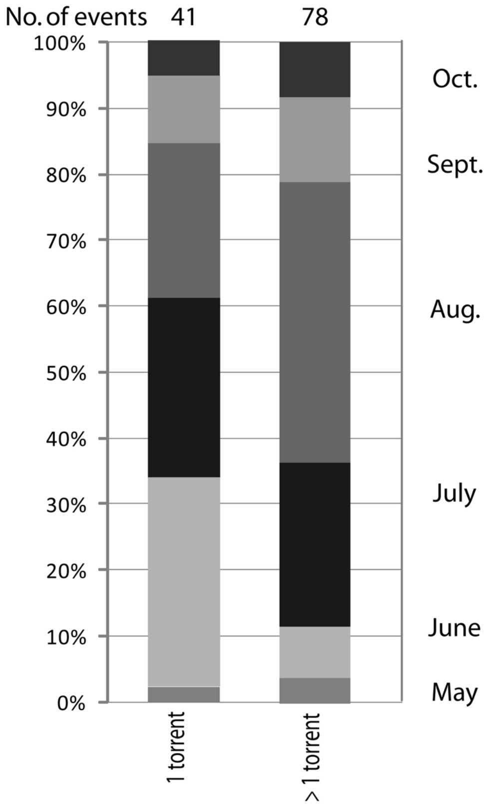

Figure 8. Differences in the temporal occurrence of debris flows for single-torrent and multitorrent debris flows. Total number of debris flows per category is given on top of the bars. Debris flows in single torrents are more common early in the debris-flow season as compared to the late summer months when more widespread debris-flow activity seems to dominate.

century when debris flows apparently were not triggered in May and October. *Stoffel et al.* [2008] observe a similar shift in the seasonality of debris flows in a high-alpine catchment in the Swiss Alps, but only for late season debris flows. We speculate that these shifts reflect impacts of climate change at high-elevation sites, which has reduced the duration of snow cover, promoted earlier rainstorms in spring and later in fall, and have enhanced active-layer thawing of the permafrost 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 of the frozen ground in the 20th century, and the lower permafrost limit has been estimated to have risen vertically by about 1 m yr^{-1} [*Harris et al.*, 2003] since the 1850 s.

[23] The assessment of rainfall totals that triggered debris flows is restricted by the absence of rain gauges in the debris-flow source areas, the coarse resolution of the precipitation record (24 h), and by the fact that the exact moment of triggering within a rainstorm is unknown. Nevertheless, this study provides valuable insights into how debris-flow occurrences depend on rainstorms and how rainfall totals leading to the formation of debris flows may change during the season. Our data show that storms with rainfall totals <20 mm might be enough to trigger a debris flow in May–June, and that greater rainfalls (>25 mm) are needed to trigger debris flows in September–October. These differences in seasonal rainfall values can be explained by the influence of early season snowmelt, which adds additional water to the system and therefore favors the formation of debris flows even at low rainfall totals. This was the case of the May 2011 Dorfbach debris flow which occurred when as little as 16 mm of rainfall was recorded by a rain gauge recently installed in its source area (C. Graf, personal communication, 2011). In addition to snowmelt, the presence of ice with the source sediments (and a thin active layer) will likely result in concentrated runoff in the permafrost bodies [*Krainer and Mostler*, 2002] and thereby facilitate the formation of debris flows. The low rainfall-threshold totals in July–August are reflective of short-duration (minutes to hours), but high intensity, thunderstorms which are only poorly represented in daily resolved precipitation records. The large threshold precipitation totals recorded during late-season debris flows (September–October) are the result of low intensity, but long-duration rainstorms in these months. The higher thresholds observed in September–October may also reflect thicker active layers in the permafrost bodies at the end of the summer [*Åkerman and Johansson*, 2008;

Table 4. Minimum Rainfall Thresholds for the Triggering of Debris Flows

		Grächen				Zermatt				Ackersand			
Duration	Months	mm	mm/ day	Norm.[a]	N	mm	mm/ day	Norm.[a]	N	mm	mm/ day	Norm.[a]	N
all	all	18	13	0.23	112	19	14	0.23	93	16	11	0.23	42
1 day	all	14	14	0.25	62	15	15	0.24	49	15	15	0.31	20
2 day	all	26	13	0.23	36	27	14	0.20	29	18	9	0.22	16
3 day	all	38	13	0.21	14	48	16	0.24	15	36	12	0.25	6
all	May–June	22	14	0.25	23	20	15	0.23	20	18	14	0.28	12
1 day	May–June	18	18	0.31	14	16	16	0.25	12	17	17	0.34	6
2 day	May–June	27	13	0.23	6	23	11	0.17	4	31	16	0.32	3
3 day	May–June	50	17	0.29	3	49	16	0.25	4	40	13	0.27	3
all	July–Aug	17	12	0.21	69	16	14	0.23	53	15	11	0.23	23
1 day	July–Aug	14	14	0.24	41	14	14	0.24	31	12	12	0.25	11
2 day	July–Aug	26	13	0.23	24	27	13	0.20	18	20	10	0.23	11
3 day	July–Aug	25	8	0.14	4	50	17	0.25	4	33	11	0.23	1
all	Sept–Oct	24	14	0.23	20	23	20	0.32	20	19	12	0.27	7
1 day	Sept–Oct	18	18	0.33	7	22	22	0.38	6	21	21	0.42	3
2 day	Sept–Oct	29	15	0.28	6	39	20	0.30	7	18	9	0.22	2
3 day	Sept–Oct	57	19	0.30	7	46	15	0.24	7	54	18	0.45	2

[a]Normalized totals correspond to the total rainfall divided by the mean monthly rainfall for the month when the debris flow occurred.

Table 5. Percentage of Triggering Rainstorms Over Fixed Thresholds

		Grächen			Zermatt			Ackersand		
	mm	Number of Debris Flows	Number Triggering	Triggering (%)	Number of Debris Flows	Number Triggering	Triggering (%)	Number of Debris Flows	Number Triggering	Triggering (%)
1 day	10	1038	106	10	881	91	10	240	40	17
	20	301	87	29	242	71	29	84	27	32
	30	106	38	36	99	38	38	32	13	41
	40	45	22	49	38	17	45	10	3	30
	50	21	10	48	15	6	40	7	2	29
2 day	20	464	98	21	409	82	20	111	33	30
	30	192	64	33	183	60	33	59	18	31
	40	47	16	34	75	28	37	29	10	34
	50	47	19	40	32	17	53	14	5	36
3 day	20	548	98	18	489	87	18	137	36	26
	30	259	74	29	249	67	27	77	25	32
	40	133	43	32	118	43	36	36	12	33
	50	75	22	29	58	22	38	22	6	27

Wright et al., 2009] allowing for more water to be absorbed by the landscape without producing a debris flow.

[24] Due to the coarse resolution of the precipitation data, common intensity-duration relationships are not presented here, but minimum thresholds are provided in order to provide an estimate of rainfall needed to trigger debris flows. As we have shown, debris flows can be triggered from high-elevation sites in the Zermatt valley under rainfalls <20 mm/day. These values are well below the rainfall threshold proposed in supra-regional studies that incorporate data from various geological and geomorphological settings [*Caine*, 1980; *Guzzetti et al.*, 2008], but are concordant with data from Spitsbergen [*Larsson*, 1982; *Rapp*, 1960] where comparably low rainfall thresholds have been reported for debris flows originating from permafrost bodies.

[25] A maximum rainfall threshold has been used by some to indicate the threshold above which each rainfall triggers debris flows [*Glade*, 1998]. In our study, the percentage of catchments responsive to a fixed rainfall total never exceeded 50%, and a definition of a maximum threshold was not therefore possible. Based on our data, however, there is reason to believe that the risk of a debris flow increases considerably as soon as rainfall exceeds 20 mm in one day, 30 mm in two days or 40 mm in three days (Table 5). The absence of a maximum threshold in our data set might be due partly to exclusion of rainfalls associated with a temperature ≤5°C (measured at 1600 m a.s.l.). Runoff will be limited in these cases as snowfall is likely in the upper catchments. Our data show that rainfall totals, storm durations, and temperature are significantly higher during debris-flow triggering storms than non-triggering storms (Table 6). Our data further show that higher temperature is significantly correlated with debris-flow occurrence. Higher temperature leads to rainfall instead of snowfall even in the highest parts of the catchment, and thus more contributing runoff area during warm rainstorms. In addition, higher temperatures allow for more humidity to be transported in the atmosphere which may result in higher rainfall totals.

[26] Dendrogeomorphic methods do not normally allow identification of repeated debris flows in the same torrent within the same year, and this can potentially affect the thresholds we have defined. On the basis of the intraannual dating of the tree ring damage, the first debris flow can be dated accurately, but this is not necessarily the case for additional debris flows within the same year [*Kogelnig-Mayer et al.*, 2011]. As a consequence, if several threshold rainfalls occur within a short period of time, only one of them will be identified as having triggered a debris flow.

[27] Antecedent rainfall and soil moisture conditions have been reported to considerably affect debris-flows and shallow landslide occurrence [*Corominas and Moya*, 1999; *Glade et al.*, 2000; *Wieczorek*, 1987]. Antecedent moisture plays a crucial role in forested areas and in catchments with thick soils [*Jakob and Weatherly*, 2003; *Johnson and Sitar*,

Table 6. Comparison of Variables for Triggering and Non-triggering Rainstorms[a]

	Mean	STDEV	p t-test	p Mann-Whitney
Total rainfall (mm)			***0.042***	0.053
Triggering	44.9	32.1		
Non-triggering	32.4	13.7		
Storm duration (h)			***0.037***	0.147
Triggering	25.5	15.6		
Non-triggering	19.1	7.3		
Average rainfall intensity (mm/h)			0.824	0.98
Triggering	1.8	0.6		
Non-triggering	1.8	0.6		
Maximum 60 min intensity (mm/h)			0.194	0.143
Triggering	6.4	1.8		
Non-triggering	5.7	1.8		
48 h antecedent rainfall (mm)			0.359	0.675
Triggering	7.6	8.8		
Non-triggering	5.7	6.9		
5 day antecedent rainfall (mm)			0.212	0.427
Triggering	12.5	11.5		
Non-triggering	9.2	8.3		
10 day antecedent rainfall (mm)			0.914	0.713
Triggering	23.3	14.6		
Non-triggering	23.8	19.7		
15 day antecedent rainfall (mm)			0.953	0.902
Triggering	35.8	26.5		
Non-triggering	35.4	26.5		
30 day antecedent rainfall (mm)			0.654	0.606
Triggering	60.6	30.7		
Non-triggering	64.6	32.8		
Temperature (°C)			***0.005***	***0.003***
Triggering	9.9	2.2		
Non-triggering	8.1	2.3		

[a]Bold italics represent statistically significant values (95% level).

1989], but is less important or even negligible in regions without a soil cover or having highly permeable shallow soils [*Brand*, 1995]. In the Zermatt valley, antecedent rainfall 5, 10, 15, and 30 days prior to a debris flow did not have any statistically significant influence on triggering debris flows. The absence of soil and the coarse grain-size distribution of sediment in the source areas of the debris-flow torrents results in a very limited capacity for storing water, and instead promotes rapid runoff. *Coe et al.* [2008] found that high antecedent moisture levels are not a prerequisite for the initiation of debris flows in periglacial environments, because runoff starts immediately and sediment along the channel becomes quickly saturated.

6. Conclusion

[28] The reconstruction of past debris flows from periglacial environments in the Zermatt Valley and their hydrometeorological triggers indicate that most debris flows occur in July and August, often related to local thunderstorms that deliver as little as 12–14 mm of rainfall in 1 day. Rainfall totals and storm durations that trigger debris flows increase in September and October when persistent (>48 h) advective rainstorms with lower intensities occur. Debris flows in May and June are generally triggered by lower rainfall totals than those in September and October because snowmelt contributes to catchment runoff and thus facilitates mass movement. The general increase of mean and maximum temperatures in the Swiss Alps since the early 20th century has resulted in an expansion of the debris-flow season. Whereas no debris flows were recorded in May and October in the last third of the 19th century, this study shows that, since 1972, 6% and 11% of the seasonal debris flows have been triggered in May and October, respectively.

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