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# Tree rings and debris flows: Recent developments, future directions

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**Abstract**

The sudden and unpredictable occurrence of debris flows poses major problems in many mountain areas in the world. For a realistic hazard assessment, knowledge of past events is of crucial importance. As archival data is generally fragmentary, additional information sources are needed for an appraisal of past and contemporary events as well as for the prediction of potential future events. Tree rings represent a very valuable natural archive on past debris-flow occurrence as they may record the impact of events in their tree-ring series. In the past few years, dendrogeomorphology has evolved from a pure dating tool to a broad range of applications. Besides the reconstruction of frequencies, tree rings allow – if coupled with spatial positioning methods – the determination of spread and reach of past events. Similarly, the wide field of applications includes the identification of magnitudes and triggers of debris-flow events. Besides demonstrating recent developments in the use of tree rings for debris-flow research, this contribution also provides a short overview on the application of tree rings for other mass-movement processes and highlights further possibilities of the method. Established techniques can be applied to related processes such as debris floods, flash floods or lahars. Data obtained can also be used to calibrate modeling approaches. The impact of past and future climatic changes on debris-flow occurrence is furthermore an important aspect where tree rings can be of help.

**Keywords**

debris flow, dendrogeomorphology, environmental reconstruction, hazard assessment, mass movement, tree ring

## I Introduction

Debris flows are mass movements involving rapid transport of water and saturated material through steep, confined channels (VanDine and Bovis, 2002). They can occur in steep drainage basins with a source of debris and an appropriate climatic event sufficient to trigger an event, such as intense rainfall or rain-on-snow (Iverson, 2000; Wieczorek and Glade, 2005; Guzzetti et al., 2008). Debris flows can be also triggered by the breaching of glacial lakes, landslide dams, or constructed dams (Costa, 1984; VanDine and Bovis, 2002). The unpredictable and sudden occurrence of debris flows represents an

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important hazard in most mountainous regions of the world where they repeatedly cause damage to communication routes, infrastructure or even loss of life (Pasuto and Soldati, 2004; Jakob and Hungr, 2005). As a result of increasing socio-economic pressure in mountain regions, conflicts between debris-flow torrents and infrastructure are of growing concern. In order to be prepared for the future occurrence of events, a detailed assessment of hazard and risk is indispensable (Bell and Glade, 2004; Glade, 2005). A major key for such an assessment is the documentation of the number (ie, temporal occurrence or frequency) and size (ie, volume or magnitude) of past incidences at the site level. In the vast majority of cases, because of the absence or incompleteness of documentary records, this information needs to be developed from natural archives or 'silent witnesses' (Aulitzky, 1992) remaining visible in the landscape after an incident. Trees physically impacted by debris flows represent a valuable natural archive as they record past events in their tree-ring series. The significant contribution of tree rings to these endeavors lies in their capacity both to preserve evidence of past events and to provide critical information on debris-flow dating with annual or even subseasonal resolution. Therefore, in many climates, tree-ring records may represent the most valuable and precise natural archive for the reconstruction and understanding of past debris-flow events, often spanning decades up to several centuries.

In this paper, we provide an overview on the possibilities of tree-ring analyses in debris-flow research. A short introduction on the background and the methods used in tree-ring studies is provided before we shed light on the nature of information and applications that can be obtained through the study of impacted trees and their tree-ring series. Results from pioneering work are presented together with contemporary papers to highlight recent progress in the field. In the concluding section, we provide an overview of future directions in tree-ring based debris-flow research, illustrate possible methodological developments and their applications, and suggest new paths for future research.

## II Background – the impact of debris flows on trees

Dendrochronology is based on the fact that trees growing in temperate regions form distinct annual growth rings. The size of each tree ring is influenced by biotic as well as by abiotic factors. Biotic factors are species- and tree-specific and include the genetic makeup and ageing of trees as well as the influence of surrounding plants. Abiotic factors include, for example, light, temperature, water, nutrient supply, and the influence of strong wind, and are more common for trees growing at a specific site (Fritts, 1976; Schweingruber, 1996). As a result, trees growing at the same site will record the same environmental disturbances and fluctuations (eg, temperature or precipitation) in their tree-ring series (Stokes and Smiley, 1968; Cook and Kairiukstis, 1990).

Apart from site-specific information common to all trees at a specific location, individual trees will record any additional information in their tree-ring series such as mechanical disturbance. The impact of a geomorphic process will be recorded in the tree-ring series of the affected tree. Tree-ring analyses of geomorphic processes – known as dendrogeomorphology (Alestalo, 1971) – are usually based on the 'process–event–response' concept as defined by Shroder (1978). A 'process' can be any kind of geomorphic agent, such as a debris flow. The 'event' represents the type of external disturbance that a process will cause and the tree will react upon this disturbance with a specific growth 'response'. In the following account, we illustrate the different impacts ('events') that a debris flow may have on trees and document the specific 'responses' (Figure 1). A more detailed description of growth reactions in trees after geomorphic disturbance can be found in Stoffel and Bollschweiler (2008, 2009). Figure 2 illustrates the external

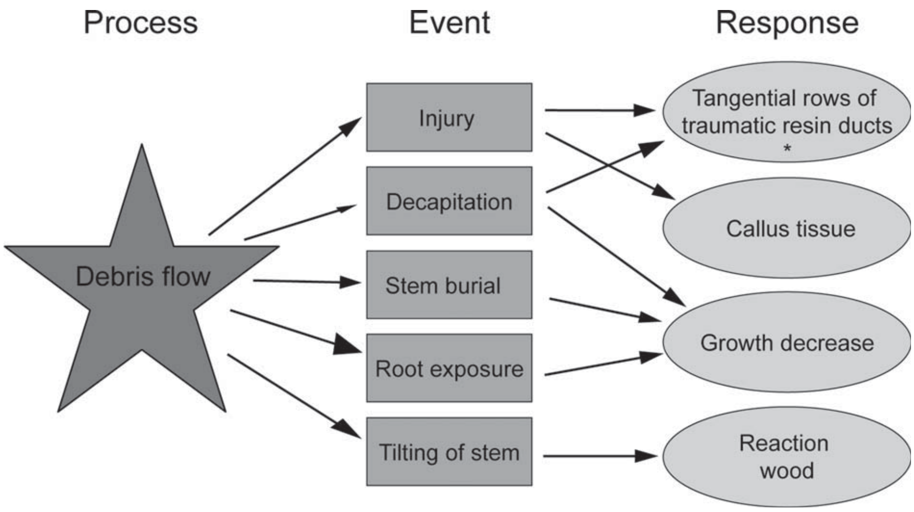


**Figure 1.** The 'process–event–response' chain is one of the key concepts in dendrogeomorphic research and was first developed by (Shroder, 1980). *Only certain conifer species respond to an injury with the formation of tangential rows of traumatic resin ducts.

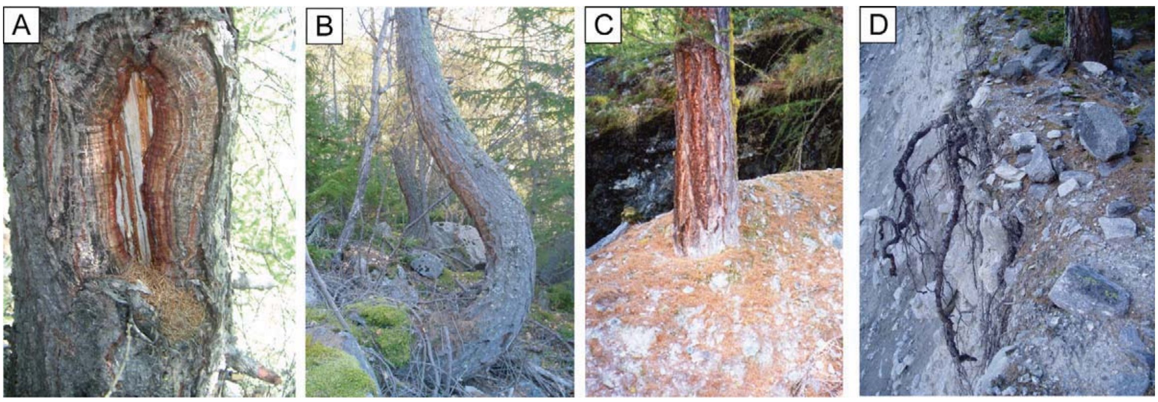


**Figure 2.** External morphology of trees impacted by debris flows. (A) Trees can be injured through boulders or woody material transported in the flowing mass. (B) The pressure of the flow can tilt tree stems. (C) Debris-flow material can be deposited around the stem base. (D) Erosion caused by the flow can denudate tree roots.

morphological growth changes of trees to the impact by debris flows and Figure 3 show how trees will react to these disturbances.

Solid charge, boulders, and woody material transported by a debris flow may cause injuries to the stem surface of trees standing in or adjacent to the flow path of debris flows. Injured trees will react immediately upon this disturbance with the production of callus tissue (Sachs, 1991; Larson, 1994) overgrowing the open wound. In addition, in several coniferous species, tangential rows of traumatic resin ducts (Bannan, 1936; Nagy et al., 2000) are formed on both sides of the wound. As tangential rows of traumatic resin ducts are normally formed directly after the impact, they represent a valuable tool for the reconstruction of past debris flows (Bollschweiler et al., 2008b) with subseasonal

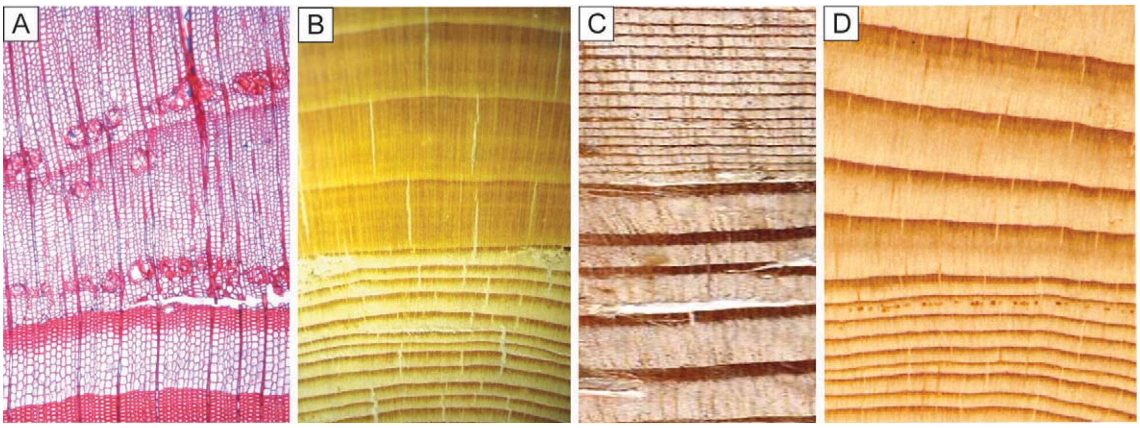


**Figure 3.** Trees will respond to the different disturbances shown in Figure 2 with changes in their growth. (A) On both sides of the injury, coniferous trees form callus tissue and sometimes tangential rows of traumatic resin ducts to protect themselves against fungi and other impacts. (B) After stem tilting, trees will produce so-called reaction wood on the tilted side of the stem. (C) If nutrient and water supply is reduced as a result of stem burial or root erosion, a sudden and abrupt decrease in the yearly increment will occur. (D) Trees may also react with a growth increase to events, provided that neighboring trees are being eliminated and that the survivors benefit from improved growth conditions.

and sometimes even monthly resolution (Stoffel and Beniston, 2006; Kaczka et al., 2010).

The unilateral pressure induced by the material transported in a debris flow can lead to a tilting of the stem axis (Lundström et al., 2008). Trees will try to compensate tilting through the formation of reaction wood (Timell, 1986; Braam et al., 1987a) and eccentric growth will become apparent in the tree-ring series. In coniferous species, reaction wood will be formed on the tilted side of the stem (so-called compression wood), whereas broadleaved trees will form tension wood on the opposite side.

The stem base of trees can be buried through the deposition of debris-flow material. The resulting shortage in water and nutrient supply will commonly lead to a sudden and abrupt decrease in yearly growth-ring increment (Hupp et al., 1987; Friedman et al., 2005). The same reaction occurs when a tree is decapitated through the impact of transported blocks (Butler and Malanson, 1985a) or if large parts of the root system are exposed following erosion (LaMarche, 1968; Carrara and Carroll, 1979; McAuliffe et al., 2006).

Large and devastating events may partly eliminate forest stands, resulting in reduced competition and improved growth conditions for survivor trees. Survivors will benefit from the improved conditions and respond with a growth increase and wider tree rings. The surfaces cleared by the devastating event will be recolonized with trees. Germination ages of trees growing on bare surfaces can be used to approximate the time of surface-clearing events (McCarthy and Luckman, 1993; Pierson, 2007; Bollschweiler et al., 2008a).

## III Methods – working with tree rings in debris-flow research

### 1 Field approach

The first step in dendrogeomorphic investigations of debris flows consists of an identification of geomorphic processes present at the study site. Trees affected by other geomorphic processes will not normally be considered for analysis so as to avoid spurious dating errors. Subsequently, trees obviously influenced by past debris-flow activity will be sampled either through destructive sampling and the preparation of cross-sections, or through core samples. As destructive sampling is not normally possible, tree-ring studies are often performed with cores extracted with an increment borer (Grissino-Mayer, 2003). At least two samples per tree are usually taken from the section of the tree with visible anomalies in tree or stem morphology (Stoffel and Bollschweiler, 2008). The position of each tree is then recorded with a GPS device or directly positioned on a geomorphic map in order to attribute reactions in trees to specific debris-flow deposits identified on the present-day cone surface.

### 2 Laboratory analysis

The standard procedures of sample analyses are described in Stokes and Smiley (1968) or Bräker (2002) and consist of surface preparation, counting of tree rings, and ring-width measurements using a digital positioning table connected to a stereo microscope and a time-series analysis program. The ring widths of the samples are then graphically and statistically compared with a reference chronology representing normal growth conditions at the study site (Cook and Kairiukstis, 1990; Vaganov et al., 2006) so as to correct faulty tree-ring series. The tree samples of affected individuals are then analyzed visually using stereomicroscopes to identify growth changes caused by debris flows.

### 3 Definition of events

Debris flows generally affect and therefore leave signs in several trees along a channel or on a cone. As a consequence, the definition of individual events will be usually based on the replication of growth disturbances in different trees resulting from the same event. Criteria for the definition of an event can be quantitative or semi-quantitative. Quantitative approaches use fixed thresholds of a percentage of trees available for the reconstruction (Butler et al., 1987) and reaction type and intensity are normally weighted (Butler, 2010; Ruiz-Villanueva et al., 2010). Semi-quantitative approaches (Bollschweiler et al., 2007; Stoffel et al., 2008b), in contrast, focus on the spatial distribution of trees simultaneously showing growth reactions without applying a minimum threshold of trees. Both approaches agree that years with a rather limited number of trees showing reactions and weak-intensity disturbances are not events, and these are disregarded for further analysis. In either case, reconstructed debris-flow frequencies will considerably improve the history of events at the site level, but the reconstructed series will remain minimum frequencies.

## IV Application of tree-ring reconstructions for debris-flow histories

The analysis of growth reactions in trees yields large amounts of data on various debris-flow parameters, such as: (1) temporal frequency; (2) spatial occurrence; (3) magnitudes of individual events; or, in combination with meteorological records, (4) invaluable information on triggering conditions and rainfall thresholds for the release of events. In the following, we provide examples on how tree-ring analysis can be used for the reconstruction and the understanding of past debris-flow occurrence and dynamics.

### 1 Frequency of debris flows

The primary goal of most dendrogeomorphic studies usually resides in the reconstruction and assessment of temporal frequencies of past debris flows. Pioneering work in the field was undertaken by Hupp (1984) or Hupp et al. (1987) documenting the past occurrence of debris flows on the slopes of Mount Shasta in California (United States). Subsequent studies were realized in North America as well, for instance by Wilkerson and Schmid (2003), who used tree rings among other methods to assess the frequency and magnitude of debris-flow events in Glacier National Park. May and Gresswell

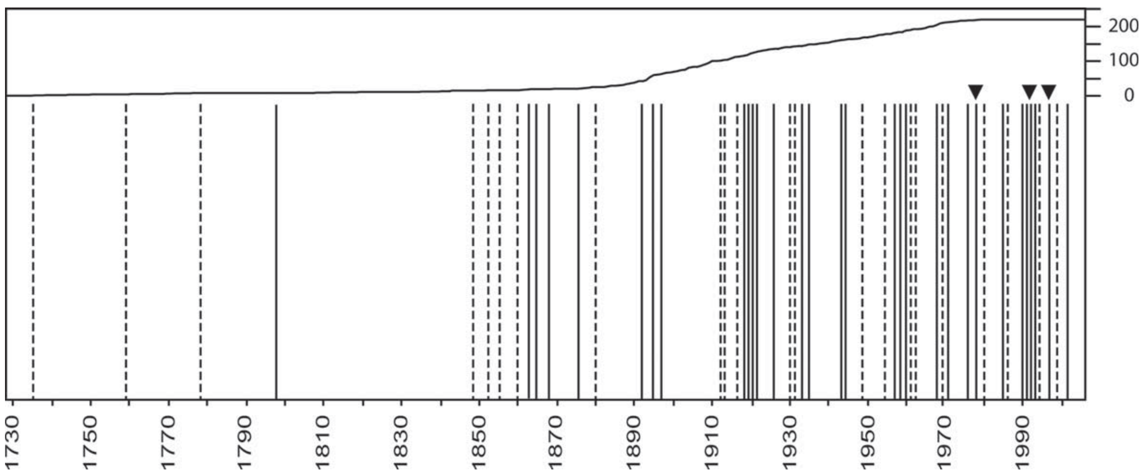


**Figure 4.** The debris-flow frequency of the Geisstriftbach torrent, Swiss Alps. In total, 53 events were reconstructed for the period AD 1736–2008; 31 events could be identified in a very large number of growth disturbances (bold lines). In contrast, for the 22 events represented with dashed lines, there is good evidence for the existence of events in these years as well, but the reduced number of trees available for analysis did not allow for them being considered events with equal confidence. Sample depth (ie, the number of increment cores, wedges and cross-sections available for analysis) is given with a solid line on top of the frequency. Triangles indicate events noted in local archival records (1978, 1993 and 1997).

(2004), in contrast, used dendrochronology to estimate the time since the last debris flow and to calculated the rate of sediment and wood accumulation in low-order streams to understand the temporal succession of channel morphology.

Most of the more recent research activities, however, have clearly focused on the European Alps. Strunk (1989, 1991, 1995) pioneered tree-ring research of debris flows in Europe and investigated the germination of adventitious roots in buried stems to reconstruct burial depths and the history of debris flows. Similarly, Baumann and Kaiser (1999) established a 500-year chronology of debris flows on a fan in the Swiss Alps. More recently, the frequency of past events was reconstructed for over 30 torrents in the Alps (Bollschweiler, 2007; Bollschweiler and Stoffel, 2007; Bollschweiler et al., 2008a; Stoffel et al., 2008b). By way of example, the frequency of the Geisstriftbach torrent in the Swiss Alps is shown in Figure 4 (Sorg et al., 2010; Stoffel et al., 2010b). On the basis of 252 disturbed *Larix decidua* and *Picea abies* trees, 53 events were reconstructed for this torrent between AD 1736 and 2008, as compared to three events known from archival records (SRCE, 2007).

While most reconstructions were rather based on the investigation of coniferous trees, Arbellay et al. (2010) and Szymczak et al. (2010) were successful in using different species of broad-leaved trees for the determination of past events. In the recent past, the focus in frequency reconstructions has shifted away from isolated at-site analyses to regional approaches covering entire valleys (Jomelli et al., 2003; Pelfini and Santilli, 2008). Such an integration of several torrents in a single reconstruction provides a much more complete picture of debris-flow activity at the regional level. In addition, the large amount of data on past debris-flow events contained in regional chronologies – for instance, 296 debris flows since AD 1850 in the case of the Zermatt valley, Swiss Alps (Bollschweiler and Stoffel, 2010a) – tend to yield much clearer and univocal results. In addition, and through their

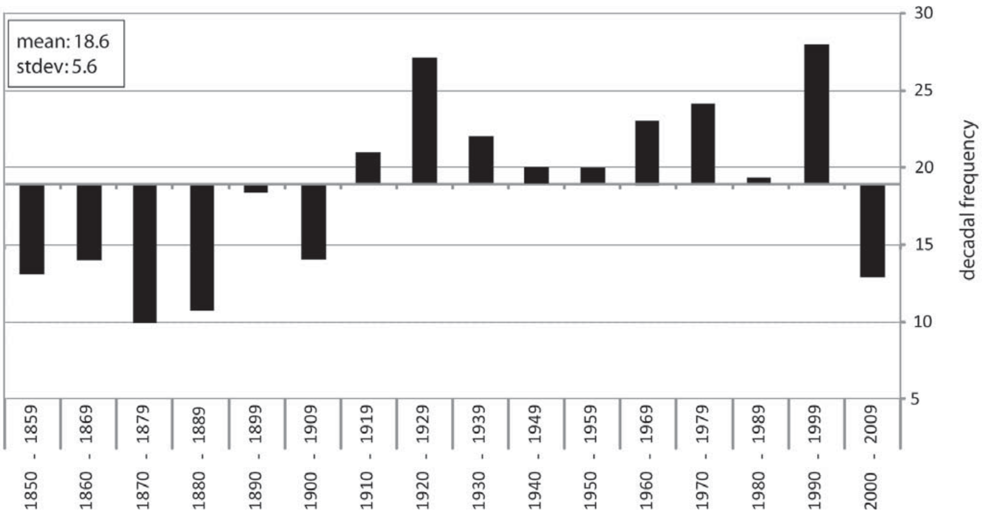


**Figure 5.** Decadal debris-flow frequency 1850–2009 for the Zermatt valley illustrated as variation from the mean (18.5 events 10 $yr^{-1}$)
*Source*: Adapted from Bollschweiler and Stoffel (2010a)

representation as decadal frequencies, it also becomes possible to identify changes and trends in regional debris-flow occurrences and to relate these changes to changing climatic conditions. By way of example, Figure 5 illustrates that increased debris-flow activity in the Zermatt valley became first apparent after the end of the Little Ice Age around 1900 (Grove, 2004) and in the early twentieth century when warm-wet conditions prevailed during summers in the Swiss Alps (Pfister, 1999). On the other hand, there is a considerable decrease in debris-flow frequency over the past few decades which represents changes in atmospheric circulation patterns and a decrease in the frequency of triggering precipitation events (Schmidli and Frei, 2005).

While debris-flow reconstructions usually yield yearly precision, recent research has explored the potential of tree rings for monthly resolution, provided that an event occurred during the vegetated period of trees. Kazcka et al. (2010) used 240 cross-sections of trees impacted by a known debris-flow event in Quebec to identify the timing of growth disturbances (ie, injuries, tangential rows of traumatic resin ducts and density fluctuations) within the tree ring. In the Swiss Alps, Stoffel et al. (2008b) have used the intra-seasonal position of debris-flow damage in trees, local rainfall records and data on floods in neighboring catchments to reconstruct more than four centuries of debris-flow activity at Ritigraben (Valais) with monthly resolution. Results of this study are illustrated in Figure 6 and clearly demonstrate that the main debris-flow season at the study location shifted from June and July during the second half of the nineteenth century to August and September over the last 50 years.

## *2 Spread and reach of debris flows on cones*

When records of the frequencies of earth-surface processes are coupled with spatial information, the spread and reach of debris flows can be determined. In particular, the use of detailed geomorphic maps and accurate positioning of trees reacting simultaneously to an event provide

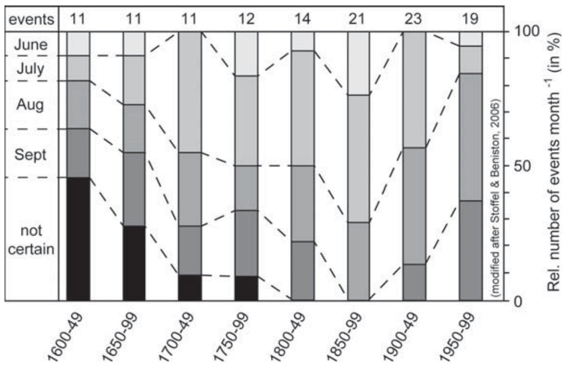


**Figure 6.** Seasonality of past debris-flow activity at Ritigraben (Swiss Alps) as inferred from the intra-annual position of tangential rows of traumatic resin ducts and injuries in the tree ring, archival data on flooding in neighboring catchments as well as daily meteorological data (AD 1864–2005)
*Source*: Adapted from Stoffel and Beniston (2006)

valuable spatial data on individual debris flows in the past. Based on (1) a detailed geomorphic map of deposits related to past debris-flow activity and (2) dendrogeomorphic results, the spatial patterns of past events were reconstructed for the Bruchji cone, Swiss Alps (Bollschweiler et al., 2007). Flow patterns were attributed to each of the 40 events documented for the period AD 1867–2004. By way of example, Figure 7 illustrates two of the five patterns identified, clearly showing that different events will affect different segments of the cone. In a similar way, spatial analysis of trees affected by an event allows identification of outbreak locations of debris flows and locations with overbank sedimentation (Stoffel et al., 2008a; Mayer et al., 2010; Sorg et al., 2010). The definition of breakout locations and the activity of channels over the past decades and centuries assumes key importance in hazard assessment and risk analysis on debris-flow cones (Bollschweiler et al., 2008a).

Spatio-temporal information on debris-flow activity can also be used for the understanding of depositional processes on cones. At Ritigraben, analysis of injured, buried, or tilted survivor trees in deposits allowed dating of 249 out of 291 lobes identified on the present-day surface of the cone (86%). Figure 8 shows that a large majority of lobes visible on the present-day surface of the cone were deposited during the last 70 years. In contrast, as few as six deposits (2%) were attributed to pre-eighteenth-century events, despite the fact that one in three debris flows was dated to the period AD 1570–1790 (Stoffel et al., 2008b). Stoffel (2010) also illustrates that smaller debris flows are characterized by higher snout elevations, early deposition of material and more limited spread of surges as compared to larger events.

## 3 Definition of debris-flow magnitudes

Based on: (1) the height or dimension of growth defects on stems, (2) the spatial distribution of trees showing signs of disturbance to a specific debris flow in their tree-ring record, or (3) the dating of individual deposits, it is sometimes also possible to determine magnitudes of past events. In his pioneering tree-ring work on debris flows at Mount Shasta (California), Hupp (1984) states that events of small magnitudes have shorter recurrence intervals than do large-magnitude ones. Strunk (1988) coupled tree-ring data with stratigraphic records (ie, layer thickness) and presented rough volume estimates for episodic debris-flow events in the Italian Dolomites. On the basis of the spread of individual surges, amount of material left on the cone during specific events, seasonality of incidences,

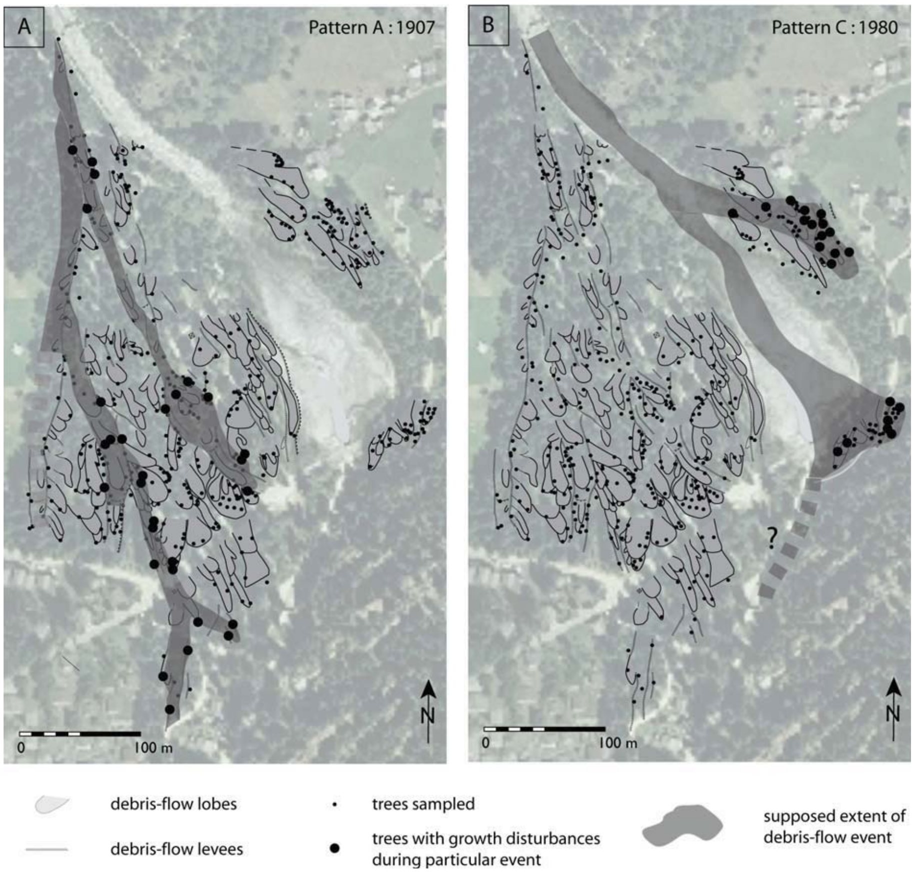


**Figure 7.** Spatial patterns of past debris-flow events at Bruchji torrent. (A) Example for event affecting the western and central part of the cone as in 1907. (B) The event of 1980 influenced only the eastern part of the cone.
*Source*: After Bollschweiler et al. (2007); aerial view: swissimage © 2010 swisstopo (BA100091)

rainfall intensities and mean rock sizes, Stoffel (2010) determined four magnitude classes of debris flows for 62 events in a small, periglacial watershed of the Swiss Alps since AD 1863.

## 4 Identification of debris-flow triggers

Debris flows are usually triggered by sudden inputs of large amounts of water (Iverson, 1997) originating from atmospheric conditions (eg, rainfall, rapid snowmelt) or geomorphic events (eg, sudden drainage of water pockets, rupture of moraine- or landslide-dammed lakes). The identification of triggers can often be identified for current events (Guzzetti et al., 2008), but it is not easy to track down triggers for events that have occurred in the past. If rainfall thresholds are to be integrated in forecasting and warning systems, the definition of thresholds needs to be based on extensive and reliable data sets. Data on past events is not normally available and thresholds based on a limited number of more recent events may potentially lead to spurious errors. Again, tree rings may be of considerable help in enlarging data sets of past triggering thresholds.

A regional analysis of torrents producing simultaneous debris flows can help the


**Figure 8.** Deposition of debris-flow material on the cone of the Ritigraben torrent between 1902 and 1934. Only events associated with >600 $m^3$ 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.
*Source*: Adapted from Stoffel et al. (2008b)

assessment of triggers. Bollschweiler and Stoffel (2010b) have recently demonstrated that debris flows occurring in a single torrent are most probably the result of very local (convective) rainfall or originating from geomorphic particularities in the catchment area such as outbreaks of water pockets or the formation of temporary landslide dams. In contrast, debris flows occurring in several torrents of a region at a time often reflect regional rainfall (ie, advective storms). In addition, the comparison of event frequencies in a torrent with data on floods in neighboring watersheds may considerably help identification of triggers and synoptic weather patterns (Stoffel et al., 2005a). Except for studies based on regional data bases, individual catastrophic events or more recent incidences from different regions (Caine, 1980; Guzzetti et al., 2008), studies on thresholds for the triggering of debris flows remain very scarce to date. In addition, the definition of thresholds for the triggering of debris flows is highly site-dependent and it does not seem possible to define fixed rainfall thresholds for a certain region.

For the Ritigraben torrent (Swiss Alps), Stoffel et al. (unpublished data) compared tree-ring based event frequencies with meteorological data to determine debris-flow triggering rainfall thresholds. At their study site, precipitation totals recorded during individual debris-flow events greatly differed and ranged from 10 to 179 mm (mean: 40.1 mm; SD: 29.8 mm) over the last 150 years. While there is a certain dependency of debris-flow magnitude on precipitation inputs (Table 1), it becomes also quite obvious that rainfall thresholds needed for the

**Table 1.** Hydrometeorological conditions observed during debris-flow events at Ritigraben since AD 1864 (JJAS stands for June, July, August, and September; bold indicates peak in activity)

| Characteristics | S | M | L | XL |
|---|---|---|---|---|
| Precipitation type | convective | convective | adv./conv. | Advective |
| Precipitation totals (mean) | 26 mm | 27 mm | 51 mm | 88 mm |
| Precipitation totals (min) | 10 mm | 12 mm | 21 mm | 49 mm |
| Precipitation totals (max) | 52 mm | 50 mm | 179 mm | 116 mm |
| Duration of rainfall event | <24 h | <24h | <24–96 h | 48–72 h |
| Seasonality | **JA**S | **JJA**S | **JJA**S | A**S** |
| Particle sizes (Ø) | < 0.5 m | 0.5–1 m | 0.5–1 m | 1–2 m |
| Magnitude ($m^3$) | **$10^2$–$10^3$** | **$10^3$–$5\times10^3$** | **$5\times10^3$–$10^4$** | **$10^4$–$5\times10^4$** |

release of events increase over the debris-flow season and will depend on the state of the rock-glacier body (ie, active layer thickness of the permafrost) located in the source area of debris flows.

In a watershed from non-permafrost environments (Swiss Alps), Szymczak et al. (2010) identified triggers of more recent events based on tree-ring and meteorological data. Triggering rainfalls occurred predominantly in June and July and were rare in August and September. Largest daily rainfall sums leading to the release of debris flows totaled 48 mm and the largest intensity observed was 12 mm/h.

## V Application of tree rings in other mass-movement reconstructions

Dendrogeomorphology has been used in the analysis and reconstruction of a wide range of mass-movement processes. This section does not claim to be exhaustive, but references some selected early studies and significant follow-up papers in the fields of mass-movement processes.

### *1 Creeps*

The slow movements of rock glaciers have been documented in several case studies. In his pioneering investigation of a glacier-like boulder deposit on Table Cliffs Plateau (Utah), Shroder (1978) documented 200 years of movements and suggests that precipitation would possibly be the trigger for the main episodes of movements. Other studies on movements in permafrost complexes have been performed elsewhere in North America ever since (Giardino et al., 1984; Carter et al., 1999; Cannone and Gerdol, 2003; Bachrach et al., 2004) but are non-existent in the European Alps or other alpine regions. Relatively little work has been realized on other creeping mass movements since Jakob's (1995) analysis of movement rates of gelifluction lobes.

### *2 Slides*

Landslides represent a type of mass movement regularly investigated with tree rings. Dendrogeomorphic analysis of landslides started in the 1980s with several case studies in Québec (Bégin and Filion, 1985, 1988; Filion et al., 1991) documenting nineteenth-century landslides along the Great Whale River using buried trunks in flowing sediments or tilted trees. In the French Alps, Braam et al. (1987a, 1987b) assessed recent landslide activity from eccentricity variations in trees sampled in the Barcelonette region. More recently, landslides were analyzed in the basin of the Llobregat River (Pyrenees) and two different rainfall patterns triggering landslides identified (Corominas and Moya, 1999). In Italy, dendrogeomorphology has been used repeatedly for the identification of landslide dynamics in Calabria and the Apennines based on growth series of *Quercus* sp. (Fantucci and McCord, 1995; Fantucci and Sorriso-Valvo, 1999; Stefanini, 2004) and results have been compared with meteorological data to identify triggering rainfall events. In the first study in the subtropics, Paolini et al. (2005) used suppression-release patterns and inception of *Alnus acuminate* to date a number of landslides in Argentina.

### 3 Flows

Various flow-type mass movements have been studied in the past with dendrogeomorphic methods with a main focus on snow avalanches as well as debris flows and related processes. In the following, we provide a short overview on tree-ring studies in snow avalanche research.

The reconstruction of snow avalanches with tree rings started with Schaerer's (1972) pioneering study on the vegetation in avalanche terrain at Rogers Pass in British Columbia (Canada). The main research then continued to take place in North America and especially in the Glacier National Park, where Butler (1985), Butler and Malanson (1985b), and Butler and Sawyer (2008) published a series of papers on the dating of trees damaged by snow avalanches. Similarly, several studies focus on snow avalanches and hazard assessement on the Gaspé Peninsula (Boucher et al., 2003; Dubé et al., 2004). Larocque et al. (2001) used impact scars, tangential rows of traumatic resin ducts and reaction wood to analyze frequency–magnitude relationships of slushflows (ie, liquefied snow) on the Gaspé Peninsula. Only a very limited number of studies have, in contrast, been published on snow avalanches in Europe, where tree-ring based analysis of snow avalanches has mainly focused on the Pyrenees (Muntán et al., 2004, 2009). In the Swiss Alps, Stoffel et al. (2006a) studied a cone affected by snow avalanches descending from three different couloirs and were able to distinguish the damage induced by the windblast from that induced by snow and transported material. Recently, snow avalanches were investigated with tree rings in Patagonia (Mundo et al., 2007; Casteller et al., 2009).

### 4 Falls

The most important mass-movement process of the fall type is rockfall, which includes the free falling, bouncing or rolling of individual or a few rocks and boulders (Berger et al., 2002). The first studies of rockfalls using tree rings focused on the identification and dating of large rock avalanches (Butler et al., 1986; Moore and Mathews, 1978) rather than on the reconstruction of the release of individual rocks and boulders during much smaller rockfalls. Lafortune et al. (1997) assessed sedimentation rates and forest edge dynamics. The first studies focusing on the seasonality, frequency, and spatial patterns of rockfalls using tree rings were undertaken in the Swiss Alps yielding data on 400 years of rockfall activity on a forested slope (Stoffel et al., 2005b, 2005c). The methods have since been applied to other sites in Switzerland by Perret et al. (2006) and Schneuwly and Stoffel (2008a, 2008b), providing a reliable basis for the analysis of rockfall risks and the accuracy assessment of rockfall models (Stoffel et al., 2006b). Recently, Moya et al. (2008, 2010) presented different strategies of tree sampling for the reconstruction of complete rockfall chronologies from visible injuries in *Quercus robur* in Solà d'Andorra (Eastern Pyrenees).

## VI Future directions

Tree rings have proved to be a very valuable source of information in the reconstruction of past mass-movement processes, as has been shown above. In the following section, we sketch out some future directions in debris-flow research using tree rings.

### 1 Methodological developments

Many different impacts can produce disturbance in tree-ring series and the problem is to identify and isolate the signal related to the process under study from other potential sources of disturbance. One important approach is to develop measures such as the 'tree-ring response index' suggested by Butler et al. (1987) so as to distinguish 'signals' from 'noise' in the chronologies developed. This approach is applicable to processes with a strong spatial footprint such as snow avalanches, floods, or wildfires. Accurate dating of past occurrences can be done with reasonable confidence based on the temporal synchronicity of signals across samples. However, more studies are needed to determine threshold levels for the reconstruction of debris flows which can affect trees in very restricted areas.

Besides the question of the signal-to-noise ratio, dendrogeomorphic studies also face uncertainties resulting from biological and tree physiological causes. Other dating limitations are more related to the fact that – although ring series develop continuously – trees are not equally sensitive responders to geomorphic disturbance over their lifetimes. As a consequence, the response and likelihood of recording an event may vary over time, and may also vary differently for different locations within the sampled network. In this sense, it appears obvious that tilting a younger tree is easier than tilting an older tree, but it is less obvious when a tree becomes rigid enough to resist unilateral pressure. Uncertainties and limitations of this kind attain key relevance when recurrence intervals or changes in frequency are assessed over time based on observing systems that may have differential responses over time. Experimental research is, therefore, needed to determine the optimal size and age (or range of ages) for sampling different species. It may be necessary, perhaps, to specify a restricted size range of 'sample responders' to avoid compromising results.

Similarly, additional and alternative 'dendrogeomorphic' techniques in debris-flow research should be initiated (Solomina, 2002). Further progress could be expected through the use of densitometric, resistograph (Lopez Saez et al., 2008, 2010) or computer tomography (CT) analyses in dendrogeomorphic research, mainly for the identification of tension wood in broadleaved trees or the identification of hidden injuries in cross-sections.

## 2 Application of dendrogeomorphic techniques to processes related to debris flows

In the past, tree-ring records have frequently been used to obtain temporal and spatial data on debris-flow activity. Significant progress has been made with respect to the methods used, dating accuracy, and the overall understanding of process dynamics. This paper has illustrated classical and recent studies on tree-ring reconstructions of debris flows, but there is, in addition, a plethora of processes related to debris flows where the different methods developed could be applied in the future as well.

(1) Debris floods and hyperconcentrated flows are characterized by a Newtonian flow behavior and much smaller proportions of solid discharge than debris flows. Recent studies have demonstrated that there is also potential for conventional dendrogeomorphic methods to be used for the reconstruction of histories of debris flood and hyperconcentrated flow. Based on the analysis of spread and reach of debris-flow events as well as on the nature of damage caused to trees, Bollschweiler et al. (2007) were able to distinguish classic debris flows from hyperconcentrated flows on a torrential cone in the Swiss Alps. Mayer et al. (2010) reconstructed 200 years of debris-flood frequency, spread and breakout location of debris floods on a fan in the Austrian Alps.

(2) In the Spanish Central System, Ballesteros et al. (2010) and Ruiz-Villanueva et al. (2010) used tree-ring series of *Pinus pinaster* to identify flash floods and to distinguish larger frequency–smaller magnitude from smaller frequency–larger magnitude events.

(3) Lahars are muddy debris flows occurring in volcanic environments and released through the sudden melting of snow and ice by volcanic activity or heavy rainfall. As a result of their unpredictable occurrence, high sediment content including large boulders, and their ability to rapidly travel long distances over low gradients, lahars represent one of the most destructive of natural hazards (Fisher and Schmincke, 1984; Vallance, 2000). Lahars have repeatedly caused loss of lives in the past, for instance at Nevado del Ruiz (Colombia) in 1985 (Pierson et al., 1990) or at Ruapehu (New Zealand) in 1953 (Cronin et al., 1997; Lecointre et al., 2004). Pioneering tree-ring work on lahars was performed by Cameron and Pringle (1986) dating events at Mount St Helens. More recently, Bollschweiler et al. (2010) calibrated growth reactions of trees to lahar impact with two known lahar events. Based on the data obtained, they were able to identify additional, previously undocumented events at Popocatépetl volcano, Mexico. Even though these studies document the suitability for and the significant contribution of tree rings to lahar research, dendrogeomorphic lahar studies have remained very rare so far.

## 3 Model calibration

Physically based debris-flow models require realistic input parameters related to initiation conditions, flow behavior, or deposition processes. For most watersheds, on-site information on such input or on the potential range of debris-flow events is rather limited if present at all. Through the coupling of tree-ring records with detailed field data (eg, laser-scan models, surface roughness, grain size distributions), data necessary for a realistic representation of past, contemporary and potential future debris-flow events may be obtained. Initial accuracy assessments of a debris-flow model are currently being performed with the two-dimensional RAMMS model (SLF, 2009) using dendrogeomorphic data from the Ritigraben torrent (Graf et al., 2009). Similar to the results obtained from tree-ring calibrated rockfall modeling results (Stoffel et al., 2006b), it is expected that the large tree-ring data sets will also facilitate realistic modeling, the quantification of inaccuracies or uncertainties as well as model improvements at Ritigraben.

## 4 Climate change impacts on debris-flow activity

There is currently much debate about the impacts of global climatic change on debris-flow frequency and magnitude (Kotarba, 1992; Jakob and Friele, 2009; Bollschweiler and Stoffel, 2010a). Some studies suggest that the current global warming might lead to an increase in the frequency of extreme precipitation events (Fowler and Hennessy, 1995; Easterling et al., 2000; Fowler and Kilsby, 2003) and therefore enhance the occurrence of high-elevation mass-movement processes (Rebetez et al., 1997). Others state that there would not be such an increase in event frequency (Van Steijn, 1996; Blijenberg, 1998; Stoffel et al., 2008b). Jomelli et al. (2004, 2007) even report a significant decrease in the number of small, low-elevation debris flows since the 1980s in the Massif des Ecrins (French Alps). However, before making conclusive statements about possible feedbacks of climatic change on the occurrence of debris flows, the natural variability of extreme weather events must be understood. Sletten et al. (2003) pertinently emphasize that records of past debris-flow activity may be particularly useful in the recognition of process dynamics and the role of precipitation events.

Several studies have tempted to relate debris-flow frequency with climate parameters in the past. Bollschweiler and Stoffel (2010a), for instance, were able to demonstrate that debris-flow activity in the southern Swiss Alps has been reduced in watersheds with high-elevation source areas throughout the Little Ice Age (LIA) and until the end of the nineteenth century. Their results also indicate that, in contrast, a largely increased number of events occurred during a series of warm-wet summers in the 1920s and 1930s (Pfister, 1999). Interestingly, a considerable decrease in debris-flow activity is observed in the eight torrents investigated during the last 10 years (2000–2009).

Stoffel et al. (2008b) observe very similar trends for the Ritigraben torrent (Swiss Alps) for the LIA, the early decades of the twentieth century and for the last decade. In addition and based on results from Regional Climate Model runs with the IPCC A2 greenhouse-gas emissions scenario (Beniston, 2006; Stoffel and Beniston, 2006), they postulate that a clear shift in the occurrence of heavy precipitation events over the Swiss Alps from summer to autumn will become obvious by the end of the century. As spring and autumn temperatures are projected to remain 2–5°C degrees below current summer temperatures (implying lower freezing levels in future springs and autumns as compared with current summers) snowfall would probably prevent the entrainment of flows from the high-elevation source areas of these watersheds and thus have a buffering effect on runoff. As model projections, at the same time, suggest a decrease in heavy summer rainfall events, it is conceivable that the overall frequency of events would be reduced (Stoffel et al., 2008b), leaving more time for debris to accumulate in the channel and possibly lead to larger-magnitude events in the future.

The examples presented above are first attempts to improve our overall understanding of climate change feedback on debris flows. Major limitations and gaps in knowledge remain, as the studies presented are focused on specific high-elevation sites in the Swiss Alps with very specific geomorphic settings. More research is therefore needed in watersheds with lower source area elevations, different lithologies or different boundary conditions so as to identify similarities or discrepancies of climate change effects on debris-flow activity, if possible through collaborative projects between geomorphologists and climate scientists.

## VII Conclusion

The initial use of tree rings in natural hazard studies was simply as a dating tool and rarely exploited other environmental information that could be derived from studies of ring-width variations and records of damage contained within trees (Stoffel et al., 2010a). In recent years, dendrogeomorphology has evolved rapidly, and is now providing copious amounts of data on the temporal and spatial occurrence of debris flows. Nevertheless, tree-ring studies have their limitations as well. Spatially, reconstructions are limited to the availability of trees forming increment rings; temporally, the limit is set through tree age. Even though these limitations exist, the unique, annually resolved tree-ring records preserve potentially valuable archives of past geomorphic events on timescales of decades to centuries. Temporal and spatial information gained from tree rings therefore is of crucial importance for the understanding of the distribution, timing, and controls of events. In addition, it provides valuable information that can assist in the prediction of mitigation and defence against these hazards and their effects on society. To foster our understanding of debris-flow occurrence and triggering, more research is needed along the lines illustrated above and to establish and compare regional or supra-regional event chronologies. Similarly, the development of databases should be one of the primary goals in future research.

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