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Research paper

How to improve dating quality and reduce noise in tree-ring based debris-flow reconstructions

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ABSTRACT

Tree rings have been used to reconstruct the occurrence of debris flows and other mass movements. Identification of past activity was typically based on the presence of growth anomalies in trees, with a focus on scars, stem tilting, trunk burial or apex decapitation. Clear guidelines have been missing so far and the dating of events has only rarely been based on thresholds so as to distinguish signal from noise. In a similar way, the spatial distribution of affected trees has not normally been considered in mass movement reconstructions, and was at best used as a subjective exclusion factor. This study therefore aims at improving dating quality of and reducing noise in debris-flow time series. Based on a dataset of 803 increment cores (385 trees) affected by debris flows, we reconstruct event histories using (i) a classical experts' approach, (ii) a weighted index (W_{it}) of responding trees as well as (iii) Moran's *I* and Getis–Ord Local Gi indices. We identify similarities and differences in results and then investigate subsets of the tree-ring sample to define ideal sampling positions on debris-flow cones and guidelines for sample depth.

1. Introduction

In recent decades, the occurrence of mass-wasting processes has repeatedly led to important economic losses and casualties (Jakob and Hungr, 2005). In an attempt to reduce disaster risk, enhanced knowledge on the occurrence and (spatial) behavior of past events is of crucial importance. As archival data is not usually very extensive or often completely missing, an urgent need exists for the creation of improved databases on past disasters (Ballesteros et al., 2011). Geochronological methods have been demonstrated in the past to have the potential to provide extensive time series of past disasters. However, several of the approaches applied in previous work (Schneuwly-Bollschweiler et al., 2012) have not been used for the assessment of hazards and risks in the first place, and thus need improvement so that more accurate and denser time series and more precise ages of mass-wasting activity can be obtained for the past decades up to centuries and for varying spatial scales.

In temperate regions, trees affected by mass movements typically record the evidence of past events in their growth-ring series and therefore provide a precise geochronological tool for the reconstruction of past mass-movement activity (Stoffel et al., 2010a). In the past, various procedures have been defined for the identification of characteristic growth disturbances (GD) and the definition of events (Alestalo, 1971; Shroder, 1978). However, the evidence left in trees and the nature and extent of damage in individual trees or entire forest stand will be dictated ultimately by the nature of the process investigated (Stoffel and Perret, 2006; Stoffel et al., 2013). Processes with a large spatial footprint (e.g., snow avalanches, landslides, floods) will tend to leave GD in a large number of trees, whereas only individual scars in one or a few trees will be found in the tree-ring record following rockfall activity (Perret et al., 2006; Schneuwly and Stoffel, 2008; Stoffel et al., 2005; Corona et al., 2013; Trappmann et al., 2013).

Different approaches and thresholds have thus been defined to reconstruct process activity. In snow avalanche research, for instance, a minimum of 10% (and up to 40%) of all sampled trees typically need to exhibit GD in the same year for an event to be accepted (Butler and Malanson, 1985; Butler and Sawyer, 2008; Dubé et al., 2004; Germain et al., 2009; Pederson et al., 2006). More recently, Corona et al. (2012) postulated that a flexible threshold is preferable over a fixed value and that this threshold should be adapted based on the number of GD and the number of trees available for analysis.

In landslide research, thresholds have less often been applied. Lopez Saez et al. (2012), for instance, demonstrated that

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simultaneous reactions in ≥10 trees and 5% of the sampled population are sufficient to date past events with high accuracy. While their threshold is comparable with those used in flash flood and debris flood research (Mayer et al., 2010; Ruiz-Villanueva et al., 2010), it differs quite substantially from values used in previous landslide research, where reactions in one single tree have been considered sufficient for the identification of past landsliding (Bégin and Filion, 2010; Fantucci and Sorriso-Valvo, 1999).

Debris flows generally affect more limited surfaces as compared to avalanches, landslides or floods (Stoffel et al., 2013) and cannot therefore be reconstructed with the same thresholds. As debris-flow surges tend to leave channels in only one or a few areas (Stoffel, 2010), they will not necessarily leave a large spatial footprint in the tree-ring record. As a consequence, quantitative thresholds have not been applied systematically so far nor have spatial patterns of affected trees been used as a criterion for the definition and reconstruction of past events.

This study therefore aims at providing a more objective means for the reconstruction of past debris flows and at improving dating quality of debris-flow time series. We present a systematic approach taking account of the intensity and number of GD and introduce geostatistical indices to account for the spatial distribution of affected trees. Based on the event chronology derived from a large set of trees affected by debris flows, we also test subsets of trees with different spatial distributions on the depositional cone to define an appropriate sampling strategy and to obtain optimal signal-noise ratios in the results.

2. Regional setting

The Wildibach torrent (46°07′N/7°47′E; Fig. 1) is located in the Zermatt valley (Valais, Swiss Alps), an inneralpine north–south oriented valley, ca. 8 km N of Zermatt. The catchment extends from 4545 m asl (Dom) to the confluence of the Wildibach torrent with the Vispa River at 1420 m asl. About 30% of the catchment is glaciated and periglacial processes and features (i.e. moraines, rock glaciers) dominate much of the remaining catchment area. Geology is composed of Permian gneisses (Labhart, 2004; Pfiffner, 2009). Mean annual air temperature in Zermatt (1638 m asl) is 3.9 °C and mean annual precipitation is 690 mm (1900–2008). High annual and day-time thermal ranges favor weathering processes which provide abundant material for matrix poor debris flows with block sizes of up to 2 m (Schneuwly-Bollschweiler and Stoffel, 2012; Stoffel et al., 2011). A large (31 ha), but relatively flat (mean slope angle: 13°) cone has formed at the outlet of the steep main channel (average 23°); it is covered with a forest composed of *Larix decidua* Mill. and some *Picea abies* (L.) Karst., but deposits of past debris flows remain clearly visible. The outermost segments of the cone are used for grazing and housing. The main road and the railway line intersect the cone in its lowermost part. The Wildibach torrent is known to produce debris-flow events; however, archival records are scarce and contain information on events in 1927, 1932, 1978, and 2000 (Valais, 2009; Zimmermann et al., 1997). The debris flow of 1978 caused extensive damage on the cone and led to the construction of deflection dams and a retention basin.

3. Material and methods

3.1. Field work and laboratory analysis

An area of 12 ha has been selected on the cone where debris flows have obviously affected trees in the past and where signs of anthropogenic influence are absent. All features related to past debris-flow activity (i.e. lobes, levees, abandoned flow paths) were

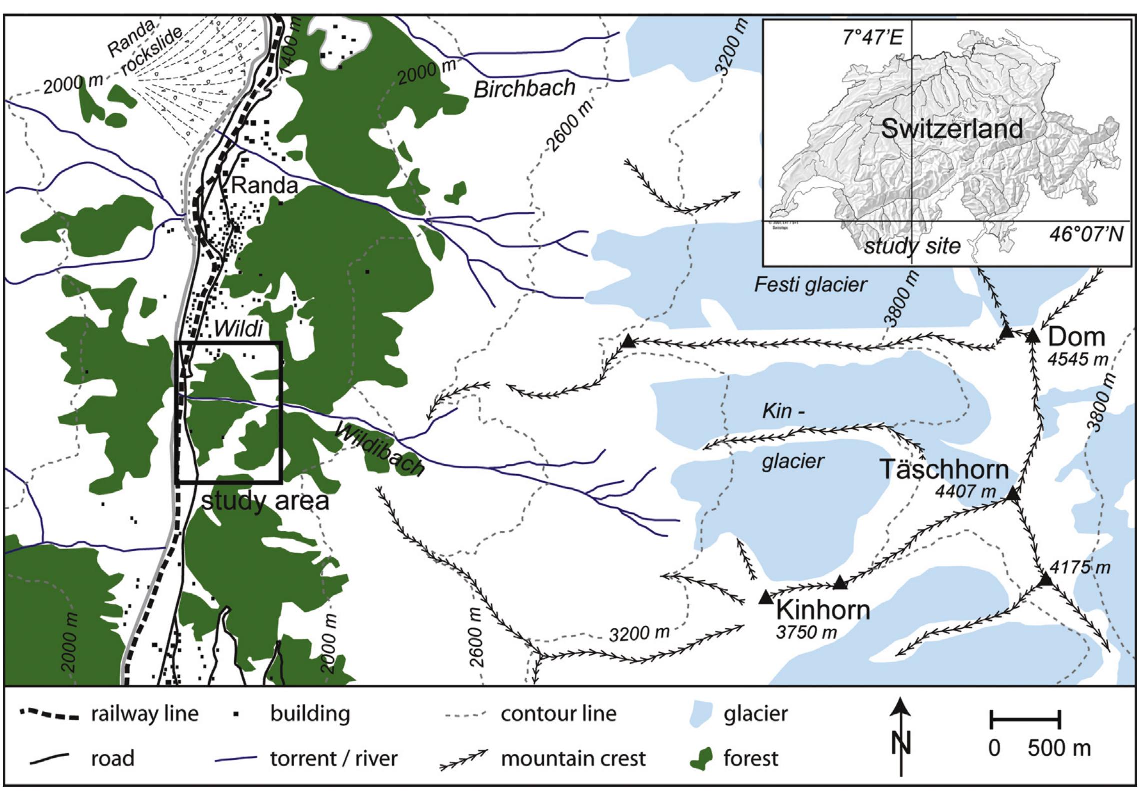

Fig. 1. The Wildibach cone is located in the Zermatt Valley, Swiss Alps. The upper parts of the catchment area are glaciated. The study area is focused on the debris-flow cone on the valley floor.

mapped in the field using tape measure, compass and inclinometer. A total of 385 trees (381 *L. decidua* and 4 *P. abies*) affected by past debris-flow activity (i.e. injured, tilted, decapitated or buried trees) were sampled with 803 increment cores. The location of each tree sampled was noted on the geomorphic map (Fig. 2).

Trees were processed following standard dendrogeomorphic procedures (Stoffel and Bollschweiler, 2008, 2009) individual series cross-dated using a local reference chronology (Stoffel et al., 2005) so as to correct for missing or false tree rings. Growth disturbances in the tree-ring series (injuries, tangential rows of traumatic resin ducts, compression wood, abrupt growth increase or suppression) and their intensity (weak, moderate, strong) were defined following the classifications of Kogelnig-Mayer et al. (2011) and Procter et al. (2011). Master chronologies of all growth disturbances were then computed for each year and the location of the disturbed trees represented graphically in a Geographic Information System (GIS).

3.2. Classical expert's approach

The identification of years with debris-flow activity was performed in a first step using a classical expert approach, where past events are accepted as such if a representative number of trees located next to each other or along the same flow path show simultaneous GD (Bollschweiler and Stoffel, 2010; Bollschweiler et al., 2008; Stoffel and Beniston, 2006; Stoffel et al., 2008). This approach is based on the experience of the investigator and does not take account of fixed thresholds (neither of GD number nor intensity).

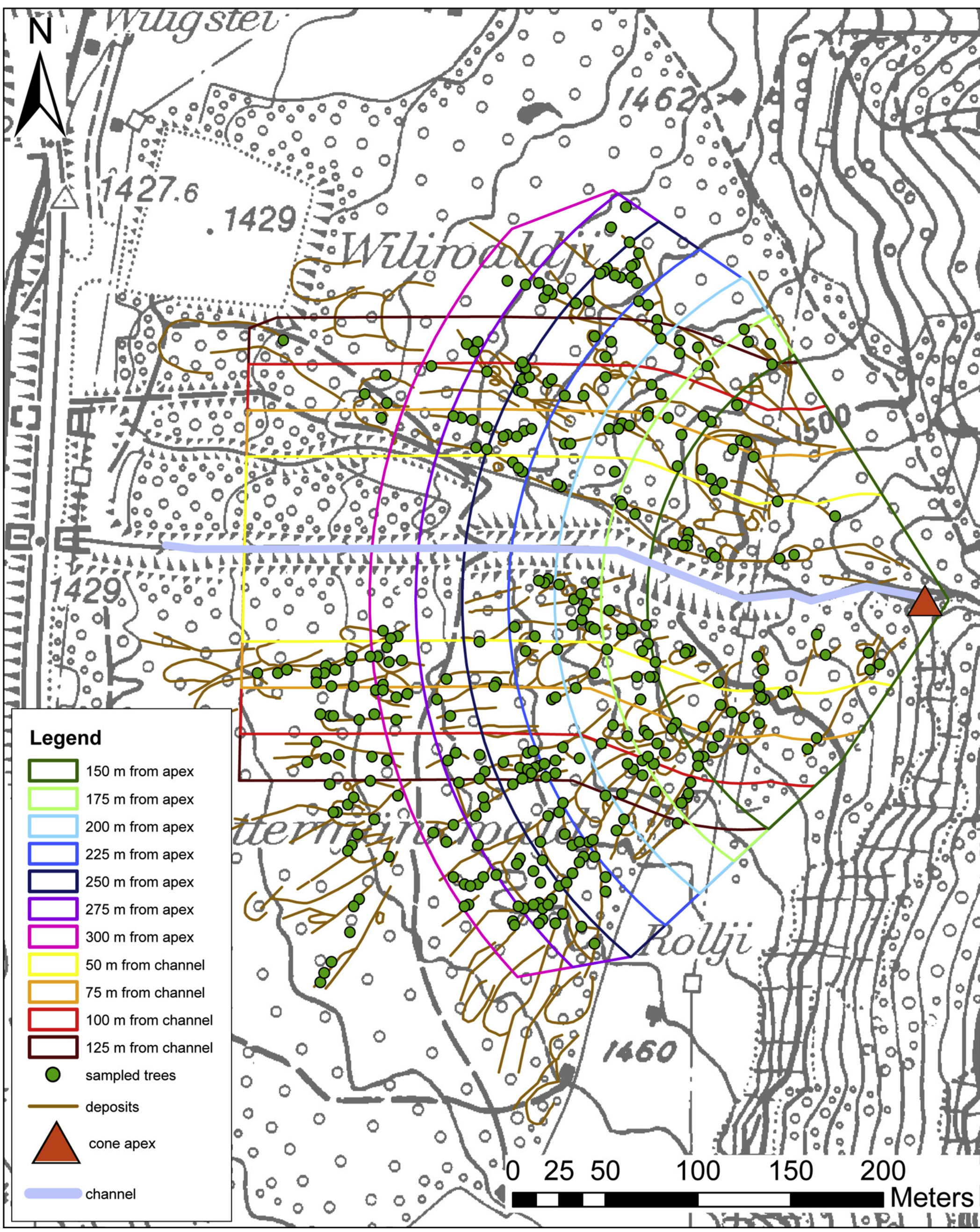

Fig. 2. Map of the Wildibach cone with all geomorphic deposit features and the position of trees sampled for this study. Subsets of the trees within certain distances (colored lines) were used for analysis of the ideal sampling strategies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Weighted index and spatial parameters

The same dataset was then analyzed with a weighted index (W_{it}; Kogelnig-Mayer et al., 2011) to distinguish signal from noise. The W_{it} takes account of the number of GD, GD intensity and the total number of trees available for the reconstruction. The W_{it} was calculated for each year of the period covered by the reconstruction (1600–2008).

In addition, we calculated Local Moran's *I* (referred to as Moran index hereafter) and Getis–Ord Local Gi (Getis index hereafter) indices (Anselin, 1995; Getis and Ord, 1994; Moran, 1950) to describe the spatial distribution of trees affected in individual years. Both approaches characterize the spatial autocorrelation of trees with simultaneous GD. The Moran index identifies clusters of points where positive values indicate a high spatial clustering of reacting trees and negative values express low clustering. The Getis index, in contrast, is used to illustrate areas of spatial clustering (Lasaponara et al., 2010). *Z* scores were used to indicate the significance of individual Moran index values. Both indices are available in commercial GIS software, and have been used in previous geomorphic research for the determination of landslide histories (Lopez Saez et al., 2012) or channel bed migrations (Takagi et al., 2007).

3.4. Testing the optimal sampling strategy

Based on the above considerations, we also aimed at defining optimal sampling strategies where the largest number of events can be identified and where noise can be minimized. Analysis was based on GD and W_{it} thresholds. Moran and Getis indices were disregarded for initial analyses. We modeled different sampling strategies, namely (i) defined sample depths (50–385) with trees being selected randomly over the cone, (ii) all trees located within a certain distance (50–125 m; see Fig. 2) from the current channel, (iii) all trees located within a certain distance (150–300 m) from the cone apex and (iv) all trees located within a certain distance (50–100 m) from the current channel and the cone apex (150–300 m). Within approach (i), 100 subsets of *n* trees were computed to reduce the dependence of results on sampling location. We then tested the influence of thresholds (GD = 2–10, W_{it} = 0.2–2) on reconstructed debris-flow series. For each of the modeled sampling strategies and thresholds, results were compared with the event chronology obtained with the classical expert approach to quantify the proportion of correctly identified (signal) and misdated (noise) debris flows. Noise is defined here a year considered an event based on the GD and W_{it} threshold but identified as a non-event in the classical expert approach (with or without Moran and Getis indices).

4. Results

4.1. Event frequency as reconstructed with the classical expert's approach

The average age of trees sampled on the Wildibach cone amounts to 193 yr (STDEV: 102 yr) with the oldest individual dating back to AD 1509 and the youngest tree reaching sampling height in AD 1980. A total of 581 GD relating to past debris-flow activity are identified in the tree-ring series. Using the expert approach, we reconstruct 50 debris-flow events between 1623 and 1978 (Fig. 3). The frequency distribution shows a clustering of events in 1815–1850 and 1890–1930, and clearly reduced activity between 1850 and 1890. Debris flows are missing in the reconstructed time series after 1978 as reflection dams are now preventing events from leaving the channel. The overall return period is 4.2 yr for 1800–1978 and the mean decadal frequency of debris-flow occurrences is 2.4.

4.2. Weighted index and spatial parameters

The number of GD and weighted index values (W_{it}) of debris flows dated with the expert approach are presented in Table 1; years with debris-flow activity show W_{it} values ranging from 0.6–5.9 (mean: 2.2) and a GD number of 3–22 (mean: 11.6).

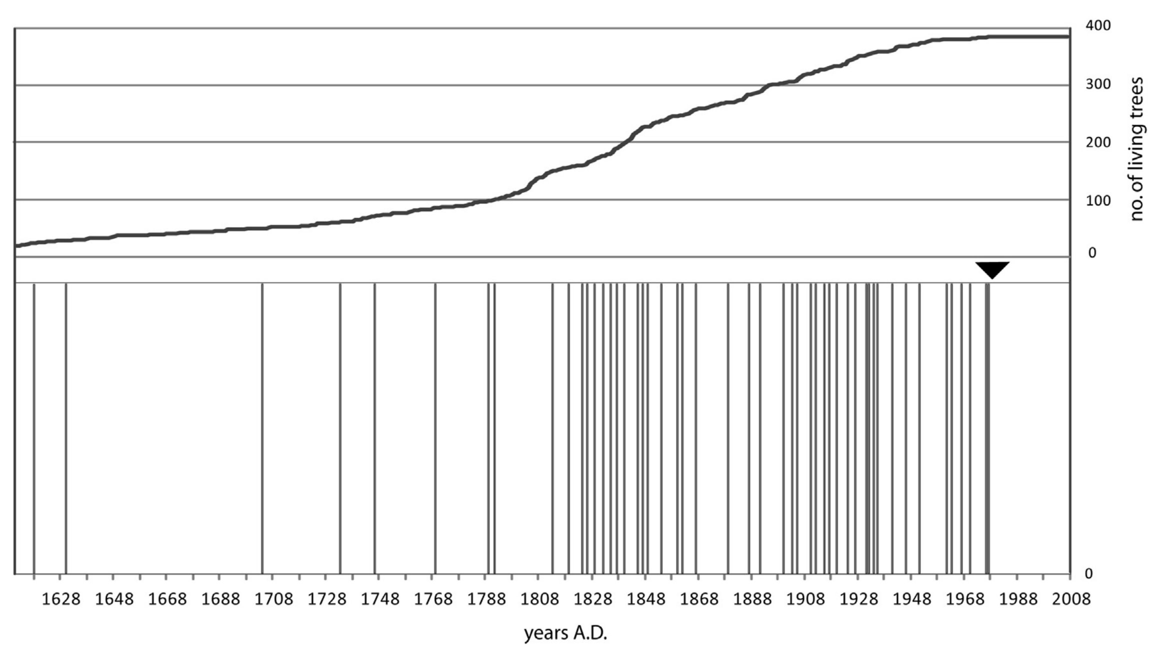

Fig. 3. Debris-flow event frequency for the Wildibach torrent. The line in the upper part of the figure indicates the number of trees available for reconstruction. The limited number of trees before 1800 also influences the reconstruction density. The black triangle indicates the moment of protection measures and therefore the last debris flow that affected the cone and trees.

All years with $W_{it} > 1$ are identified as events in the expert approach; this value is suggested to represent a reasonable threshold for the identification of debris flows in the region under investigation. For the 13 years with lower weighted index values ($0.5 \leq W_{it} \leq 1$), five were considered events (signal) in the expert approach and eight regarded as noise. As the consideration of W_{it} as the only quantitative criterion may lead to a misclassification of events in debris-flow histories, we added Moran's *I* and Getis-Ord Local Gi index values in Table 2 for all years with $0.5 \leq W_{it} \leq 1$. All years with high spatial clustering of responding trees (i.e. $I \geq 0.023$; $Z > 2.44$ and $Gi > 0.018$; $Z > 3.31$) have been identified debris-flow events in the expert approach. All years considered non-events in the expert approach exhibit random distributions of reacting trees and low index values ($I < 0.016$; $Z < 1.59$) and ($Gi < 0.009$; $Z < 1.96$). The inclusion of spatial metrics clearly improves the quality of the reconstructed time series based on W_{it} and GD values, but will not prevent the inclusion of noise in the time series.

In that sense, eight years are considered events due to the large enough number of GD and high W_{it} values. The same years have been disregarded in the expert approach due to the spatial arrangement of reacting trees.

Table: 1
Number and intensity of growth disturbances (GD) and weighted index values (W_{it}) for all event years. For details see text.

Year	No. of living trees	Weak GD	Medium GD	Strong GD	Injuries	No. of GD	Index value
1978	384	3	6	9	1	19	3.6
1977	384	1	5	9	0	15	2.4
1971	381	2	4	3	0	9	0.7
1968	381	0	9	6	0	15	2.2
1964	380	4	6	7	0	17	2.6
1962	380	1	10	3	0	14	1.7
1952	371	4	6	7	0	17	2.6
1947	369	3	7	7	0	17	2.7
1942	360	1	13	7	0	21	4.4
1936	356	1	7	4	0	12	1.4
1935	355	2	7	13	0	22	5.5
1933	352	0	7	3	0	10	1.0
1932	352	0	3	4	0	7	0.6
1928	345	2	5	7	0	14	2.1
1925	337	4	4	4	0	12	1.3
1921	333	3	6	2	0	11	1.0
1918	329	2	3	15	0	20	5.2
1916	325	2	5	5	0	12	1.6
1913	321	3	7	4	0	14	1.9
1911	319	0	7	5	0	12	1.7
1906	307	2	10	3	0	15	2.3
1904	306	0	4	5	0	9	1.1
1901	303	0	11	5	0	16	3.1
1892	287	2	5	5	0	12	1.8
1888	277	1	3	5	0	9	1.1
1880	270	1	6	1	0	8	0.7
1868	252	0	6	7	1	14	3.3
1863	248	3	5	4	0	12	1.8
1861	247	2	7	1	0	10	1.1
1855	236	1	9	4	0	14	2.8
1850	225	0	10	3	0	13	2.6
1848	217	2	9	5	0	16	4.0
1846	206	1	7	1	1	10	1.7
1841	191	3	6	3	0	12	2.3
1838	182	0	5	4	0	9	1.7
1836	179	0	7	2	0	9	1.6
1833	172	0	5	2	1	8	1.5
1830	165	2	5	6	0	13	3.7
1827	163	1	6	3	0	10	2.1
1825	162	0	10	6	0	16	5.9
1820	156	3	3	1	1	8	1.2
1814	142	1	3	4	0	8	1.7
1792	101	0	4	3	0	7	1.9
1790	100	0	5	1	0	6	1.2
1770	88	0	4	4	0	8	2.9
1747	70	0	3	2	0	5	1.4
1734	64	1	4	0	0	5	1.0
1705	55	0	0	3	0	3	0.8
1631	33	2	2	0	0	4	1.0
1623	27	0	2	2	0	4	2.4
Total	385	66	292	218	5	581	
Average	250.9	1.3	5.8	4.4	0.1	11.6	2.2

Table 2
Moran's *I* and Getis–Ord Local Gi index for all years with $0.5 \leq W_{it} \leq 1$. The higher the index values and *Z*-scores are, the higher the spatial clustering and the reliability of the result.

Year	Index value	Getis classification	Getis–Ord Local Gi index	*Z* score	Moran classification	Moran's *I* index	*Z* score
Events							
1971	0.69	Cluster	0.019	2.44	High cluster	0.018	3.31
1932	0.57	High cluster	0.023	2.69	High cluster	0.019	3.57
1880	0.71	Cluster	0.018	1.71	Cluster	0.008	1.67
1705	0.82	High cluster	0.074	5.58	High cluster	0.030	6.15
1631	0.97	High cluster	0.040	3.61	High cluster	0.021	4.13
Non-events							
1973	0.73	Random	0.013	0.52	Random	0.001	0.59
1950	0.61	Random	0.012	0.16	Random	0.006	1.45
1949	0.66	Random	0.016	1.59	Cluster	0.009	1.96
1941	0.78	Random	0.015	1.3	Random	0.004	1.04
1894	0.77	Random	0.008	−0.77	Random	−0.007	−0.65
1859	0.61	Random	0.009	−0.46	Random	−0.006	−0.49
1810	0.59	Random	0.009	−0.38	Random	−0.004	−0.17
1708	0.6	Random	0.0132	0.19	Random	−0.0007	0.35

4.3. *Defining the optimal sampling strategy*

In a further step, we tested the optimal number and spatial position of trees on the cone so as to maximize signal and minimize noise between the expert approach and data obtained with subsets of the tree-ring sample and/or varying thresholds. By way of example, Fig. 4A illustrates the number of events reconstructed in all trees. If a threshold of $W_{it} \geq 0.5$ and a $GD \geq 3$ are selected, a reconstruction of all events identified with the expert approach will be possible. As a result of the low threshold, however, eight cases of noise will be included in the debris-flow time series. These eight years were excluded in the expert approach as reactions were largely dispersed on the cone. The same years were also regarded non-events in the W_{it}–GD approach and based on the low Moran and Getis index values.

Fig. 4B illustrates that a subset of 150 trees will be sufficient to date 90% of the events correctly and to limit noise to 3 events. If analysis is based on all trees located within 250 m of the cone apex (no = 231), 94% of the events are reconstructed with a noise of 4 events (Fig. 4C). In contrast, Fig. 4D shows that sampling at a maximum distance of 125 m from the channel results in high noise even if "Moran years" are excluded.

Table 3 summarizes the best combinations of GD and W_{it} with the lowest noise for thresholds of 75, 80, 85, 90, 95, and 100% of debris flows reconstructed with the expert approach. In addition, the number of "Moran years" is given in parentheses in the noise column. If all trees within a distance of 100 m from the channel were selected, the best match to reconstruct a minimum of 85% was with $W_{it} \geq 0.5$ and $GD \geq 2$. However, noise will be huge in this case with 16 events, of which 5 were "Moran years". Table 3 also shows that 85% of the events can be reconstructed with a sample size of 150 trees ($W_{it} \geq 0.3$; $GD \geq 2$), resulting in a noise of only 4 events that are all "Moran years". The missing 15% events were all spatially limited events affecting a small number of trees. To reconstruct 95% of the events, a minimum of 200 trees need to be selected randomly

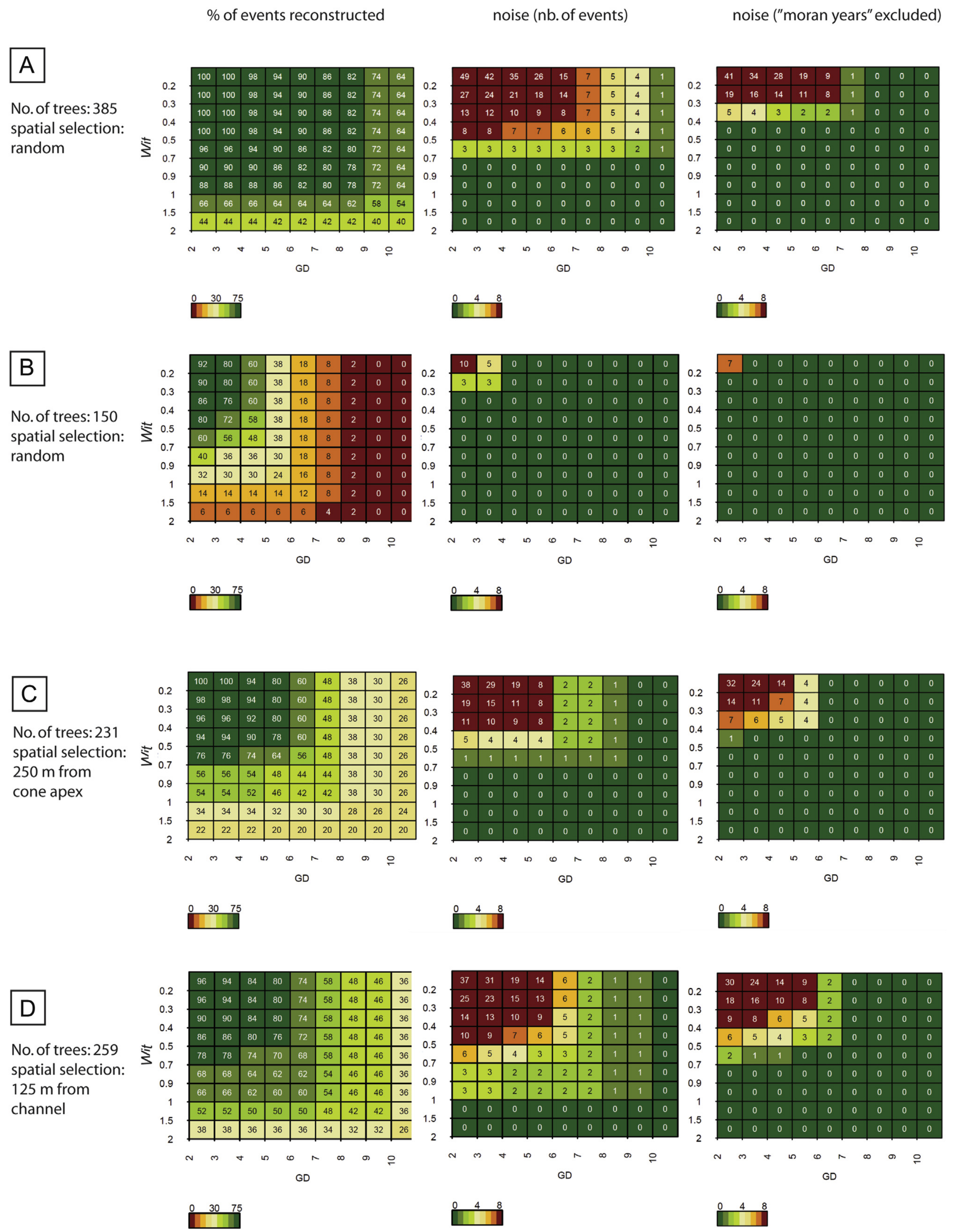

Fig. 4. Percentage of reconstructed events (left panel) and number of additional events (noise; central panel) depending on the number of growth disturbances (GD) and the index value (W_{it}). The right panel shows the noise if "Moran years" are excluded.

Table 3
W_{it} and GD necessary to identify a certain percentage of the reconstructed event and associated noise based on different numbers of tress sampled in different spatial positions. Number in parentheses in noise represent the number of "Moran years" (see text for details). An example: if we select 300 trees randomly distributed on the cone, we are able to find 95% of the events if we consider a threshold of 0.5 for W_{it} and a minimum of 3 GD. At the time, we also obtain 4 events that have to be considered as noise; however, all 4 noise years were "Moran years".

Distance from apex	Distance from channel	No. of trees	Percentage of reconstructed events																		
			75%			80%			85%			90%			95%			100%		
			W_{it}	GD	Noise	W_{it}	GD	Noise	W_{it}	GD	Noise	W_{it}	GD	Noise	W_{it}	GD	Noise	W_{it}	GD	Noise
Random	Random	50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Random	Random	100	0.3	2	3 (3)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Random	Random	150	0.3	2	0	0.4	2	0	0.3	2	4 (4)	0.2	2	9 (2)	–	–	–	–	–	–
Random	Random	200	0.5	4	0	0.5	3	0	0.4	3	2 (2)	0.4	2	3 (3)	0.3	2	7 (6)	–	–	–
Random	Random	250	0.7	5	0	0.7	3	0	0.7	2	0	0.5	2	2 (2)	0.4	2	7 (7)	–	–	–
Random	Random	300	0.9	4	0	0.9	3	0	0.7	3	0	0.7	3	0	0.5	3	4 (4)	0.4	2	9 (9)
Random	Random	385	1	8	0	1	7	0	1	5	0	0.9	4	0	0.7	3	3 (3)	0.5	3	8 (8)
150 m	Random	50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
175 m	Random	87	0.2	2	23 (2)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
200 m	Random	129	0.2	3	13 (4)	0.2	3	13 (4)	0.2	2	24 (5)	0.2	2	24 (5)	–	–	–	–	–	–
225 m	Random	169	0.5	3	7 (3)	0.4	3	10 (4)	0.3	3	11 (4)	0.2	3	13 (4)	–	–	–	–	–	–
250 m	Random	231	0.7	3	1 (1)	0.5	3	4 (4)	0.5	4	4 (4)	0.5	4	4 (4)	0.4	3	10 (4)	0.2	3	29 (5)
275 m	Random	285	1	4	0	0.9	4	0	0.7	4	1 (1)	0.7	3	1 (1)	0.5	4	6 (4)	0.4	3	9 (5)
300 m	Random	328	1	4	0	0.9	5	0	0.9	4	0	0.7	3	1 (1)	0.5	4	4 (3)	0.5	3	5 (4)
Random	50 m	58	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Random	75 m	134	0.5	2	14 (4)	0.4	2	19 (5)	–	–	–	–	–	–	–	–	–	–	–	–
Random	100 m	192	0.7	2	8 (4)	0.5	3	14 (5)	0.5	2	16 (5)	0.4	3	18 (6)	–	–	–	–	–	–
Random	125 m	259	0.7	3	5 (4)	0.5	4	7 (3)	0.5	3	9 (5)	0.4	3	13 (7)	0.3	2	25 (7)	–	–	–
150 m	50 m	84	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
150 m	75 m	143	0.4	2	22 (10)	0.4	2	22 (10)	0.4	2	22 (10)	–	–	–	–	–	–	–	–	–
150 m	100 m	192	0.7	2	8 (3)	0.5	3	14 (5)	0.5	3	14 (5)	0.4	3	18 (6)	–	–	–	–	–	–
200 m	50 m	142	0.5	3	5 (1)	0.4	3	7 (2)	0.4	2	11 (3)	0.2	2	26 (6)	–	–	–	–	–	–
200 m	75 m	188	0.5	4	7 (2)	0.7	3	3 (2)	0.5	3	9 (4)	0.5	3	9 (4)	0.2	2	37 (7)	–	–	–
200 m	100 m	218	0.7	3	5 (3)	0.5	4	11 (4)	0.4	4	14 (4)	0.5	3	13 (8)	0.3	2	25 (7)	–	–	–
250 m	50 m	232	0.7	4	1 (1)	0.4	5	9 (3)	0.5	4	4 (4)	0.5	4	4 (4)	0.4	3	11 (4)	0.3	3	27 (4)
250 m	75 m	262	0.7	4	2 (2)	0.7	4	2 (2)	0.5	4	4 (3)	0.5	4	4 (3)	0.5	3	5 (1)	0.3	3	21 (4)
250 m	100 m	280	0.9	3	2 (2)	0.7	4	2 (2)	0.7	4	2 (2)	0.5	4	8 (4)	0.5	4	8 (4)	0.5	3	9 (5)
300 m	50 m	327	1	4	0	0.9	5	0	0.9	4	0	0.7	3	1 (1)	0.5	4	4 (4)	0.5	3	5 (4)
300 m	75 m	344	1	7	1 (1)	1	5	1 (1)	0.9	4	1 (1)	0.7	5	1 (1)	0.7	3	1 (1)	0.5	3	7 (5)
300 m	100 m	354	1	7	0	1	5	0	1	4	0	0.7	4	3 (3)	0.5	4	5 (4)	0.5	2	6 (5)

on the cone and for 100%, 300 trees will be needed. In both cases, noise can be eliminated completely if "Moran years" are excluded.

Noise can also be reduced considerably as soon as the distance from the cone apex is enlarged from 225 (e.g. 13 cases of noise for 90% of reconstructed events) to 250 m (90% of events reconstructed with no noise). The sampling of trees near the cone apex generally resulted in better results with less noise than the hypothetical sampling of trees along the debris-flow channel. Complementing the sample of apex trees with trees growing along the channel did not improve the signal-noise ratio. Again, the percentage of reconstructed events increases and the noise decreases as soon as the first 250 m from the cone apex are included, independently of the horizontal distance from the channel taken into account.

The inclusion of more trees generally allowed a better definition of appropriate W_{it} and GD values and the subsequent reduction of noise. As a rule of thumb, the use of higher W_{it} thresholds and lower GD numbers normally resulted in more reconstructed events with lesser noise. It seems that W_{it} could be the preferred indicator for debris-flow reconstructions and that it shall be given more weight than the absolute number of GD.

5. Discussion

In this paper, we reconstruct a debris-flow history with classical dendrogeomorphic approaches, a weighted response index (W_{it}) and a measure for the spatial distribution of affected trees. Moran's *I* and Getis–Ord Local Gi indices were introduced to quantify the spatial distribution of trees with GD in the same year. The use of spatial indices enhances the distinction of signal from noise and facilitates the quantitative construction of debris-flow time series.

In the classic expert approach, events with a large spatial fingerprint have been reconstructed with high certainty in the past (Stoffel et al., 2008), but doubts often remained for years with more limited evidence in the tree-ring series (Bollschweiler et al., 2007, 2008). In this paper, we demonstrate that the use of Moran and Getis–Ord indices can be of particular help for years with limited debris-flow evidence in trees as they provide valuable data on the spatial clustering of reacting trees.

This study also illustrated the positive impact of increasing sample sizes on the number of reconstructed events and on signal-to-noise ratios. At the same time, however, we realize that a sample size of ca. 150 trees selected randomly on the cone will suffice to capture 85% of past events. In the present case, the missed 15% of debris flows is characterized by small W_{it} and a limited spatial footprint on the cone, and might thus stem from smaller debris flows. Whereas these smaller events are important for the absolute frequency of debris flows, they can presumably be neglected in hazard and risk assessments and/or for the dimensioning of countermeasures (Stoffel et al., 2010b).

The optimal sample depth for debris flows defined in this contribution is slightly higher than that for snow avalanches. Based on results from a site in the Chamonix area, Corona et al. (2012) recommends that ca. 100 trees are needed to obtain the best match between reconstructed events and data from historical archives. As debris flows typically affect smaller surfaces than snow avalanches, a larger number of trees is needed to obtain results of similar quality. At the same time, we realize that three out of four debris flows (75%) could have been reconstructed at Wildibach with 100 trees and that noise could have been ruled out provided that "Moran years" were excluded.

Results also suggest that tree-ring sampling near the cone apex will provide better results than will sampling along the debris-flow channel, presumably because most frequently outbreaks would occur at this position in the present case.

The use of a $W_{it} \geq 1$ threshold has proven helpful to reconstruct Wildibach debris flows with high certainty. Debris flows with $0.5 > W_{it} < 1$ were analyzed further with Moran's I and Getis–Ord Local Gi indices. The W_{it} thresholds used here cannot probably be transferred directly to other study sites as the intensity of GD will depend strongly on tree species composition, grain size distribution of debris flows, characteristic flow depths, slope angles, and on the number of trees available for reconstruction (Stoffel et al., 2013; Stoffel and Corona, 2013). In addition, optimal threshold values tend to decrease with increasing sample size since debris flows will not normally affect significant portions of a cone, and thereby support the concept of sample-size dependent, variable thresholds of Corona et al. (2012).

6. Conclusion

The use of fixed thresholds for GD and W_{it} alone does not allow for a correct reconstruction of debris-flow histories and tends to leave significant noise in reconstructed debris-flow histories. Dating quality can be improved considerably through the coupling of GD and W_{it} thresholds with Moran's I and Getis–Ord Loc Gi indices which allow for an objective analysis of the spatial clustering of trees affected during specific debris-flow events. A sample size of 150 trees is sufficient to reconstruct 90% of past events with no noise. Future debris-flow reconstructions can thus be realized with fewer trees, which will in turn improve cost-benefit ratios of dendrogeomorphic work and rendering the approach (even) more attractive for practitioners and natural hazard authorities.

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