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RECONSTRUCTION OF DEBRIS-FLOW DYNAMICS AND TRIGGERS SINCE AD 1570 - LOOKING BACK TO A DECADE OF TREE-RING RESEARCH AT RITIGRABEN (VALAIS, SWITZERLAND)

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ABSTRACT

Records derived from trees growing in temperate regions can provide annually resolved data on past debris-flow activity that span several centuries. They therefore allow identification and accurate dating of events prior to instrumental records or missing in historical archives. As a result, dendrogeomorphic methods have repeatedly been used over the last decades to reconstruct debris-flow frequencies in mountain regions of Europe or North America. While these studies furnished valuable data on the minimum frequency of events that would have occurred in the channels and cones chosen for analysis, they did, however, not explicitly take account of e.g., depositional processes on cones, volumes, periods of activity in currently abandoned channels or on the age of individual lobes and levees.

Over the past eleven years, dendrogeomorphic investigations on past debris-flow activity in the Ritigraben catchment (Valais, Swiss Alps) and its intermediate cone went several steps beyond the assessment and pure dating of debris-flow "signatures". Through the analysis of some 2450 tree-ring sequences obtained from more than 1200 trees growing on the cone and along the current flow path, we were able to identify evidence of 123 events since 1570. The large amount of data also allowed analysis of the spread and deposition of material on the cone as well as determination of activity in currently abandoned channels. A combination of tree-ring with ground survey data, channel recharge rates and debris delivery in the departure zone (i.e. a rock glacier) allowed estimation of frequency-magnitude relationships. We also related debris-flow events reconstructed for the Ritigraben torrent with flooding records of neighboring rivers.

Key words: *debris flow, tree-ring analysis, dendrogeomorphology, deposits, sediment, triggering events, permafrost, climate change, Swiss Alps*

INTRODUCTION

Records derived from trees provide annually resolved data on past mass movements spanning several centuries, thus allowing identification and accurate dating of events prior to instrumental records (Stoffel *et alii*, 2010). As a result, dendrogeomorphic approaches have been applied repeatedly in the past to determine time series of past debris flows in mountain regions (Bollschweiler & Stoffel, 2010b). Pioneering work on tree-ring damage resulting from debris-flow impacts was performed by Hupp (1984; Hupp *et alii*, 1987) on the slopes of Mount Shasta (California). A few years later, Strunk (1989, 1997) was the first to use the approach in Europe, reconstructing time series of debris flows in the Italian Dolomites. More recently, dendrogeomorphic techniques have been improved significantly through the inclusion of wound-induced tangential rows of traumatic resin ducts (TRD) in tree-ring studies (e.g., Bollschweiler *et alii*, 2008b; Schneuwly *et alii*, 2009; Stoffel & Hitz, 2008). As a result, replication and identification of past events in conifer trees was greatly facilitated (STOFFEL, 2008), as signs of past damage are more easily identified in the form of TRD and as these remain recognizable in the tree-ring record even if the wound becomes completely overgrown. In recent work, TRD have been used extensively for the reconstruction of event histories of debris flows (BOLLSCHWEILER & STOFFEL, 2010c; BOLLSCHWEILER *et alii*, 2008a), hyperconcentrated flows (BOLLSCHWEILER *et alii*, 2007), debris floods (MAYER *et alii*, 2010), and lahars (BOLLSCHWEILER *et alii*, 2010).

While these studies provided invaluable data on minimum frequencies, they did not explicitly take account of depositional processes and patterns, magnitudes, age of deposits, debris-flow triggers or rainfall thresholds. In 2000, dendrogeomorphic research on the cone of the Ritigraben torrent (Valais, Swiss Alps) started with the reconstruction of event frequencies of debris flows (STOFFEL *et alii*, 2005), but has since evolved into a very detailed and probably the most complete database on past debris-flow activity in mountain regions (STOFFEL *et alii*, 2008). This contribution aims at summarizing the key findings of more than a decade of tree-ring based debris-flow research at Ritigraben and at providing possible tracks for future research.

STUDY SITE

The Ritigraben torrent is located on the west-facing slope of the Mattertal valley (Valais, 46°11'N, 7°49'E). The system spans a vertical range of 2000 m from the summit of the Seetalhorn (3100 m asl) to the torrent's confluence with the Vispa River at 1080 m asl. A rock glacier occupies a large part of the headwater basin (1.4 km^2) between 2500 and 2800 m asl (Figure 1a), representing the principal source of loose material in the upper part of the catchment area and constituting the main starting zone of debris flows. DC resistivity soundings detect low resistivity values inside the rock-glacier body (10 to 110 kΩm, LUGON & MONBARON, 1998), being characteristic of temperate permafrost with temperatures close to the melting point. Five boreholes located near the front of the rock-glacier body confirm this interpretation (LUGON & STOFFEL, 2010). Temperature profiles indicate a mean annual temperature varying between -0.3 and -0.6 °C in the permafrost body for the period 2002-2005 and a depth of the zero annual amplitude (*ZAA*) at -13 m with a mean annual temperature of -0.3 °C.

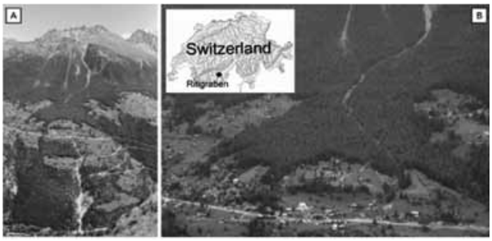


Fig. 1 - Ritigraben torrent: (A) View of the debris-flow system (catchment area: 1.36 km^2, channel lengths: 3.5 km) (B) Detail of the intermediate debris-flow cone (32 ha) and its conifer stand

Following an active-layer detachment at the rock glacier front in 1993, massive ice lenses were exposed at the front of the rock glacier. In summer 1994, degradation of the exposed ice lenses caused intense retrogressive erosion at a monthly rate of ca. 1 m at the rock-glacier front (LUGON & MONBARON, 1998). The accumulated material was partly removed during a rain-on-snow event on September 24, 1994, resulting in a debris flow with a volume of roughly 5,000 m^3 (ZIMMERMANN *et alii*, 1997). Retrogressive erosion continued in summer 1995, leading to the formation of subsidence close to the front of the rock glacier.

On its downward course to the Mattervispa river, the Ritigraben torrent passes a large forested cone (32 ha; ca. 4.3 x 10^6 m^3) on a structural terrace (1500-1800 m asl), where debris-flow material affects trees within an old-growth stand composed of European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) Karst.) and Swiss stone pine (*Pinus cembra* L.). Figure 1b illustrates the intermediate debris-flow cone, which is of Holocene age.

MATERIAL AND METHODS

Analysis of past debris-flow activity included a detailed mapping of all features associated with past events, such as lobes, levees or abandoned flow paths on a scale of 1:1000. In addition, mean sizes of blocks were measured for each lobe and levee (< 0.5 m, 0.5-1 m, 1-2 m) and the vegetation cover present on the features was qualitatively assessed (light, medium, dense).

On the debris-flow cone, most of the century-old conifers show growth disturbances (GD) related to past debris-flow activity (i.e. tilted stems, partial trunk burial, denudation of roots, scars). Based on the geomorphic map and an outer inspection of the trunk surface, we sampled trees obviously disturbed by past debris flows. We also selected undisturbed reference trees from a forest stand located next to the cone. In total, 1204 trees were sampled (2450 increment cores): 539 *L. decidua*, 429 *P. abies* and 134 *P. cembra* trees (2246 cores) from the debris-flow cone as well as 102 trees (204 cores) of the same species from undisturbed reference sites.

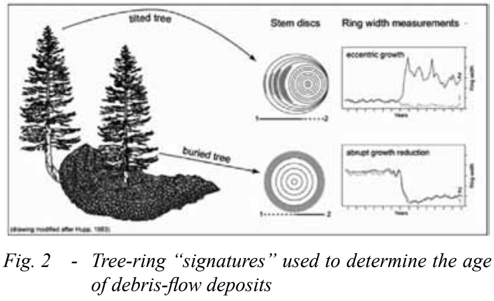
Samples were analyzed and data processed following the standard procedures described in Stoffel & Bollschweiler (2008, 2009). Single steps of sample analysis included surface preparation, skeleton plots as well as ring-width measurements using digital positioning tables, a stereo microscope and TSAP 3.0 (Time Series Analysis and Presentation) software (Rinntech, 2010). Growth curves of the disturbed samples were crossdated with the reference chronology constructed from undisturbed trees to separate insect attacks or climatically driven fluctuations in tree growth from GD caused by debris flows (Cook & Kairiukstis, 1990).

Growth curves were then used to determine the initiation of abrupt growth reduction or recovery (McAuliffe *et alii*, 2006). In the case of tilted stems, both the appearance of cells (i.e. structure of the reaction wood cells) and the growth curve data were analyzed (e.g., Fantucci & Sorriso-Valvo, 1999; Figure 2). Finally, the cores were visually inspected so as to identify further signs of past debris-flow activity in the form of callus tissue overgrowing abrasion scars or TRD formed following cambium damage (Schneuwly *et alii*, 2009; and references therein).

As conifer trees react immediately to damage with the formation of callus tissue or TRD, the position of GD within the tree ring was used to assess the timing of debris-flow activity in particular years, rendering dating of events possible with monthly precision (Kaczka *et alii*, 2010). The results obtained on the intra-seasonal timing of debris flows were then compared with rainfall records from a local meteorological station, operational since AD 1863, and with archival records on floods in rivers of the Valais Alps (Lütschg-Lötscher, 1926; Röthlisberger, 1991).

The age of lobes was assessed by attributing severe GD in the tree-ring series to deposits in the field. As exemplified in Fig. 2, dating of a lobe was possible if (i) a survivor tree was injured through the deposition of material; (ii) its stem base buried by debris; or (iii) if it was tilted (Fig. 2). Special attention was addressed to multiple GD identified in the tree-ring series. Here, only the geomorphic features left during the most recent event could be dated. While much of the field evidence typically resides on cones (Haeberli *et alii*, 1991), subsequent incidences may overprint or remove geomorphic and botanical evidence of previous events (Hupp, 1984). An assessment of debris-flow magnitude considering exclusively deposits visible on the present-day surface will run the risk of underestimating the size of individual events. To account for this problem, the assessment of event magnitude and magnitude-frequency (M-F) relations was not only based on volumetric data of lobate deposits, and mean/maximum grain sizes of boulders, but also included analysis of a series of second-order surrogate variables, including (i) snout elevations of lobes as a proxy for stream power; (ii) damage caused to the forest along the tracks and to tree survival inside lobes as indicators of impact energies involved; as well as (iii) the distribution of lobes and levees belonging to the same event as a proxy for the lateral spread of flows. In addition, we used (iv) eyewitness reports and (v) volumetric data of the most recent events (1993, 1994, 2002, 2008) to further increase magnitude control. Based on the above criteria, four different size classes of debris flows are presented and given as *S*, *M*, *L*, and *XL*, reflecting a magnitude estimate of event sizes at the cone apex (Stoffel, 2010). The temporal frequency of events was analyzed per size class with the FHX2 software (Grissino-Mayer, 2001). Parameters assessed include debris-flow frequency, mean debris-flow intervals, Weibull median intervals, minimum and maximum debris-flow intervals as well as lower (0.125) and upper (0.875) exceedance intervals.

In the source area of debris flows, variations in horizontal rock-glacier movement rates were assessed with high-resolution geodetic surveys (1995-) and low-resolution photogrammetric analyses covering the last 50 years. The rate of sediment delivery to the foot of the rock-glacier snout was determined through



(drawing modified after Hupp, 1983)

Fig. 2 - Tree-ring "signatures" used to determine the age of debris-flow deposits

an assessment of creep velocity [cm yr^{-1}], rock-glacier width [m], and depth of the shear zone [m]. In addition to sediment yield, we analyzed changes in the position of the upper limit of the rock-glacier snout (i) to identify visible signs of retrogressive erosion and (ii) to derive volumes eroded at the front. Tree-ring data on M-F relations of events recorded at the cone were then compared with (iii) volumes transported to the source area of debris flows through rock-glacier creep and (iv) changes in the position of the upper limit of the rock-glacier snout (Lugon & Stoffel, 2010).

In a last analytical step, data on former debris-flow events were coupled with meteorological records (AD 1863-2008; Stoffel *et alii*, in review) to study (i) precipitation totals recorded during events, (ii) the role of antecedent rain or snowmelt (i.e. "rain-on-snow" events), and (iii) storm type (i.e. advective or convective) leading to the release of debris flows at Ritigraben, before (iv) the role of meteorology on debris-flow magnitude and (v) the implications that climatic change might have on the occurrence of debris flows are discussed.

RESULTS AND DISCUSSION

The study of the 2246 tree-ring sequences sampled from 1102 trees allowed reconstruction of 124 events since AD 1570 (Fig. 3). Geomorphic mapping permitted identification of 769 features related to past debris-flow activity on the intermediate cone. The features inventoried in the study area included 291 lobes, 465 levees and 13 well-conserved paleochannels. Based on tree-ring records of disturbed trees growing in or next to the deposits, ~86% of the lobes identified on the present-day surface could be dated. Figure 4 illustrates that a majority of the dated material was deposited over

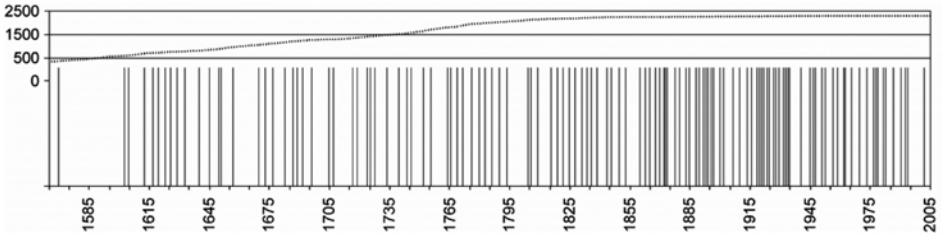


Fig. 3 - Tree-ring based reconstruction of debris flow activity at Ritigraben between AD 1566 and 2005 containing 123 events. The sample depth (dotted line) shows the number of cores available for analysis at specific years in the past

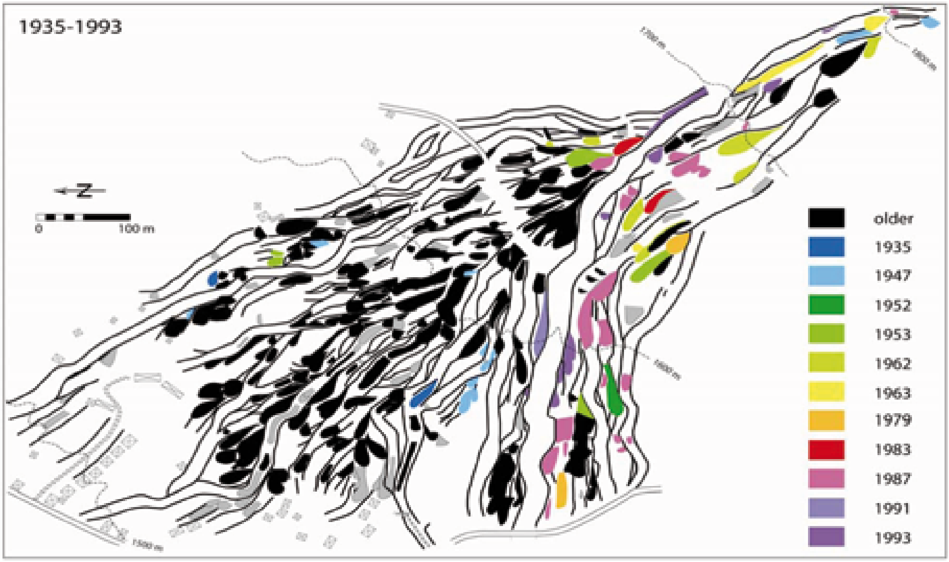


Fig. 4 - Deposition of debris-flow material on the intermediate cone during past events: Material deposited between 1935 and 1993. Only events that are associated with >600 m³ on the present-day surface of the cone are indicated on the map. Deposits shown in black are dated, but are older than the time segment illustrated

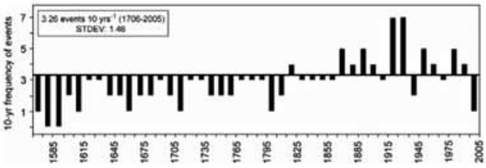


Fig. 5. Reconstructed 10-yr frequencies of debris-flow events between AD 1566 and 2005. Data are presented as variations from the mean decadal frequency of debris flows of the last 300 years (AD 1706-2005)

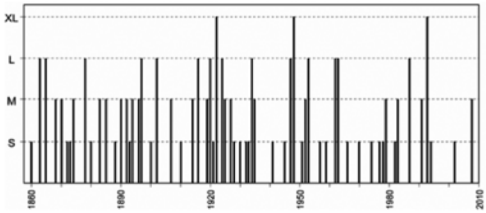


Fig. 6. Reconstructed time series of debris-flow magnitudes, in four classes, for the period from 1858 to 2008. Note the clustering of important events in the early decades of the twentieth century and the absence of class XL debris flows before 1922

Temporal frequency of events	*Class S*	*Class M*	*Class L*	*Class XL*	Total
Events (no.)	25	20	14	3	62
Debris-flow frequency	0.18	0.14	0.10	-	0.42
Mean debris-flow interval (yr)	5.42	7.37	9.54	-	2.38
Weibull median interval (yr)	4.94	5.96	8.14	-	2.18
Standard deviation (yr)	3.19	6.65	6.88	-	1.49
Debris-flow interval (min., yr)	1	2	1	-	1
Debris-flow interval (max., yr)	12	27	24	-	8
Lower exceedance interval (yr) [a]	1.95	1.60	2.59	-	0.85
Upper exceedance interval (yr) [a]	9.20	14.31	17.48	-	4.09

Tab. 1 - Statistics of temporal frequency of debris flows for different magnitude classes. Thresholds for the lower and upper exceedances set at 0.125 and 0.875

the past century. Signs of pre-20th century events are often recognizable in the tree-ring record of survivor trees, but the material that caused the growth anomaly in trees has been completely overridden or eroded by more recent debris-flow activity.

Based on the tree-ring records, we believe that cool summers with frequent snowfalls in the headwater of the Ritigraben torrent regularly prevented the release of debris flows between the 1570s and 1860s; the warming trend combined with greater precipitation totals in summer and autumn between 1864 and 1895 provided conditions that were increasingly favorable for releasing events from the source zone. It can also be seen from Figure 5 that enhanced debris-flow activity continued well into the 20th century and reconstructions show a clustering of events between 1916 and 1935 when warm-wet conditions prevailed during summer in the Swiss Alps. In contrast, very low activity is observed for the recent past (1996-2005) with only one debris flow recorded on August 27, 2002. Since sediment availability is not a limiting factor, this temporal absence of debris-flow activity is due to an absence of triggering events, which shifted from June and July to August and September over the 20th century.

Magnitude-frequency (M-F) relations were assessed for 62 debris flows since A.D. 1863, i.e. for the period where meteorological records are available. *Class S* and *M* debris flows ($<5\times10^3$ m^3) encompass a typical size of events and have mean recurrence intervals of 5.4 (SD: 3.2) and 7.4 years (SD: 6.7), respectively (Table 1). *Class XL* events (10^4-5×10^4 m^3) are, in contrast, only identified three times over the past 150 years, and major erosional activity on the cone was restricted to two of these events in 1948 and 1993 (Fig. 6). A comparison of results with hydro-meteorological records shows that *class L* and *XL* events are typically triggered by advective storms (with rainfall totals >50 mm) in August and September, when the active layer of the permafrost body in the source area of debris flows is largest. It also becomes obvious that over the past ~150 years, climate has exerted control on material released from the source area and prevented triggering of *class XL* events before 1922.

Debris production and volumetric changes at the rock-glacier front are compared with debris-flow activity recorded on the cone and potential couplings and feedbacks between debris sources, channel processes and debris sinks. Acceleration in rock-glacier movement rates is observed in the 1950s and 1960s, followed by a decrease in flow rates by the 1970s, before movements increase again after the early 1990s. At a decadal scale, measured changes in rock-glacier movements at Ritigraben are in concert with changes in atmospheric temperatures in the Alps. Geodetic data indicates displacement rates in the frontal part of the rock glacier of up to 0.6-0.9 m yr^{-1} since the beginning of systematic measurements in 1995. While the Ritigraben rock glacier has always formed a sediment reservoir for the as-

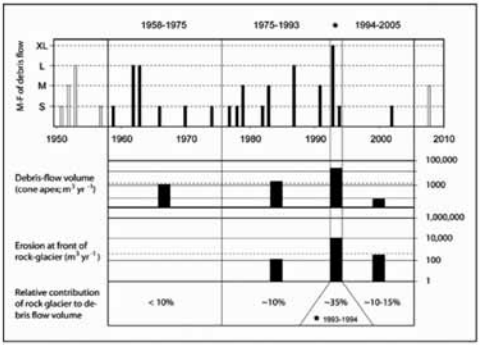
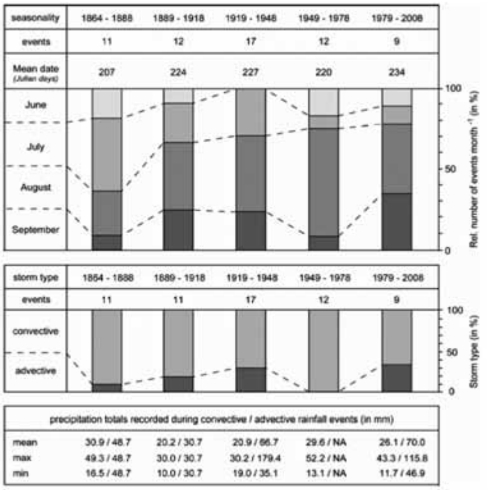


Fig. 7 - *Sediment delivery of the rock glacier and M-F relationships of debris flows at Ritigraben*

sociated debris-flow system, annual horizontal displacement rates of the rock-glacier body have remained quite small and are in the order of decimeters under current climatic conditions. Sediment delivery from the rock-glacier front alone could not therefore be sufficient for the alimentation of the 16 debris flows reconstructed on the cone since 1958. On the contrary, debris accumulated at the foot of the rock glacier, landslide and rockfall activity as well as the partial collapse of oversteepened channel walls have to be seen as important sediment sources of debris flows at Ritigraben and represent 65-90% of the material arriving on the Ritigraben cone. Noteworthy, as shown in Figure 7, there does not seem to exist a direct coupling between displacement rates of and sediment delivery by the rock-glacier body and the frequency of *class S* and *M* debris flows. In contrast, a direct link between source and sink processes clearly exists in the case of active-layer failures. In this case, failure processes at the rock-glacier snout and debris-flow events in the channel occur simultaneously and are both triggered by the rainfall event.

Based on observational meteorological data, we then assessed changes in rainfall characteristics and their impact on the triggering of debris flows over the past ~150 years. No trends are visible in the frequency of heavy rainfall events, but we observe a cluster of the overall frequency of debris flows in the early decades of the 20th century and a concentration of advective storms in late summer and early autumn since the late 1980s (Fig. 8). At the same time, dendrogeomorphic data point to a reduction of convective rainfall capable of triggering events and a lowering of the overall debris-flow activity since the mid-1990s.

These changes in triggering meteorological conditions may be mirroring the observed changes in persistent high-pressure systems over the Alps. In addition to the long-term changes in debris-flow systems, we observe changing responses of the watershed to the amount of rain at different moments within the debris-flow season (i.e., early June through late September). Differences in system response clearly reflect the state of the permafrost body in the source area of debris flows, which allows for very small debris-flow events after limited rainfall inputs (<20 mm) in June and July. The same quantities of rain will result in non-responses of the system in August or September, when a large active layer of the permafrost body is capable of absorbing water without producing debris flows. With the projected amplitude of climatic change, changes will probably occur in the seasonality, return intervals and volumes of debris flows. Regional climate model projections suggest a decrease in heavy summer rainfall events which will most likely result in a reduction of the overall frequency of debris-flow events, leaving more time for debris to accumulate in the channel. Such increases of channel accumulation rates along with the projected destabilization of the steep rock-glacier body will ultimately exert control on the volumes of material released from the source areas during future debris-flow events. It is thus possible that extremely large "*class XXL*" events, beyond historical experience and with volumes surpassing 5 × 10^4 m^3 at the level of the debris-flow cone, may be observed in the future originating from this periglacial environment.



precipitation totals recorded during convective / advective rainfall events (in mm)					
mean	30.9 / 48.7	20.2 / 30.7	20.9 / 66.7	29.6 / NA	26.1 / 70.0
max	49.3 / 48.7	30.0 / 30.7	30.2 / 179.4	52.2 / NA	43.3 / 115.8
min	16.5 / 48.7	10.0 / 30.7	19.0 / 35.1	13.1 / NA	11.7 / 46.9

Fig. 8 - *Changes in seasonality of debris-flow events (top), storm types triggering debris flows (centre) and rainfall totals recorded during convective and advective storms with subsequent debris-flow releases (bottom)*

OUTLOOK

The significant contribution of dendrogeomorphology (Stoffel *et alii*, 2010) to the endeavors of mass-movement research lies in their capacity to both preserve evidence of past events and to provide critical information on their dating with annual or sub-annual resolution. Therefore, tree-ring records may represent the most valuable and precise natural archive for the reconstruction and understanding of past events over the last several centuries. The initial employment of tree rings in earth-surface process studies was simply as a dating tool (Alestalo, 1971) and rarely exploited other environmental information that could be derived from studies of ring-width variations and records of damage contained within the tree itself. However, these unique, annually resolved, tree-ring records usually preserve potentially valuable archives of past geomorphic events on timescales of a few decades to several centuries. As many of the earth-surface processes are significant natural hazards, documenting time series of events, understanding their areal extent and controls provides valuable information that can assist in the prediction, mitigation and defense against these hazards and their effects on society. This thesis will illustrate how tree-ring analysis can be used to reconstruct natural hazards and provide information that may be used to understand the future occurrence of events. The different approaches illustrated above show the breadth and diverse applications of contemporary dendrogeomorphology and underline the growing potential to expand these studies, possibly leading to the establishment of a range of techniques and approaches that may become standard practice in the analysis of debris-flow hazards in the future.

Dendrogeomorphic studies, similar to the one outlined above, should be replicated on other sites and in variety of contrasting geographic environments. First data from the Valais Alps show that analysis of neighboring catchments may further improve understanding of debris-flow dynamics at a regional level (Bollschweiler & Stoffel, 2007, 2010a) and help the apprehension of rainfall events that are likely to lead to debris-flow events. Dendrogeomorphic data should also be used for the retrospective modeling of events (Graf *et alii*, 2009), as an accurate calibration and a detailed accuracy assessment of debris-flow models may greatly help to enhance parameter control in scenario-defined runs for potential future events.

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