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Hydrometeorological triggers of debris flows derived from historical archives and tree-ring data: Insights from the Swiss National Park

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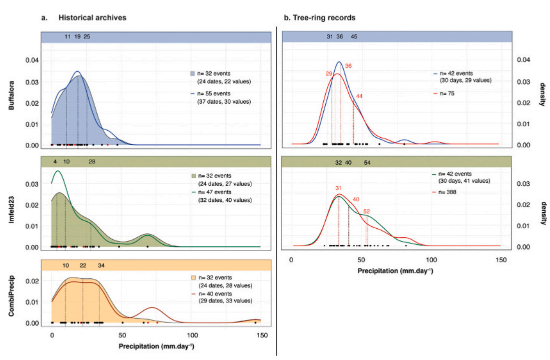
HIGHLIGHTS

- We present a very dense dataset of precisely dated debris flows in small catchments and interpret triggers
- Climate station data have a limited potential to capture small-scale convective precipitation triggering debris flows
- Datasets combining radar and station data are promising for debris-flow triggering analyses but only exist since 2005.
- Debris flows only occasionally occur on the day with the highest daily summer rainfall sums
- Dendrogeomorphic reconstructions do not often have the resolution needed to analyze hydrometeorological triggers

GRAPHICAL ABSTRACT



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ABSTRACT

Data on past debris flows is normally scarce and biased towards large events or catchments close to settlements. Reconstructing past process activity with dendrogeomorphic approaches can help develop unbiased and spatially comprehensive timeseries, typically at annual resolution. Likewise, hydrometeorological data are often limited by low spatial or temporal resolutions, especially as one goes back in time. In the Swiss National Park (Swiss Alps), we rely on a comprehensive dataset of precisely dated debris flows covering the last >35 years and on annually-dated dendrogeomorphic timeseries of past activity at some of these sites. The completeness of records allows evaluation of different hydrometeorological datasets to assess triggers of debris flows: (i) a highly resolved, spatially explicit (1 × 1 km, hourly records) dataset extending back to 2005; (ii) daily-resolved station records available since 1917; and (iii) spatially resolved (1 × 1 km) daily temperature and precipitation fields

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reconstructed back to 1763. All datasets have some skills to capture debris-flow triggering storms but also limitations: While the meteorological station lacks spatial resolution and does not capture localized, convective storms well, the highly-resolved, spatially-explicit timeseries remains excessively short for the time being. As for the long-term precipitation fields, the dataset has limited skills in capturing localized, convective precipitation. We also show that debris flows only rarely occurred on the day for which maximum one-day summer rainfall was recorded. This has strong implications for the identification of hydrometeorological triggers in tree-ring studies in which reconstructed debris flows are available at annual resolution and the detection of triggering is typically based on maximum precipitation sums of a given debris-flow season. Statistical assessment of possible triggers will lead to spurious correlations with such an approach and wrong results. Dendrogeomorphic studies should refrain from venturing into triggering analysis based on annually resolved debris-flow timeseries, unless dating is possible at intra-seasonal or monthly resolutions.

1. Introduction

Debris flows are fast-moving mixtures of unsorted sediment and water that flow down steep channels in mountain regions (Jakob et al., 2024). As they regularly put people, settlements and infrastructures at risk (Mani et al., 2023; Jacquemart et al., 2024), it has become increasingly crucial to understand their frequency, magnitude and spatial patterns as well as the hydrometeorological conditions that typically lead to their occurrence. Short-duration, high-intensity storms, oftentimes linked to convective processes, are a key driver of debris-flow activity in alpine regions (Kaitna et al., 2024). The intense rainfall involved in these storms will exceed the infiltration capacity of soils and lead to surface runoff. This process can ultimately result in debris flows, provided that the site hit by the storm has sufficient amounts of loose sediments that can readily be entrained (Jakob, 2022; Stoffel et al., 2024a). Stratiform precipitation, typically associated with advective processes, is another potential trigger of debris flows in which antecedent rainfall can add to increase soil moisture further and ultimately lead to saturation (Moser and Hohensinn, 1983; Stoffel et al., 2011). In addition, snowmelt or rain-on-snow events have been reported to play a significant role in triggering debris flows by adding additional moisture to an already wetted system (Cardinali et al., 2000; Beniston and Stoffel, 2016; Morán-Tejeda et al., 2016; Fehlmann et al., 2019). Finally, the sudden emptying of glacier lakes –also known as glacier lake outburst floods (GLOF) – has been reported as a cause for often catastrophic debris flows (Zaginaev et al., 2016, 2019; Zheng et al., 2021: Colavitto et al., 2024; Gorsic et al., 2025).

Modeling approaches have considered multiple hydrometeorological variables in the past to predict the occurrence of debris flows at the regional scale, but results often remained elusive (Prenner et al., 2018; Kaitna et al., 2023). This is in part related to the fact that assessments of hydrometeorological conditions remain challenging at the scale of a given catchment. On the other hand, the difficulty lies in the definition of rainfall intensity-duration relationships of debris flows for a given catchment or region (Mostbauer et al., 2018) because of the often rare and irregular occurrence of individual debris flows (Berger et al., 2011; Rengers et al., 2020; Ballesteros-Cánovas et al., 2024; de Haas et al., 2024), a virtually complete lack of recording meteorological stations in the source areas of debris-flow catchments where most precipitation falls on rocky headwaters contributing immediately to runoff (Bernard and Gregoretti, 2021; Marchi et al., 2021; Ponziani et al., 2023; Bernard et al., 2025), and/or the localized occurrence of downpours (Feldmann et al., 2021, 2023; Ghasemifard et al., 2024). These limitations are exacerbated as one goes back in time: meteorological records become scarcer, fewer data exist on debris flows and methods for their reconstruction may be limited in terms of temporal resolution (i.e. often annual, at best; Schneuwly-Bollschweiler et al., 2013b). Historical archives, by contrast, can yield fairly detailed information on past mass movements, especially in terms of timing, but they tend to overrepresent major events close to human settlements or severe damage to infrastructure while ignoring the more frequent, yet smaller debris flows (Jakob, 2005).

In regions with no or very limited data on past debris-flow activity, evidence of past events has repeatedly been generated from growth-ring records of trees impacted by past debris flows. The technique, commonly referred to as dendrogeomorphology (Alestalo, 1971; Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014), allows the construction of debris-flow histories, often covering several centuries (Stoffel and Beniston, 2006; Stoffel et al., 2008; Qie et al., 2024), and can yield detailed insights into the frequency (Bollschweiler and Stoffel, 2010; Procter et al., 2011; Schraml et al., 2015), magnitude (Stoffel, 2010; Schraml et al., 2013; Ballesteros-Cánovas et al., 2024) or spatial extent (Bollschweiler et al., 2008; Stoffel et al., 2008; Procter et al., 2012; Schneuwly-Bollschweiler et al., 2013a) of past events. Under certain circumstances, a dating of past mass-movement damage in trees can be achieved an intra-annual, or seasonal, dating resolution (Stoffel et al., 2006; Stoffel et al., 2006, 2024b). This is the case when research is based on scars or the occurrence of tangential rows of traumatic resin ducts (TRD) in certain conifer species (Stoffel, 2008, 2010; Schneuwly et al., 2009a, 2009b), and provided that the position of damage can be assessed with precision within the growth ring (Bollschweiler et al., 2008; Arbellay et al., 2010a, 2010b).

At many instances, dendrogeomorphic reconstructions of debris-flow activity have also been employed to assess hydrometeorological triggers of past process activity (see Tichavský, 2023 for a recent review). Yet, the debris-flow histories used for the assessment of hydrometeorological triggers were oftentimes dated to a given calendar year, whereas meteorological time series were of daily, and sometimes even hourly, resolution. As a result of the huge difference in temporal resolution between datasets, many past studies relied on mere descriptions of high (or even the highest) daily rainfall departures occurring over some period of a given year – usually summer (June to August, or JJA; e.g., Germain et al., 2018) – during which debris flows typically occur in the inner part of the European Alps and in other regions with continental precipitation regimes. Such approaches often relied on the assumption that the most intense daily JJA precipitation event *(P_{maxJJA})* recorded by the nearest rain gauge would have been the trigger of the reconstructed debris flow. Another approach that is sometimes used relies on statistical differences in rainfall data in years with and years without debris-flow activity (Tichavský et al., 2017; Šilhán, 2023). Whereas these approaches may, at best, provide some preliminary insights into factors that could have played a role in triggering past debris flows, they suffer from multiple limitations: First and foremost, debris flows are often triggered by very localized convective storms occurring several (dozens of) kilometers away from the recording weather station. One can therefore question whether the rainfall recorded by a rain gauge is representative for the processes in the release area of debris flows (Simoni et al., 2020). In addition, the small number of years for which debris flows are reconstructed typically prevents solid interpretations and the use of statistical approaches (Tichavský, 2023). A further limitation is the unknown seasonality (and even less so the specific date) of past debris flows; as a result, the commonly considered maximum precipitation sums recorded over one or multiple days in any given year will not therefore reflect the hydrometeorological episode by which the debris flow was triggered in reality (Procter et al., 2011).

In view of these uncertainties and the incomplete understanding of past hydrometeorological triggers of debris flows, this paper focuses on 9 debris-flow catchments within or next to the Swiss National Park (canton of Grisons). In these unmanaged systems, debris-flow activity has been recorded systematically for the last >35 years. We complement the historical dataset with dendrogeomorphic reconstructions in four of these catchments. For the analysis of triggers, we rely on three different datasets: in fact, local climate station records, reconstructed precipitation fields as well as a coupling of radar with on-the-ground rain gauge data (CombiPrecip) are used here to investigate the potential and to explore limitations of hydrometeorological trigger analyses relying on dendrogeomorphic and precipitation timeseries with different spatial and temporal resolutions. The objectives of this study thus were to (i) construct a regional chronology of annual debris-flow activity in the Swiss National Park from historical archives (since 1989) and dendrogeomorphic reconstructions (since 1917), (ii) explore possible triggers of past debris flows with daily climate station data (1917–2022), daily reconstructed temperature and precipitation fields (1763–2020) and daily CombiPrecip data (2005–2022), and to (iii) make recommendations for future research linking archival and/or dendrogeomorphic time series of debris flows with meteorological data. The dendrogeomorphic reconstruction was restricted to 106 years to allow comparison of the tree-ring derived debris flows with the Buffalora climate station.

2. Study area

This study relies on nine small torrential catchments, of which eight are in the Swiss National Park (SNP), canton of Grisons (Swiss Alps; Fig. 1) and one located close to the border of the SNP in Val Müstair. Catchments range in size from 0.52 to 5.34 km^2 (Table 1), with a mean catchment size of 2.07 km^2, and are all tributaries to the Ova dal Fuorn, except for the Multetta catchment which flows into Il Rom. The Ova dal Fuorn tributaries are found between Pass dal Fuorn (46°38′23.21”N, 10°17′31.72″E; 2148 m asl) and Punt La Drossa (46°39′14.36”N, 10°11′20.68″E; 1712 m asl) from South to North, and between Munt la Schera (46°38′42.55”N, 10°12′38.82″E; 2586 m asl) and Piz Foraz (46°41′26.37”N, 10°16′36.49″E; 3092 m asl) from West to East. The Multetta catchment (Fig. 1) is located next to the SNP but was included in this study due to the existence of a 456-year-long chronology of debris-flow events derived from tree-ring data (Qie et al., 2024). The catchments selected for analysis have elevations ranging from 1751 to 3092 m asl and average slopes of 31.5 ± 5°. Table 1 provides a summary of the main characteristics of these catchments.

Debris flows in the study area originate from abundant scree slopes (Fig. 2) formed by Permian to Triassic metasedimentary rocks (i.e. dolomites, limestones, and evaporite lithologies) of the S-charl–Sesvenna nappe (Zimmermann et al., 2014). Whereas freeze-thaw cycles play a critical role in feeding the scree slopes, the slopes per se are located below the limit of locally occurring continuous permafrost (Manchado et al., 2024). Slope surfaces mainly consist of rendzina soils with high permeability and low available water capacity (Bigler and Rigling, 2013). Forests are abundant in the SNP and cover 28 % of its surface. Three-quarters of the forest surfaces are formed by Swiss mountain pine (*Pinus mugo* ssp. *rotundata*) and dwarf mountain pine (*Pinus mugo* ssp. *mugo*), and only 11 % are formed by European larch (*Larix decidua* Mill.) (Zoller, 1995). The understory is sparse and primarily composed of

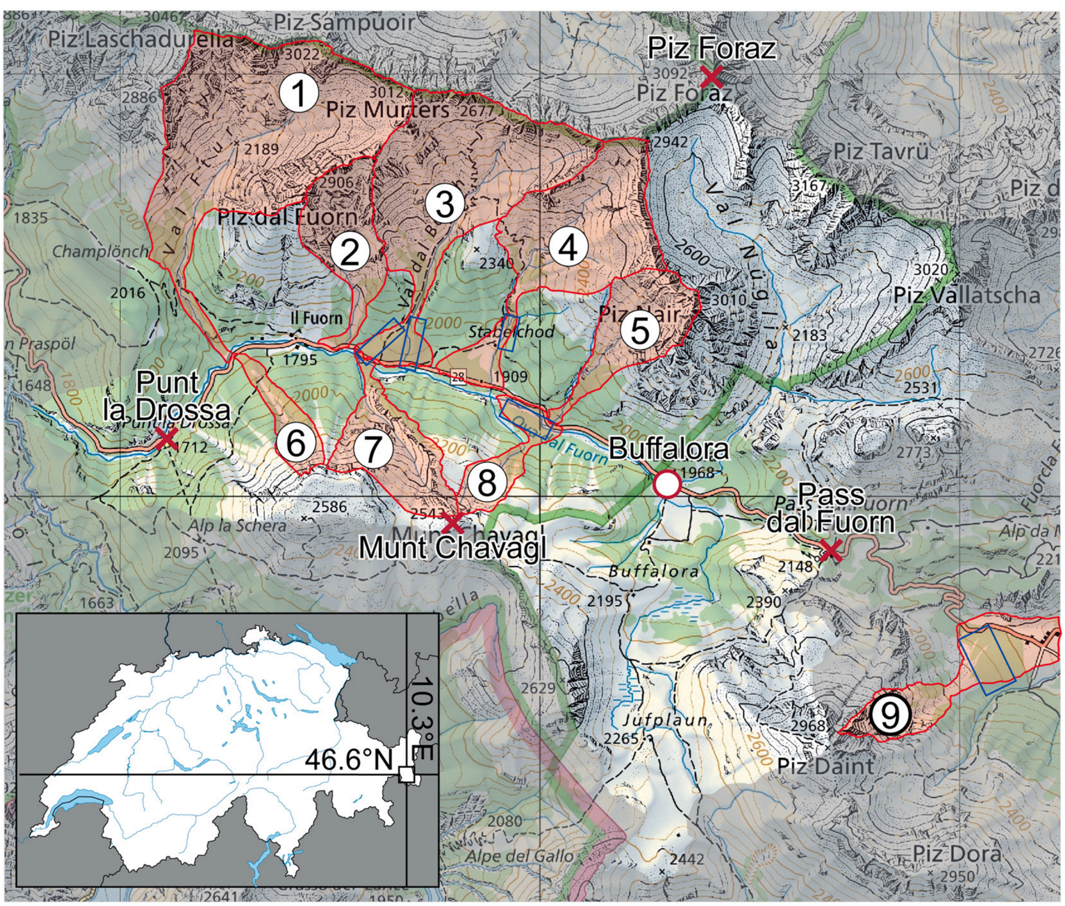

Fig. 1. (a) Overview and (b) characteristics of the nine debris-flow catchments in the canton of Grisons (Eastern Swiss Alps) analyzed in this study. Catchments 1–8 are located within the Swiss National Park, catchment 9 is located outside the park boundaries. Whereas past debris-flow data exist for all catchments in abundant historical archives, we also have information on reconstructed debris flows for four sites (blue rectangles) for which dendrogeomorphic analyses have been realized. The red-white dot demarks the position of the Buffalora climate station.

Table 1
Centroid coordinates and characteristics of the nine debris-flow catchments considered in this study.

Region	Site	N° Site	Coordinates of the catchment (centroid; long / lat)	Area (km^2)	Elevation (m asl) (Ø, min, max)	Mean slope (°)	Aspect
Ova dal Fuorn	Val Ftur	1	46°41′09.7533″N, 10°12′19.5836″E	5.34	2500 (1751; 3042)	34.5	NW
	Val dal Fuorn	2	46°40′29.6052″N, 10°13′05.8278″E	1.30	2365 (1805; 2905)	38.4	SW
	Val dal Botsch	3	46°40′46.4934″N, 10°14′08.0578″E	3.94	2399 (1835; 3011)	30.7	SW
	Val da Stabelchod	4	46°40′23.3619″N, 10°15′09.6994″E	2.85	2389 (1872; 2942)	28.6	S
	Val Naira	5	46°39′49.6944″N, 10°15′44.0100″E	1.27	2462 (1911; 3007)	35.1	NE
	Lavinar La Drossa	6	46°39′17.7549″N, 10°12′29.1387″E	0.52	2116 (1768; 2510)	30.0	N
	Val Chavagl	7	46°39′04.0378″N, 10°13′27.5849″E	1.32	2208 (1842; 2543)	34.9	S
	Val Brüna	8	46°38′59.9176″N, 10°14′28.7515″E	0.64	2139 (1893; 2543)	26.5	SW
Val Müstair	Multetta	9	46°37′29.0174″N, 10°18′37.3411″E	1.46	2075 (1744; 2966)	23.9	E

Buffalora meteo station: 46°38′54.30’’N, 10°16′01.97″E.

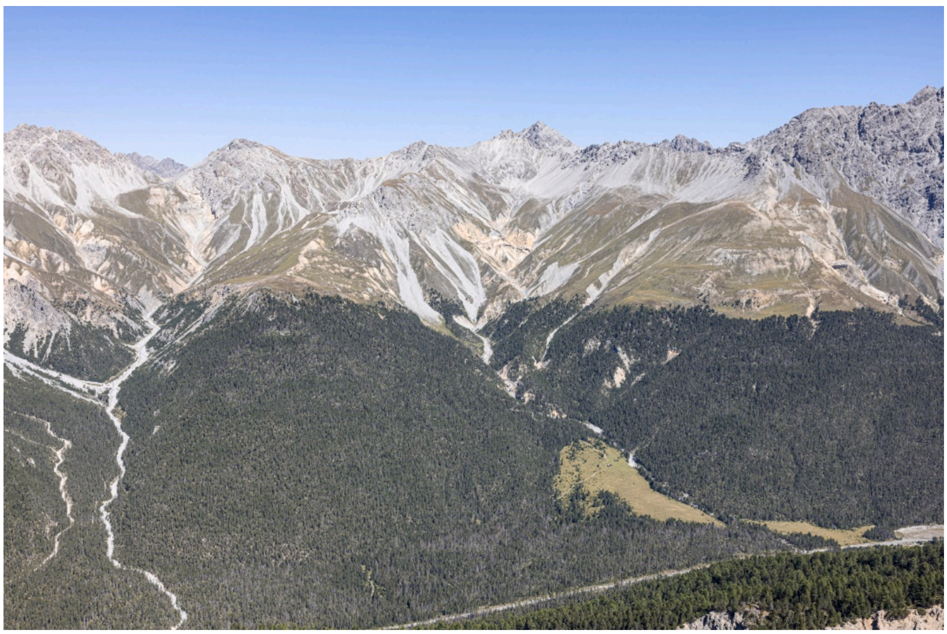

Fig. 2. The Swiss National Park (Grisons, Eastern Swiss Alps) is characterized by a multitude of debris-flow catchments and frequent process activity: Overview picture taken from Munt la Schera showing (from left to right) the central portion of the Val dal Botsch, the Val Stabelchod and part of the headwaters of the Val Naira catchments (© Tamara Estermann, SNP, 2023).

herbaceous species.

The Buffalora climate station (1971 m asl; Fig. 1) is located between the Multetta cone and the eight catchments within the SNP. Over the reference period (1991–2020), the station recorded a mean annual total precipitation sum of 936 mm and a mean annual air temperature of 1.1 °C. Whereas a vast majority of precipitation is recorded between May and November (712 mm), primarily in the form of rain, summer (JJA) is the wettest season with 358 mm. Summer rainfall primarily occurs during storms. According to the station records, MeteoSwiss (2024) provides daily precipitation sums for return periods of 10, 100, and 300 years at 73.9 mm (95 % confidence interval CI: 65.4–88 mm), 137.3 mm (CI: 101.6–211.7 mm), and 186.4 mm (CI 123.8–329.3 mm), respectively, based on values recorded over the standard period 1961–2020.

3. Data and methods

3.1. Observed debris-flow events

The SNP has a strict protection status but also a clear research mandate. For this reason, the SNP services started to invest substantial efforts to meticulously document natural events occurring in the park in 1987 (Hauenstein and Haller, 2008). All events are carefully recorded and geo-localized by park rangers since 1988 and have, over time, resulted in a unique and comprehensive record of specific occurrences related to flora and fauna, but also to larger-scale disturbances such as snow avalanches, landslides, rockfall or debris flows. Each event is characterized by the date of observation, the estimated time of occurrence, its precise location, its nature, and the prevailing weather conditions at the time of the event. In addition to the SNP database, we consulted the natural hazard database from the canton of Grisons *(Amt für Wald und Naturgefahren)* for the Multetta fan. By contrast to the SNP dataset, the natural hazard database only contains a few records on past debris flows and is much less complete.

3.2. Sampling strategy and detection of past debris-flow events in tree-ring series

The dendrogeomorphic dataset used in this study combines debris-flow reconstructions from Multetta (Qie et al., 2024) with three new chronologies developed for the Val da Stabelchod (Schlechten, 2020), Val Brüna, and Val dal Botsch catchments. The study relies on 1382 increment cores and 39 cross-sections sampled from 1062 *P. mugo* trees. Collection of tree-ring samples followed the guidelines of Stoffel and Corona (2014). For each of the debris-flow paths and cones analyzed, we sampled both old (often >250 yrs) and relatively younger (>100 yrs) trees (Šilhán and Stoffel, 2015), regularly distributed across the study sites (Schneuwly-Bollschweiler et al., 2013a), with a minimum of 97 trees at Val Stabelchod and a maximum of 476 trees at Multetta (Table 2).

Clear injuries, the adjacent callus tissue (Schneuwly et al., 2009a) as well as compression wood (CW) and sharp growth suppressions (Kogelnig-Mayer et al., 2013) were identified on the samples and cross-dated using the CDendro-CooRecorder 9.8.1 software suite (Maxwell and Larsson, 2021). To ensure proper dating, we employed the local *P. mugo* chronology from Bigler and Rigling (2013) as a reference. Cross-dating quality was assessed with COFECHA (Holmes, 1983). In the present study, and unlike many other investigations relying on samples from conifers, we disregarded the occasional occurrence of resin ducts because *Pinus* frequently forms these conduits but not in the form of tangential rows of traumatic resin ducts that can be found following mechanical disturbance in most other gymnosperm species (Stoffel, 2008; Procter et al., 2011).

We classified the remaining growth disturbances (GDs; Kogelnig-Mayer et al., 2011) according to signal strength into weak (intensity class 1), intermediate (2), and strong (3) reactions. In addition, clearly visible injuries resulting from debris flows were considered intensity class 4. To reconstruct past debris-flow events, we used the four-step procedure proposed by Favillier et al. (2017) and adapted to local conditions by Qie et al. (2024). This procedure untangles potential effects of debris flows on tree growth from disturbance pulses caused by climatic or exogenous factors, such as frost, drought or insect outbreaks. The spatial distribution of disturbed trees of the same event was mapped in a Geographic Information System (GIS) to filter out non-debris flow events in the reconstructions. During this process, we also assigned a confidence level to each reconstructed event (Qie et al., 2024).

3.3. Precipitation data

The precisely dated debris flows in the SNP database and those reconstructed to a given year with dendrogeomorphic approaches were compared to different precipitation products. We use three datasets of differing length and spatio-temporal resolutions. At the border of the SNP, and conveniently located between the catchments analyzed in this paper, MeteoSwiss has been running the Buffalora climate station (1971 m asl; Fig. 1), providing daily precipitation sums continuously since 1917. The station belongs to the automatic measurement network of MeteoSwiss and is equipped and is currently equipped with a heated tipping bucket rain gauge. The station in its current form thus provides measurements at 10-min intervals and is used here for a point rainfall estimate near the ground surface.

Relying on a large suite of climate records from various Swiss stations, Imfeld et al. (2023) reconstructed daily temperature and precipitation fields with a resolution of 1 × 1 km for the national territory since 1763. We refer to this dataset as *Imfeld23* in the following. For analysis, we then used the grid point that was closest to the center of the polygon representing the catchment for which a debris flow was found in the historical database and the dendrogeomorphic reconstruction in GIS.

The last product used in this study is known as the CombiPrecip precipitation dataset (Germann et al., 2022) and is the best estimate of ground-level precipitation distribution derived from a combination of radar data and information from automated rain gauges at land-based weather stations, again at a resolution of 1 × 1 km (same grids as for *Imfeld23*). The CombiPrecip data is provided in the form of hourly precipitation amounts at ground level and is available since 2005.

3.4. Analysis of debris flow triggers

For the Buffalora climate station and the *Imfeld23* datasets, daily precipitation sums are directly available. In the case of the CombiPrecip datasets, we aggregated hourly precipitation sums into daily sums for reasons of comparability between the three datasets. In a next step, relying on events recorded in the SNP debris-flow database and for which the date of debris-flow occurrence is known, we assessed daily precipitation sums for the day of the event *(n)* and the day preceding the event *(n-1)* in the three datasets, hereafter referred to as P_{event}. The latter was considered as debris flows may occur early on day *n* because of precipitation that fell primarily on day *n-1*. Rather than summing precipitation of the two days, we considered the day recording larger precipitation sums.

In the case of the debris-flow events reconstructed from dendrogeomorphic analysis, the intra-annual or intra-seasonal timing of events remains unknown. To be consonant with literature in the field (Tichavský, 2023 and references therein), we used the maximum daily JJA precipitation sum of the year to which the debris flow was dated and refer to this data as P_{maxJJA} hereafter.

4. Results

4.1. Debris flow series from observations and reconstructions

Between 1989 and 2022, a total of 64 individual debris flows were documented in the SNP (58) and cantonal (6) databases in the 9 catchments analyzed. A vast majority of debris flows (i.e. 27 each) occurred in July and August, only 1 in May, 5 in June and 4 in September. Due to the altitude of the release areas and the snow conditions at these sites, no debris flows were documented during the remaining months. No debris flows were observed between 1990 and 1996 as well as in 2009, 2011, 2012 and 2013. By contrast, 42 debris flows were observed between 2014 and 2022. Fig. 3 provides an overview of the debris-flow activity in the different catchments over time as provided by archival timeseries.

Based on the descriptions in the historical database, some 33 debris flows occurred during or immediately after heavy yet localized storms, whereas 8 debris flows occurred as a result of stratiform precipitation. For the remaining events ($n = 23$), the database does not provide any information on the triggering factor. Several storms triggered debris flows in multiple catchments, namely on August 5–6, 1999 (4 debris flows), July 25–26, 2014 (4), August 13, 2014 (4), and July 20–21, 2022 (5). As a result, the 64 debris flows correspond to 43 different event dates.

Table 2
Overview of trees sampled (sample depth) in the four catchments analyzed with dendrogeomorphic approaches and relative frequency of growth disturbances observed. CT = callus tissue.

Catchment	Period	Sampled trees	Injuries and CT	Compression wood			Growth suppression			Total
				Strong	Medium	Weak	Strong	Medium	Weak	
Val Brüna	1728–2021	341	26	39	42	34	31	246	333	751
Val dal Botsch	1738–2022	148	23	21	22	19	3	127	294	509
Val da Stabelchod	1926–2010	97	10	3	7	–	36	20	–	76
Multetta	1600–2020	476	118	54	32	–	216	997	–	1417
TOTAL		1062	177	117	103	53	286	1390	627	2753

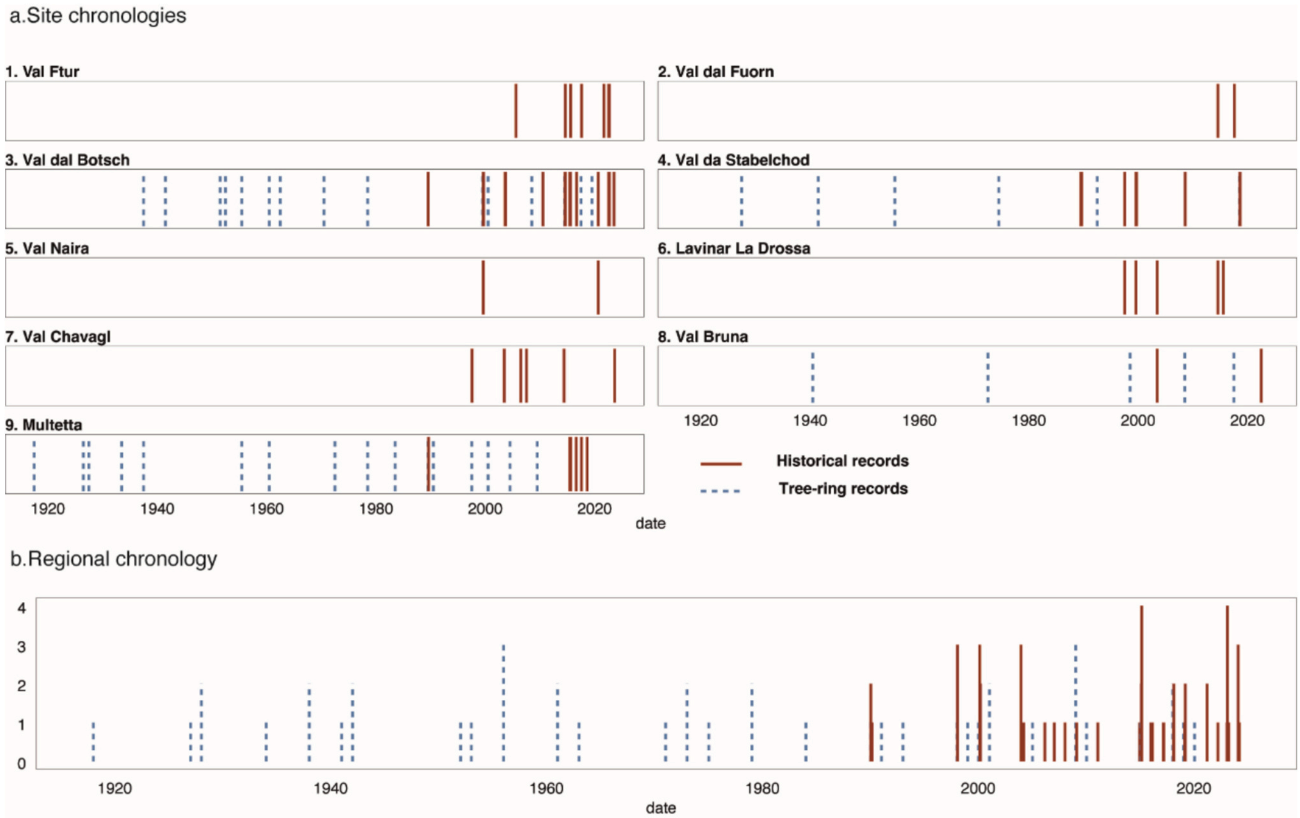

Fig. 3. (a) Site and (b) regional debris-flow chronologies of the nine catchments from 1917 to 2022 based on historical archives (red lined) and reconstructed activity based on tree-ring data (blue dotted lines). The study relies on 64 historical events from archives and 42 debris flows as reconstructed with dendrogeomorphic approaches.

4.2. Debris flow chronology derived from tree-ring records

Analysis of growth disturbances in the 1382 increment cores and 39 cross-sections selected from 1062 *P. mugo* trees growing on the Multetta, Val da Stabelchod, Val Brüna and Val dal Botsch debris-flow cones yielded data on 42 debris flows in 29 different years between 1917 and 2022 (Fig. 3). The actual reconstruction of past debris flows relied primarily on the occurrence of growth suppression and compression wood, and – to a minor degree – to the occurrence of scars. Table 2 provides an overview of the different growth disturbances found in the tree-ring records. Of these events, only 17 occurred in 13 years between 1989 and 2022, that is during the period for which the SNP archival data is also available. The debris flows dated to 1989 (Multetta), 2014 (Val dal Botsch) and 2018 (Val da Stabelchod) correspond to events that are also present in the historical database.

4.3. Triggers of debris flows documented in archives

Based on the dates of past debris flows as provided by the historical database, we analyzed P_{event} recorded (i) at the Buffalora climate station and (ii) in the *Imfeld23* precipitation fields closest to the center of the catchment in which the debris flow occurred. Analysis included P_{event} recorded on the day of the debris flow *(n)* or the day preceding the event *(n-1)*. In addition, we also investigated the CombiPrecip dataset, available since 2005, in which radar data was combined with station records to provide a realistic estimate of precipitation on the ground.

Fig. 4a illustrates the distribution of P_{event} provided for the 32 historical debris flows that occurred between 2005 and 2020, i.e. during the period for which we have climate station, *Imfeld23* and CombiPrecip records. Based on these products, we obtain a median P_{event} at days *n* and *n–1* of 19 (with an interquartile range of 11–25 mm; Buffalora climate station), 10 (4–28; *Imfeld23*) and 22 (10–34; CombiPrecip) mm d^{-1}. The largest P_{event} sums triggering debris flows during this same period were 47 mm (August 29, 2020) at the Buffalora climate station, 69 mm (August 13, 2014) in the *Imfeld23* precipitation fields and 146 mm in the CombiPrecip dataset (July 5, 2006).

Strong differences sometimes exist when P_{event} is analyzed for a given event in different datasets: By way of examples, the thunderstorm triggering a debris flow in Val Chavagl (see ⑦ in Fig. 1) on July 5, 2006 was heavily underestimated in the *Imfeld23* precipitation field with only 7 mm of rainfall (Fig. 5a), whereas the CombiPrecip dataset captures the thunderstorm cell with a P_{event} = 146 mm (Fig. 5b). The Buffalora climate station, indicated with a circle in Figs. 5a-b, is located *c.* 2.8 km from the source of the debris flow and recorded a total of 36 mm of rainfall during that same event.

The distribution of P_{event} does not change markedly if the time window is extended from 2005 to 2022 for the Buffalora climate station (40 historical debris flows; 15 mm with an interquartile range of 6–24 mm; Fig. 4a) and the CombiPrecip dataset (40; 25 mm, 13–35 mm; Fig. 4a). When considering the full period for which historical debris-flow data as well as the Buffalora climate station records and the *Imfeld23* precipitation fields are available (1989–2020), we obtain median P_{event} sums triggering 47 debris flows at 17 mm (12–24 mm) for the Buffalora climate station and 7 mm (4–24 mm) for the reconstructed *Imfeld23* precipitation fields (Table 3).

4.4. Estimating triggering rainfall sums for debris flows reconstructed from tree-ring data

The dendrogeomorphic reconstructions performed in this study allow dating of past process activity to a given year. Due to the nature of the species used and the absence of resin ducts or information on the

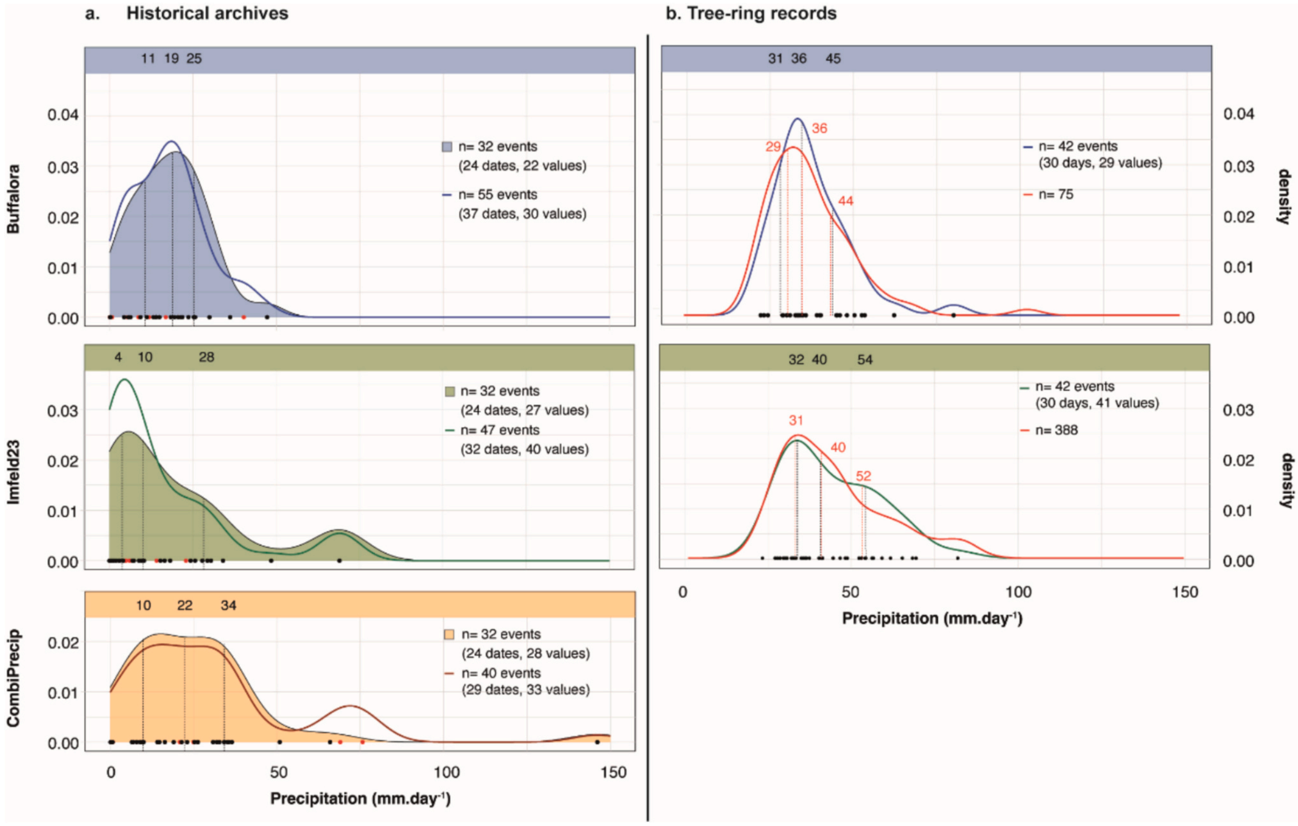

Fig. 4. Overview of rainfall sums recorded by the Buffalora climate station (1917–2022), reconstructed with precipitation fields (Imfeld et al., 2023; 1917–2020) and derived from the CombiPrecip dataset (2005–2020): (a) Precipitation sums (P_{event}) triggering debris flows for which the day of occurrence was known from historical archives. The black dots mark debris flows for which precipitation data exist from all datasets; red dots indicate debris flows for which CombiPrecip data is not available. To test the validity of hydrometeorological triggering analyses as used in dendrogeomorphic studies, we (b) also assessed precipitation sums for debris flows that were reconstructed to a given year with tree-ring records. For these events, we considered the maximum JJA daily rainfall sums (P_{maxJJA}). For the historical archives, (a) the shaded surfaces correspond to the period 2005–2020 for which we have rainfall data from all three products. The blue (1917–2022), green (1917–2020) and red (2005–2022) lines consider the full period for which data is available. In panel (b), analysis relies on P_{maxJJA} of the summer to which a debris-flow was reconstructed (blue and green lines). These maxima are compared to P_{maxJJA} (red lines) in years in which no debris flow was reconstructed.

intra-ring position of injuries, the intra-annual (or intra-seasonal) timing of past debris flows remains unknown. Any identification of possible triggers thus has to be based on some measure of precipitation that occurred in the year to which the debris flow was dated. In line with past work, we considered P_{maxJJA} recorded by the Buffalora climate station and *Imfeld23* precipitation fields.

To test the ability of P_{maxJJA} to provide meaningful results in terms of precipitation sums triggering debris flows, we performed analyses for the period 1989–2020 for which we have both the SNP archival records (Fig. 4a) and debris flows reconstructed to a given year with dendrogeomorphic techniques. The latter yields information on 18 debris flows for the period 1989–2020 and median P_{maxJJA} sums of 36 (34–40 mm) and 54 (46–58) mm for the Buffalora climate station and the *Imfeld23* precipitation fields, respectively (not shown). This means that the values obtained with P_{maxJJA} exceed those found for the historical debris flows for which the day of occurrence and therefore P_{event} was known by 212 % (or 17 vs. 36 mm) and 771 % (or 7 vs. 54 mm), respectively.

When considering the full period covered by dendrogeomorphic reconstructions, the Buffalora climate station records and the *Imfeld23* precipitation fields (i.e. 1917–2020), one can study precipitation sums of storms that assumedly triggered 42 debris flows in 30 different years. As shown in Fig. 4b, analysis suggests almost identical P_{maxJJA} values with 36 mm (31–45 mm) for the Buffalora climate station, but strong differences in the *Imfeld23* dataset where we observe a drop in P_{maxJJA} values from 54 to 40 (32–54) mm (−26 %). Last not least, the distribution of P_{maxJJA} – i.e. the maximum precipitation sums in any given summer (JJA) – does not show any significant difference between event years and non-event years, irrespective of whether the Buffalora climate station records (32 vs. 36 mm day^{-1}) or the *Imfeld23* precipitation fields (40 vs. 39 mm day^{-1}) are considered.

5. Discussion

In the study presented here, we investigated a database consisting of 64 debris flows recorded in a database compiled by the Swiss National Park (SNP) and the state authority in charge of natural hazards in the canton of Grisons. Debris flows in this database have known occurrence dates which allowed us to consult three different climatological timeseries (i.e. Buffalora climate station data, radar data corrected with station records to yield precipitation sums at the ground, as well as reconstructed precipitation fields) to assess absolute and median precipitation sums that were recorded on the days to which the debris flows were attributed in the database. In addition, we reconstructed debris flows with dendrogeomorphic approaches to create a database of 42 events that occurred between 1917 and 2022 and analyzed the maximum daily precipitation sums that were recorded in JJA in these years. The idea of this comparison was to test whether the definition of hydrometeorological triggers – as often used in dendrogeomorphic studies – can withstand a critical assessment and a comparison with recent, more highly resolved timeseries.

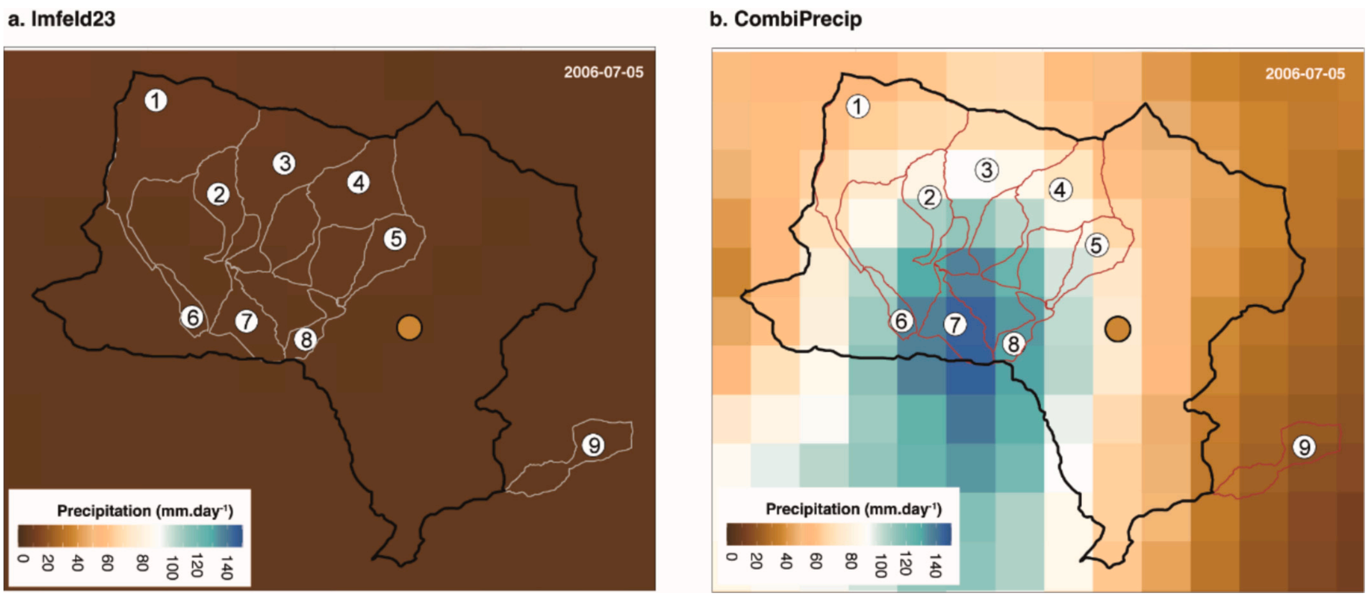

Fig. 5. Comparison of the P_{event} sums obtained by different products for the thunderstorm that triggered a debris flow on July 5, 2006 in Val Chavagl (⑦). The Buffalora climate station is located c. 2.8 km away from the source area of the debris flow and recorded a total of 36 mm of rainfall (orange circle). (a) The reconstructed precipitation field (Imfeld et al., 2023) did not show the thunderstorm adequately with just 7 mm, a limitation that is well known and inherent to reconstructed precipitation fields with often limited skills in representing extremes such as localized thunderstorms. By contrast, (b) the CombiPrecip dataset nicely captures the thunderstorm cell over the Val Chavagl catchment and suggests a rainfall sum of 146 mm during this event.

Table 3
Comparison of precipitation sums obtained only with historical records of debris flows with event dates (1989–2020) vs. those including historical debris flows and those reconstructed with dendrogeomorphic techniques (1917–2020). Precipitation sums were obtained from the Buffalora climate station records and the gridded precipitation fields of Imfeld et al. (2023). The table also shows differences between the precipitation sums recorded on the day of the event (P_{event}) against those obtained if considering the highest summer precipitation episode (P_{maxJJA}) to be the one triggering a debris flow.

Period	*Dataset*	P_{maxJJA} (mm)	P_{event} (mm)	P_{event} / P_{maxJJA} (%)
1989–2020	Buffalora	36 [34–40]	17 [12–24]	+ 112 %
	Imfeld23	54 [46–58]	7 [4–24]	+ 671 %
1917–2020	Buffalora	36 [31–45]	36 [29–44]	+ 0 %
	Imfeld23	40 [32–54]	40 [31–52]	+ 0 %

5.1. Meteorological triggers of debris flows

Debris flows are known to be triggered by different types of precipitation ranging from convective thunderstorms to stratiform precipitation (Borga et al., 2014; Prenner et al., 2019). In addition, intensive snowmelt or rain-on-snow events have been shown to play a significant role in debris-flow initiation (Mostbauer et al., 2018; Stoffel and Corona, 2018). Following the pioneering work of Caine (1980), multiple studies have focused on the definition of critical rainfall characteristics for the initiation of debris flows (e.g., Guzzetti et al., 2008; Berti et al., 2012; Marra et al., 2017), also under future conditions (Stoffel et al., 2011, 2014; Kaitna et al., 2023).

Here, we rely on a very dense database of 64 historical debris-flow records covering a fairly small geographic area (23 km^2) but a period of >30 years (1989–2022). As the sites investigated are (almost exclusively) located in the SNP, debris flows occur in unmanaged catchments and under completely natural conditions. The study also takes stock of a climate station located at relatively “high” altitude (1971 m asl) between the 9 debris-flow catchments (whose mean elevation is 2′421 ± 111 m asl, min: 2′246 m asl [Val Chavagl], max: 2′562 m asl [Val Ftur]), reconstructed precipitation fields (Imfeld et al., 2023) and CombiPrecip, the best estimate of ground-level precipitation distribution derived from a combination of radar data and information from automated rain gauges at land-based weather stations (Panziera et al., 2018; Barton et al., 2020).

The different precipitation datasets yield varying rainfall sums for the different debris flows analyzed. Over the period for which we have the Buffalora climate station, reconstructed *Imfeld23* precipitation field and CombiPrecip data (2005–2020), the median P_{event} triggering a debris flow of which the date of occurrence is known was found to be 19 (with a interquartile range of 11–25 mm), 10 (4–28) and 22 (10–34) mm d^{-1}, respectively.

The Buffalora climate station record is used as a local “ground truth” in the calibration and verification of the reconstructed precipitation fields (Imfeld et al., 2023) and the CombiPrecip dataset – a usual procedure to improve climate fields or remote rainfall sensors such as weather radars (Habib et al., 2001; Upton and Rahimi, 2003). In this study, we consider the rain gauge as a reliable local reference, even if (i) localized storms in the source areas of debris-flow catchments may not be recorded by a climate station due to its location elsewhere in the catchment or (ii) systematic errors are known to occur in ground-based measurements due to wind or errors due to in- and out-splashing of water (Lanza et al., 2005; WMO, 2008). In addition, (iii) tipping bucking rain gauges are known to systematically underestimate rainfall at higher intensities because of the rainwater amount lost during the tipping movement of the bucket (Barbera et al., 2002).

Radar rainfall intensity is derived indirectly from measured radar reflectivity (Kirsch et al., 2019), with often negative effect on the accuracy of radar measurements, especially in the case of extreme rainfall magnitudes (Einfalt et al., 2004, 2005; Marra and Morin, 2015; Bárdossy and Pegram, 2017) and/or storms in mountain environments (Germann et al., 2022; Kopp et al., 2022; Ghaemi et al., 2023). In a study realized in the Dolomites (Italy), Bernard and Gregoretti (2021) illustrated that radar images tend to underestimate precipitation sums recorded by rain gauges, which in turn resulted in an underestimation of predicted debris-flow occurrences. The authors improved predictions considerably by correcting the radar images with local rain gauge data. The CombiPrecip dataset used in this study is a combination of radar measurements and precipitation data from the automated rain gauges at land-based weather stations. The product already includes a comparable correction and has been shown as a reliable, spatially explicit dataset at high resolution, especially for smaller rainfall intensities and increasing accumulation times. Instead, in the case of extreme rainfall episodes, agreement between products is just in the order of 50 %, with a tendency for slightly smaller sums given by CombiPrecip (Panziera et al., 2018). In our case, median triggering precipitation sums are comparable between the Buffalora climate station and the CombiPrecip dataset, with correlations of 0.72 between the datasets and when looking at all rainfall events that triggered debris flows in the study area.

The *Imfeld23* precipitation fields were obtained by approximating an areal estimate using point measurements (Villarini et al., 2008). Rain gauges have a typical catch area of c. 20 cm and provide a highly-resolved point information of precipitation. They are used as input for the construction of precipitation fields. Yet, precipitation is highly variable in space, even more so in mountainous environments, and one may therefore wonder to what degree the use of a single or multiple rain gauges can yield realistic rainfall fields across larger regions. Imfeld et al. (2023) evidenced that errors in their data increase with increasing intensity of a rainy day, especially in summer and at higher altitudes, thereby resulting in a considerable underestimation of strong precipitation events. The authors also indicate that extreme precipitation is underestimated by a median of up to 10 mm, which we confirm in this study. The most considerable limitation of the dataset is related to the fact that convective, oftentimes very local summertime storms are poorly captured in general and in particular in the southern part of Switzerland (i.e. Ticino, south-eastern Grisons) where our study region is located. This limited ability to capture convective storms can be illustrated by the limited agreement on the magnitude of debris-flow triggering P_{event} values which is only 0.27 for rainfall sums >20 mm.

5.2. Limits of dendrogeomorphic assessments of hydrometeorological triggers

Triggering meteorological conditions – especially rainfall sums – have repeatedly been derived in dendrogeomorphic studies to reconstruct and understand the occurrence and likely drivers of past natural hazard processes. Tichavský (2023) provides a recent review of published work and the approaches that were employed to link geomorphic process activity to a triggering precipitation event. A first, yet major limitation inherent to such an approach is the generally scarce network of climate stations in mountain regions, resulting in both horizontal and vertical distances between the source area of debris flows and the recording weather station (often exceeding 20 km in distance and 1000 m difference in elevation). Due to the small-scale nature of storms in fragmented mountain environments, this can result in considerable differences between what happens in the source area of debris flows and at the recording weather station (Schneuwly-Bollschweiler and Stoffel, 2012).

A second major limitation is that, in the absence of any hints on the seasonality/timing of the mass movement process that was documented in tree-ring records, a majority of past studies simply established links between the occurrence of a debris flow and a possible trigger by describing rainfall episodes that could have led to the triggering of the event during a given "event year" (e.g., Germain et al., 2018; Novak et al., 2020; Tichavský et al., 2022). Other papers relied on basic statistics to detect possible differences in short-term (i.e. ranging from single days to a week), maximum monthly, seasonal, or annual precipitation sums for years with and years without debris flows (e.g., Tichavský et al., 2017; Šilhán, 2021, 2022, 2023; Šilhán et al., 2022), but all suffered from a limited numbers of years with a reconstructed debris flow and a vast majority of years without process activity. A third set of studies relied on generalized linear models by which binary values were assigned to years with and without debris-flow activity before the most effective explanatory covariates and the best-fitting probability model were defined (e.g., Jomelli et al., 2007; Tichavský and Horáček, 2022; Šilhán et al., 2023;). Again, due to the infrequent occurrence of debris flows in a given catchment, it is at least questionable whether the approaches used in these studies were appropriate.

Looking at Fig. 4b, we realize that, irrespective of the precipitation dataset used, the maximum rainfall recorded in any given summer (i.e. JJA) – in this paper referred to as P_{maxJJA} – only rarely triggered debris flows in our study area. When considering the Buffalora climate station records, P_{event} as recorded at the station only triggered a debris flow in 4 (!) out of the 55 cases (or 7 %) for which the date of occurrence is known from historical data. Conversely, this also means that in the absence of a given event date, one would likely have picked the wrong precipitation episode from the local climate station to assess the triggering of a debris flow in 93 % of all cases if relying on P_{maxJJA}. In a similar way, and because of the limited ability of the *Imfeld23* precipitation fields to capture convective storms, P_{maxJJA} only triggered debris flows in 5 out of the 47 cases (11 %) for which the date at of the debris flow was known. Agreement is slightly better when relying on the CombiPrecip dataset as the calendar dates of 12 out of the 40 P_{maxJJA} sums (or 30 %) found in the catchment in which an event occurred also corresponded to the rainfall episode that indeed triggered the debris flow.

In addition to all limitations inherent to the analysis of discontinuous data on past debris flows (i.e., limited number of events, a vast majority years without activity, short station data which, in addition, are often located far away from the source areas of debris flows), we show in this study that statistical analysis of triggering meteorological conditions cannot yield meaningful results when relying on process reconstructions which date past activity to a given year, as is most often the case with dendrogeomorphic approaches. This is the case for debris flows, but we posit that these limitations, by analogy, also exist in annually resolved snow avalanche and landslide data. In the absence of a higher dating resolution, future work should refrain from speculating on hydrometeorological drivers of past process activity, even more so in hillslope and mountain environments where topography can affect both the distribution and amounts of precipitation significantly, even over relatively short distances (Foresti et al., 2018; Panziera et al., 2018).

A possible way forward for dendrogeomorphic reconstructions to become useful sources for the intra-seasonal analysis of process activity and the related assessment of likely triggers lies in the detection and interpretation of anatomical markers induced by past mass movements. Such markers can be found in the form of chaotic callus tissue at the margin of wounds of both conifers (Bollschweiler et al., 2008; Schneuwly et al., 2009a, 2009b) and broadleaved species (Arbellay et al., 2010a, 2010b, Arbellay et al., 2013; Ballesteros et al., 2010), vessel size changes (Arbellay et al., 2012a, 2012b) or as tangential rows of traumatic resin ducts (TRDs) in the case of some conifer species (notably *Abies*, *Larix*, *Picea*, or *Pseudotsuga*, but not *Pinus*; Stoffel, 2008, Bollschweiler et al., 2008; Stoffel et al., 2012). First attempts to date wound-inducing or cambium-disrupting disturbances have been realized successfully on fire-scarred trees (Farris et al., 2010) and have thereby prepared the ground for the intra-seasonal dating of different types of mass movements occurring during the growing season of trees (which lasts from May to October in the case-study region; Müller, 1980; Stoffel et al., 2005a).

In addition to rockfall activity which was repeatedly dated with sub-seasonal or even monthly precision (Stoffel et al., 2005b; Perret et al., 2006; Mainieri et al., 2021; Stoffel et al., 2024b), injuries and TRDs were also used successfully to discriminate snow avalanche scars from rockfall and debris-flow injuries (Stoffel et al., 2006; Stoffel and Hitz, 2008; Szymczak et al., 2010; Kogelnig-Mayer et al., 2011) or to date past debris flows with sub-seasonal to almost monthly resolution (Stoffel and Beniston, 2006; Stoffel et al., 2008; Arbellay et al., 2010a; Ballesteros et al., 2010; Toreti et al., 2013; van den Heuvel et al., 2016). In these studies, it was not only possible to narrow down the occurrence of past debris flows to a few weeks, but also to assess possible hydrometeorological triggers as all study sites were located in a dry, inner-alpine valley of the Swiss Alps where storms do occur, but not frequently, and where stratiform precipitation is mostly limited to fall and winter

(Stoffel et al., 2005b). At these sites, located in the Zermatt valley, dendrogeomorphic timeseries of past debris flows could thus be employed for the analysis of hydrometeorological triggers debris flows for the last 170 years (Schneuwly-Bollschweiler and Stoffel, 2012), despite some limitations regarding the availability of meteorological stations in the vicinity of the source areas of debris flows.

6. Conclusion

Debris flows in small mountain catchments of dry inneralpine valleys of the European Alps are often triggered by summer thunderstorms, and records from a climate station located in the vicinity of small catchments and at "high" elevation (1971 m asl) aided in defining daily rainfall sums that have triggered debris flows in the past. Likewise, estimates of ground-level precipitation derived from a combination of radar data and information from automated rain gauges at weather stations provided comparable results, with a slight underestimation of precipitation sums. By contrast, past debris flows with known dates of occurrence only rarely occurred on the day for which the maximum daily summer rainfall was recorded. This has stark implications for debris-flow studies relying on tree-ring data by which past events are reconstructed to the year, because statistical assessment of possible hydrometeorological triggers will lead to spurious correlations and by analogy to fundamentally wrong conclusions.

Whereas future tree-ring based research should refrain from venturing into any triggering analysis based on annually resolved timeseries, we call for the construction of records relying systematically on anatomical indicators with intra-seasonal resolution (e.g., injuries, TRD) so as to help the interpretation and contribute to an improved understanding of hydrometeorological triggers of past mass movements. In terms of precipitation products, and whenever possible, future research should rely on radar (−derived) data or on 10-min or hourly rather than daily precipitation sums from stations located in the upper part of a basin.

CRediT authorship contribution statement

Jiazhi Qie: Writing – original draft, Investigation, Funding acquisition, Formal analysis. **Christophe Corona:** Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adrien Favillier:** Supervision, Formal analysis, Data curation. **Stefanie Gubler:** Validation, Formal analysis. **Tamara Estermann:** Validation, Resources, Formal analysis. **Markus Stoffel:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Markus Stoffel reports financial support was provided by Forschungskommission Schweizerischer Nationalpark. Jiazhi Qie reports financial support was provided by Chinese Scholarship Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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