

Landslides

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Are the historically known landslide events really the biggest? An insight using dendrogeomorphology



Abstract The construction of the magnitude-frequency relationship is one of the key bases for the estimation of landslide hazard. However, data on past landslide occurrence are mostly from archival sources, and it is assumed that only the largest events are recorded. This situation may result in a critical underestimation or overestimation of the resulting landslide hazard. Therefore, in this study, chronological and spatial parameters were verified using dendrogeomorphic methods for six selected landslides for which at least one reactivation was historically known. The selected tree-ring-based parameters were thus compared between historically known events and other events that were identified using dendrogeomorphic reconstruction. In total, disturbed trees were analyzed, and growth disturbances were identified from their tree-ring series, from which landslide reactivations (including historically known ones) were reconstructed. The results suggest that for half of the landslides studied, the historically known event can indeed be assumed to have been the largest in area over the time period covered by the tree-ring data. However, for some of these landslides, the results suggest that the magnitude of movement (the rate of rotation of the landslide blocks) was significantly smaller than historically known. Conversely, for landslides whose reactivated area was smaller than that of historically known landslides for all unknown events, the results suggest that the magnitude of movement was significantly larger. In the case of only one landslide, the results suggest that the historically known event was one of the smallest, and most of the previously unknown reactivations (revealed by dendrogeomorphic analysis) were larger in area with greater rates of movement. The results thus provide new and original insight into the issue of the size of historically known landslide reactivations.

Keywords Dendrogeomorphology · Landslides · Magnitude · Historical records

Introduction

Knowledge of the past occurrence of landslides is crucial for assessing their current activity, but also for estimating their behavior under future climatic conditions (Gariano and Guzzetti 2016). This information is crucial because landslides represent a significant natural hazard causing annual damage to property and loss of human life (Petley 2012; Froude and Petley 2018). The problem, however, is that for the vast majority of landslides in the world, virtually no chronological data are available (Nikoobakht et al. 2022). This is due to the frequent remoteness of landslides or the absence of damage at their onset (Lopez Saez et al. 2012). A possibility to obtain chronological information on past landslides is to apply

absolute dating methods or to obtain archival data (Lang et al. 1999). However, these are very limited or even completely lacking (Raška et al. 2015). When working with archival data, it is generally assumed that the further we go into the past, the fewer landslide events can be traced. Moreover, only those with the largest magnitude will be considered, with smaller events with higher frequency being completely missing. This is probably due to the fact that in the past, only those events that caused material damage or fatalities were recorded and therefore those that were large enough.

Meanwhile, the magnitude of a landslide event and the frequency of its occurrence in the past are key parameters used to determine the magnitude of a landslide hazard through the magnitude-frequency (M-F; Corominas and Moya 2010) relationship. The M-F relationship is one of the basic tools for landslide hazard assessment and allows estimation of the frequency of different sized landslides in the future (Tanyaş et al. 2019; Nanehkaran et al. 2021, 2023). This implies that if only the events with the largest magnitude are historically known from the past, the average magnitude and the overall frequency of all actual landslide events are biased. While the reconstructed M-F relationship of only the largest events may be consistent with the real situation, even if only large events are preserved from the past, it is not certain that all large events are involved. Therefore, results in the form of reconstructed M-F relations based on such incomplete data may lead to a critical underestimation of landslide hazard, which may have serious material and socio-economic consequences.

The M-F relationship can be constructed using data on the occurrence of landslide movements during one large-scale landslide calamity (Tanyaş et al. 2019) according to the frequency of occurrence of landslides of given sizes. In this case, limited knowledge of past landslide occurrence has no effect on the result. However, in the framework of the M-F relationship, the frequency can also be expressed chronologically (Corominas and Moya 2010). In the cases of both components of the relationship, problems already arise. Frequency can be refined compared to archival data using absolute dating methods (Pánek 2015), but with these methods, it is generally very problematic to impossible to determine the magnitude of the event. Especially with radiometric methods, it is assumed that again, only the largest events can be reconstructed, which in effect brings the same problem as when using archival data.

An exception in this respect may be methods based on the study of tree rings (dendrogeomorphology; Alestalo 1971), which work on the principle of identifying and dendrochronologically dating growth disturbances by which trees respond to the influence of landslide movements (e.g., trunk lean) on their growth (Shroder

1978). Currently, this is the most accurate dating approach, with precision down to a few months and a range of up to thousands of years (Stefanini 2004; Stoffel et al. 2013; Zhang et al. 2019). An advantage over other absolute dating methods is their ability to estimate the magnitude of past landslide events, which can be expressed either in areal form, as the area of reactivated land defined by the positions of trees containing growth disturbance in a given year (Corominas and Moya 2010), or by the total proportion of trees disturbed during a dated landslide event (Šilhán, 2020).

However, it is not possible to determine the velocity of the displacement from the reactivated landslide area using other absolute dating methods (Mehrabi et al. 2023). In this respect, dendrogeomorphology offers two possible solutions. The velocity of mutual displacement of landslide blocks can be determined by dating anatomical changes in tree roots exposed between these blocks (Přecechtělová and Šilhán 2019). The second option is to determine the magnitude of movement through proxy indicators, which are the intensity and duration of growth disturbances in tree-ring series of affected trees induced by landslides. These parameters are directly correlated in the magnitude of the tree trunk lean (Šilhán 2017a), which can correspond to the magnitude of the landslide movement. However, this thought pattern can only be applied to selected types of landslides, most typically rotational landslides where the degree of rotation will directly affect the angle of the tree's tilt.

In any case, research procedures based on the study of tree rings of disturbed trees represent the best tool to verify whether historically known landslide events were indeed the largest ones during a given period, or whether equally large or larger events occurred, but are not known from archival sources. Resolving this question would

bring a new perspective to the degree of potential uncertainty in establishing M-F relationships and defining landslide hazard based solely on historically known events.

Thus, based on the above challenges and opportunities, the objective of this study is to confirm whether the historically known events are indeed the largest ones, or to define the proportion of historically unknown events with comparable magnitude, by comparing dendrogeomorphic parameters of dated unknown landslide events with historically known events. Meeting these objectives should contribute to the efficiency of landslide hazard determination.

Study area

The Vsetín Hill highland (centered at 18° 9' E; 49° 23' N; Fig. 1), an area with one of the highest densities of landslides in Central Europe (Van Den Eeckhaut and Hervás 2012), was selected for this study. There are landslides of various types (rotational, translational, earthflows, debris flows, rockfall), which occur either individually or in the form of landslide calamities (Kirchner and Krejčí 1998; Krejčí et al. 2002; Bíl and Müller 2008). The area is geologically formed by a series of nappes with fold and thrust structure of tertiary age. The individual nappes are formed by intercalation of alternating layers of varying strengths of conglomerates, sandstones, siltstones, and mudstones of Mesozoic to Neogene age. In addition, the rocks locally contain elevated amounts of swelling minerals (e.g., smectite) that may reduce slope stability (Baroň 2004). Morphologically, the area is composed of a series of ridges with peaks reaching more than 1000 m a.s.l. at their culmination and maximum slope inclinations of up to 25°. The area receives above-average

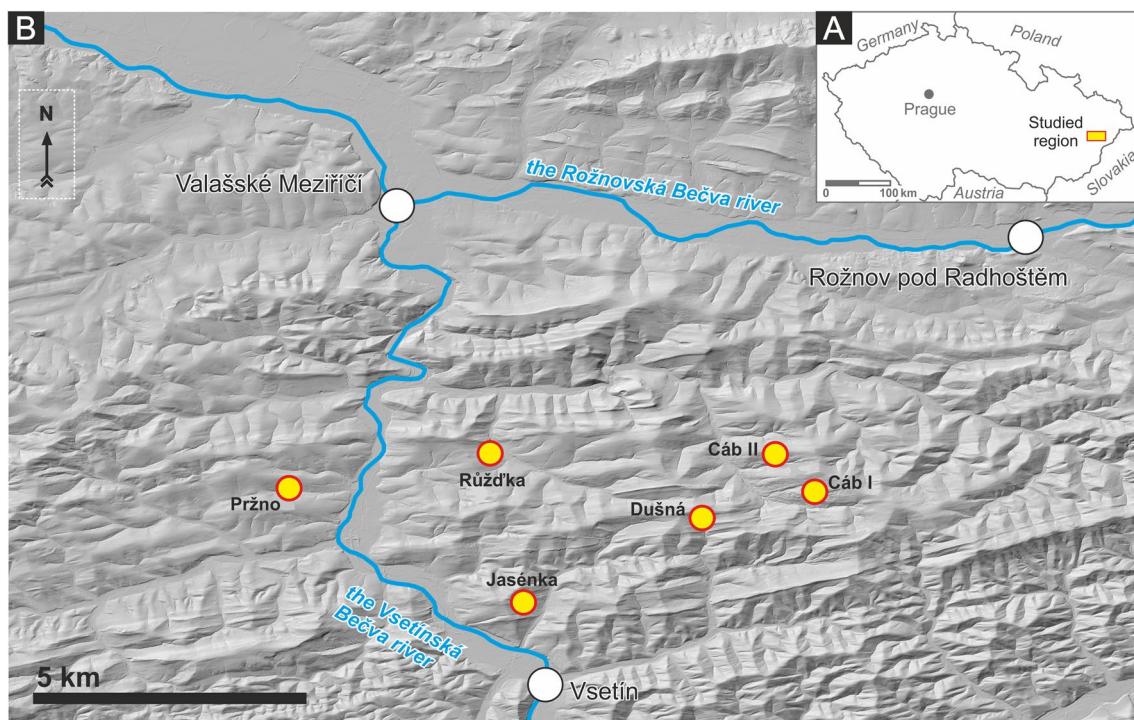


Fig. 1 Position of the studied landslides within the Czech Republic (A) and within the wider region (B) (position of the landslide, yellow circle)

rainfall compared to the surrounding lowland areas, with average annual rainfall of more than 1000 mm. However, in the summertime, more than 100 mm of rain can fall during thunderstorms with cloudbursts. Snow cover occurs on average during 100 to 120 days a year and average annual temperatures reach 5 to 6 °C (Tolasz et al. 2007). It is the combination of high rainfall with high intensity, the flysch geology and steep slopes that represent the key combination of factors leading to slope deformation. A large part of the study area has been deforested and used for pastoralism in the past. In contrast, most of the area is now covered by forests dominated by common spruce (*Picea abies* (L.) Karst.) and European beech (*Fagus sylvatica* L.). Other tree species that occur within the study area are silver fir (*Abies alba* Mill.), sycamore maple (*Acer pseudoplatanus* L.), or European larch (*Larix decidua* Mill.).

For the purpose of this study, six landslides with a dominant rotational component of their movement were selected and analyzed in detail dendrogeomorphically, which was one of the key parameters for the feasibility of this research. The spatial distribution of the studied landslides can be seen in Fig. 1. The average area of the landslides was about 65,900 m², the average length was 414 m, and the average width was 263 m. The average slope of the landslide areas was 14.0°, and the average subbasin area was about 48,500 m². Details of the morphometric parameters of each landslide are given in Table 1. All the landslides studied were previously analyzed as part of a large-scale regional reconstruction of landslide movements in the wider region, and their raw chronologies were published in a study by Šilhán et al. (2018). However, this study reanalyzed all the obtained samples focusing on a completely new quality (duration and intensity of growth disturbances). At the same time, these landslides were selected because for all of them, the moment of their reactivation is historically known, which was the second absolutely necessary condition for the successful setup of the research design. In the case of all the landslides, the year 1997 was the year when an exceptionally large amount of precipitation fell in early July, exceeding 500 mm in 3 days in some locations. During this extraordinary rainfall event, several hundred landslides occurred within the study region; however, for the landslides selected for this study, their reactivation is recorded in local sources and in the Czech historical landslide database (CHILDA; Bíl et al. 2021).

Methods

The surface of each landslide was first geomorphically mapped (based on LiDAR-based DEM) to verify the rotational nature of the landslide movement and to define the spatial extent of the individual landslide blocks (Fig. 2). Thus, the key parameters for the selection of the landslides studied were (i) the rotational nature of the landslide movement and (ii) the presence of trees with obvious signs of being affected by landslide movements. Subsequently, disturbed trees (leaning trunks, visibly damaged roots) were sampled for dendrogeomorphic analysis. Two increment cores were taken from each tree using a Pressler increment borer (maximal length: 50 cm; diameter: ca 0.5 cm) at the height of maximum trunk bend. The first core was taken from the upper side and the second core from the lower side of the leaning trunk. The position of each tree was recorded using a GNSS device. In addition, two cores were taken from 30 reference trees growing outside the landslide area but in the same microclimatic conditions to establish a reference chronology.

All increment cores were subsequently processed using standard dendrochronological methods (Bräker 2002), including air drying, gluing into woody supports, sanding with a set of sandpaper, and measuring tree-ring widths using the dendrochronological timetable and the PAST4 program (V.I.A.S. 2005) under a stereoscope. All increment cores were cross-dated against reference chronology to correct for any false/missing rings. The reference chronology was constructed in Arstan, and the quality of cross-dating was checked using Cofecha. Subsequently, the growth disturbances (GD) that were not present in the reference chronology were identified and dendrochronologically dated. Attention was focused on the presence of reaction wood (brown-reddish color of woody material), which occurs in response to leaning of the tree trunk (Timell 1986) and on abrupt growth suppression in response to root damage. In the case of reaction wood, this GD was identified as a sudden appearance of this wood structure in the tree-ring series. Since this type of GD usually exhibits inertia in its duration, only the first year with the occurrence of reaction wood was considered as the time of the landslide event. The abrupt growth suppression was calculated as the percentage change in tree-ring width compared to the average width of the four previous tree rings (Fig. 3; Schweingruber et al. 1990). Reaction wood intensity was determined as the percentage (rounded to the nearest tenth of a percent) of reaction wood structure occurrence in the second year after reaction wood

Table 1 Basic morphometric parameters of studied landslides

Landslides	Length (m)	Width (m)	L/W	Subbasin area (m ²)	Mean elevation	Mean slope (°)	Area (m ²)
Cáb III	340	105	3.2	47,825	626.1	16.0	24,884
Cáb I	292	181	1.6	26,875	723.0	10.0	39,058
Pržno I	506	414	1.2	19,575	435.1	13.6	93,731
Růžďka	575	201	2.9	46,800	420.0	12.0	92,597
Jasénka	650	247	2.6	74,500	454.6	15.3	100,686
Dušná	123	427	0.3	75,375	651.6	14.2	44,682

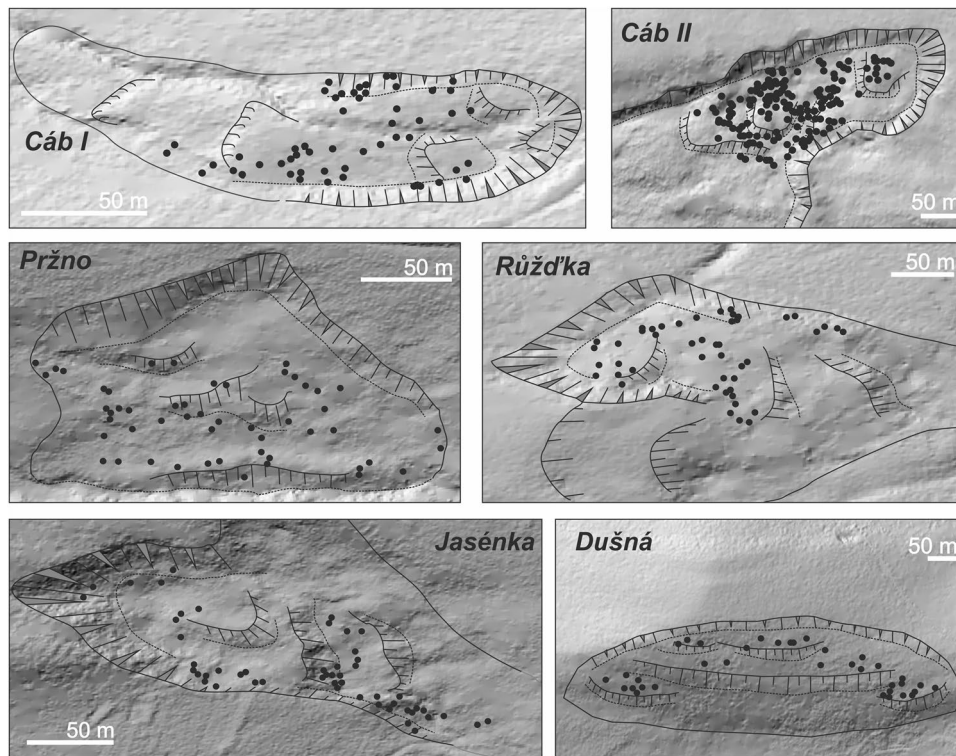


Fig. 2 Basic morphological features of the studied landslides (main scarp, partial blocks) and their extent including the position of the analyzed trees (black dots)

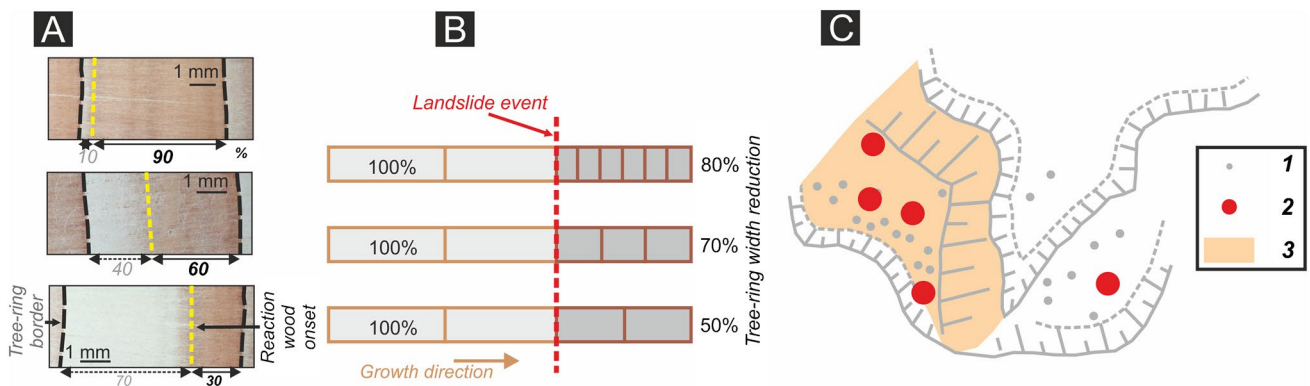


Fig. 3 Selected tree-ring-based indicators of landslide activity used. **A** Principle for defining the intensity of reactive timber based on the percentage of its structure within the tree-ring width. **B** Principle for defining the intensity of abrupt growth suppression (following Schweingruber et al. 1990) as the percentage change in tree-ring width compared to the average width of the four previous tree rings. **C** Principle for defining the reactivated landslide area following Corominas and Moya (2010)

onset (Fig. 3). In addition, the duration (in years) of both types of GD was recorded. The GD duration and intensity parameters can be used as a proxy indicator of rotational movement rate in the case of rotational landslides, which is the reason for their inclusion in this research. However, direct verification of this approach is not possible due to the lack of real monitoring data. Therefore, the results of these two parameters should be considered only as complementary.

All identified GDs were then summarized into individual years, and landslide activity was expressed using a standard

event-response (I_t) index (Shroder 1978), which expresses the percentage of trees with GDs present out of all sampled trees living in a given year. The threshold for detecting a landslide event was set at 5% based on the total number of all sampled trees on each landslide (sample size) (Stoffel et al. 2013). At the same time, at least three trees had to show the presence of GD in a given year (Corona et al. 2014). Thus, the landslide chronology was constructed only from events during which an I_t index value of 5% was reached in a given year and at least three trees contained GD.

The area of the reactivated part of the landslide areas (reactivating areal magnitude) was determined according to the procedure adapted after Corominas and Moya (2010). First, the area of each sub-mapped landslide block (motion homogeneous units) was determined. These units were considered active if at least two trees containing GD were growing on the unit in a given year (procedure adapted after Bollschweiler et al. (2007) used for debris flows). The area of all active units was summed for each event year. To reflect the degree of concentration of individual landslide movements to specific locations in the landslide area, the Moran index (an index of spatial autocorrelation; Moran 1950) was calculated for each event year to determine whether trees affected by landslide movements tend to cluster spatially or whether their spatial occurrence is random. In general, it can be assumed that during landslide events, disturbed trees will show a tendency towards spatial clustering. In contrast, dispersive spatial patterns may indicate the influence of other slope movements (especially creep). For this purpose, individual trees were converted to geo-objects, and the Moran I statistics function in ArcMap 9.3 was used for the calculation.

To check for any differences or similarities between the known events (1997 for all six landslides) and the other events, the percentage differences of the parameters of the other events from the known events were calculated. Comparisons were made between (i) GD intensity, (ii) GD duration, (iii) event area, (iv) Moran index values, and (v) I_t index values. These parameters were chosen because they can potentially provide the most information about the characteristics of landslide events (magnitude, frequency, affected area). Since the dated events were always compared with only one historically known event (1997), the quantitative evaluation of the results was done only by a simple comparison of the obtained values (larger or smaller). To express the influence of known events on the M-F relationship, for each landslide, this relationship was constructed based on the event area determined from the activated blocks during single events and their frequency, which was determined as the ratio of the years covered by living sampled trees and the number of landslide events reaching the minimum value of the I_t index (Corominas and Moya 2010; Šilhán 2020).

Results

Analyzed trees, growth disturbances, and chronology of landslide events

A total of 403 trees were sampled on all study landslides through 806 increment cores. *P. abies* was the only species analyzed. Thus, on average, 67.2 trees were sampled on each landslide (stdev: 43.2 trees). The highest number of trees was 155, and the lowest number of trees was 43. The overall mean age of the trees was 70.1 years (stdev: 27.2 years). Details of the number of trees and their age at each landslide are given in Table 2.

A total of 352 GDs were identified in all tree-ring series, with the occurrence of reaction wood dominating (266 cases; 75.6%) over the occurrence of abrupt growth suppression (86 cases; 24.4%). The average intensity of GDs in other event years (previously unknown) was 72.8% and in the known year 1997 had an average value of 83.0%. The mean duration of all GDs in other event years was 9.0 years (stdev: 1.4 years), whereas in 1997, it was 11.1 years (see Table 2 for details). A total of 59 landslide events were reconstructed from the dated GDs, which means that 53 (89.8%) completely new,

Table 2 Sampled trees, dated growth disturbances, and reconstructed event frequency

Landslide	Sampled trees	Mean age	Maximal age	Minimal age	Total GD	Reaction wood	Growth suppression	Chronology length (min. 10 trees)	Events	Recurrence
Cáb I	53	100.6	110	33	11	11	0	106	17	6.2
Cáb II	155	101.0	115	70	120	73	47	102	8	12.8
Pržno I	52	67.3	103	44	54	49	5	74	9	8.2
Růžďka	48	70.6	122	46	56	46	10	72	11	6.5
Jasenka	52	47.0	77	36	65	50	15	48	8	6.0
Dušná	43	34.3	57	28	46	37	9	38	6	6.3

previously unknown events were identified (Fig. 4). Thus, with an average chronology length of 73.3 years (stdev: 27.5 years) (a period covered by at least five live trees), the recurrence intervals of landslide events on individual landslides ranged from 6.0 to 12.8 years, with an average value of 7.7 years (stdev: 2.6 years) (details in Table 2).

The average value of the I_t index in other event years was 9.5% (stdev: 2.1%) and ranged from 7.7 to 13.5%. However, the average values at all landslides in 1997 were 35.5% (stdev: 26.6%) with a

range of 13.0 to 65.4%. The I_t index values at all landslides were on average lower than in 1997, with an average difference of 62.4% (stdev: 24.0%) (Fig. 5). Of all other events, 50 had I_t index values lower than in 1997 and only three had values higher than in 1997 (Fig. 6). The mean GD duration values in other event years were lower than in 1997 for five landslides and higher (by 18%) for only one. Overall, however, the mean GD duration values in other event years were 17.9% lower than in 1997 (Fig. 5). Within individual events, 17 (32.1%) had a value higher than the 1997 event and 36

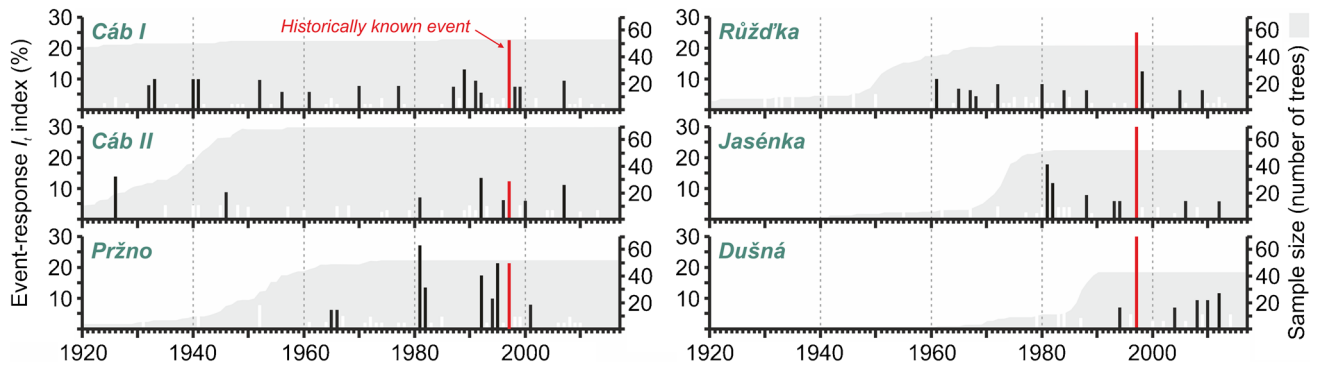


Fig. 4 Reconstructed landslide event chronologies using tree-ring-based data, chronological evolution of sample size, and marking of historically known events. Event intensity is expressed using the event-response (I_t) index

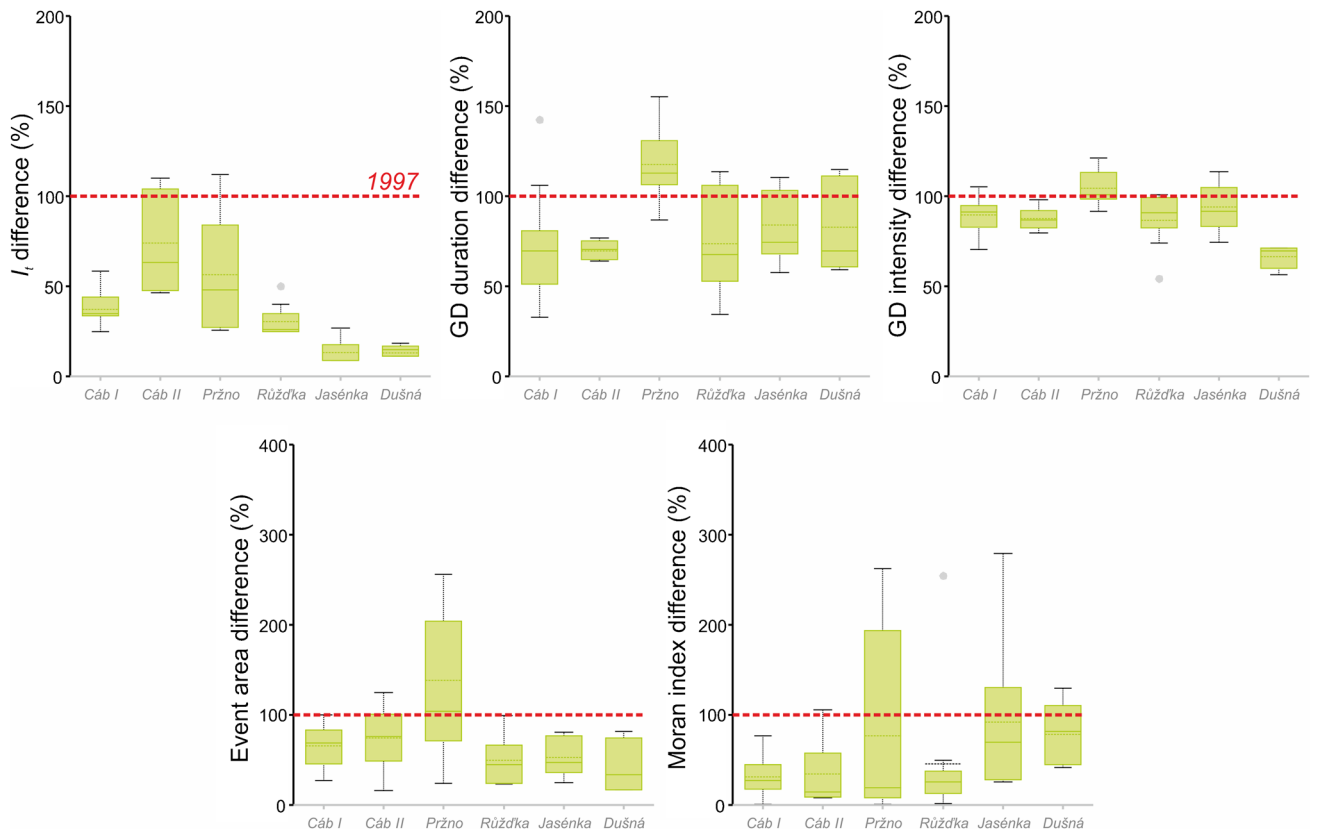


Fig. 5 Percentage differences in values of the studied dendrogeomorphic parameters in all unknown reconstructed events compared to values in historically known events (100%)

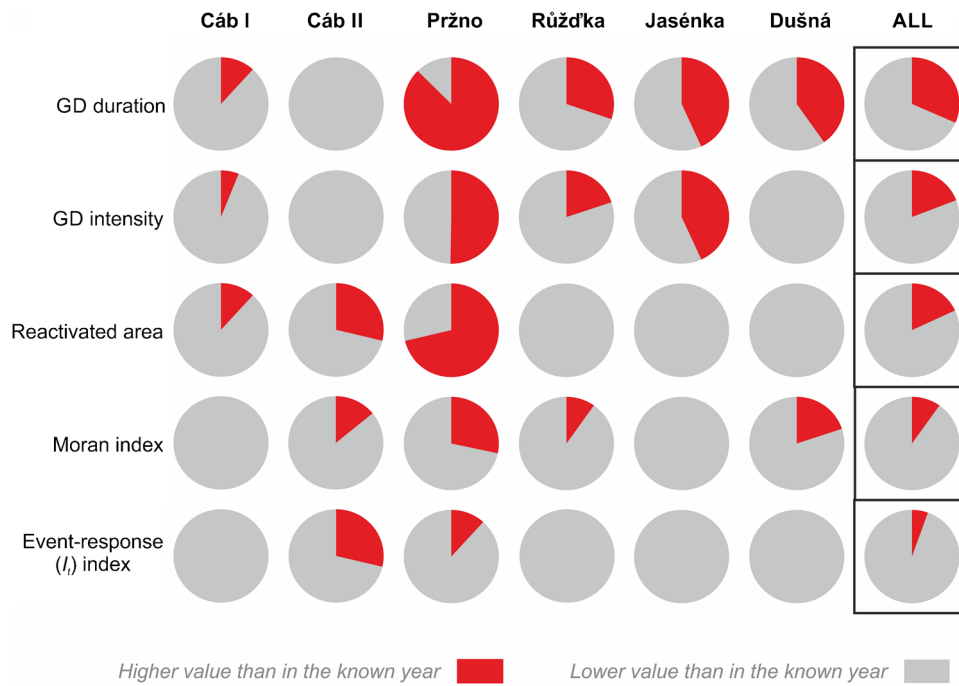


Fig. 6 Relative proportions between unknown events whose value of the selected parameter is higher and lower compared to the value of the corresponding parameter in the historically known event

had a value lower (67.9%) (Fig. 6). In the case of GD intensity, five landslides also had values on average lower than in 1997 and only one event had values higher than in 1997 (Fig. 5). Thus, overall, GD intensity values in the other event years were on average 11.7% lower than in 1997. At the individual event level, 10 events (18.9%) had values higher than in 1997 and 43 lower (81.1%) (Fig. 6).

Spatiality of landslide movements and their magnitude

The average area of the reactivated part of the landslide during the other event years was 9330 m² (stdev: 5 106 m²), while in 1997,

it was 13,850 m² (stdev: 6575 m²) (Table 3.). The values of reactivated landslide area were lower in five of the six landslides in the other event years than the values of reactivated area in 1997 (Fig. 5). At the level of individual other events, their reactivated area was greater than in 1997 in only nine cases (17.0%) (Fig. 6) and lower than in 1997 in 44 cases. The mean value of the Moran index in the other event years was 0.081 (stdev: 0.060), whereas its mean value in 1997 was 0.207 (stdev: 0.072) (Table 3.). For all landslides analyzed, the average Moran index values were lower in other event years than in 1997 (Fig. 5). At the individual event level, in only five cases (9.4%) was the Moran index value in the other event year

Table 3. Mean values of studied dendrogeomorphic parameters in known and other years

	Cáb I	Cáb II	Pržno	Růžďka	Jasenka	Dušná
Mean GD duration (other events)	9.2	8.4	11.5	9.2	8.2	7.4
GD duration (1997)	13.2	12.1	9.8	12.5	9.8	9.0
Mean GD intensity (other events)	76.6	71.4	79.6	78.2	71.7	59.1
GD intensity (1997)	85.5	81.7	76.4	89.1	76.3	88.8
Mean reactivated area (m ²)	4932.9	12,101.5	15,991.3	5530.4	13,403.7	4043.3
Reactivated area (1997)	7492	17,267	11,945	11,096	25,519	9769
Mean Moran index (other events)	0.054	0.078	0.138	0.010	0.039	0.166
Moran index (1997)	0.254	0.245	0.234	0.236	0.062	0.212
Mean I_t index (other years)	8.4	9.6	13.5	7.7	8.6	8.8
I_t index (1997)	22.6	13.0	24.0	25.0	65.4	62.8

higher than the 1997 value, and in 48 cases (90.6%), it was lower (Fig. 6). For all the landslides studied, an M-F relationship of their reconstructed events was constructed (Fig. 7), with magnitude expressed in an areal manner. The results show that in half of the cases, the historically known events were indeed the largest ones with the lowest frequency of occurrence. Conversely, for the other half of the landslides, the historically known events were medium in magnitude in their areal extent, and in one case even one of the smallest (Pržno landslide). When the studied dendrogeomorphic parameters were compared with the recurrence values of the dated events (Fig. 8), only one significant positive relationship was found. The average I_t index values from all event years on each landslide were positively correlated with the event recurrence values ($r=0.88$; p -value < 0.05).

Discussion

This study aimed to test the theory that it is mainly large events that are preserved within the archival landslide record. The use of such skewed data may lead to an underestimation or overestimation of landslide hazard with potentially severe impacts. To test this theory, dendrogeomorphic methods were used in which six landslides with one officially known event for each. In total, 403 *P. abies* individuals were sampled for the analysis, and a total of 59 landslide events were reconstructed, including historically known events (all in 1997). There are many types of landslides, and each has a specific effect on tree growth, and therefore, dendrogeomorphic approaches must be different for each type. Therefore, only rotational landslides were selected for this study. Thus, the results

of this study can only be considered valid for rotational landslides, and future research should also focus on other types of landslides.

Assessment of the suitability of the methodology used (limitations of used dendrogeomorphic methods)

The research design consisted of the analysis of special dendrogeomorphic indicators that can be used to calculate the frequency and estimate the magnitude of past landslides. From a dendrogeomorphic point of view, the results can generally be negatively affected by the limited number of trees analyzed. In this case, the average number of trees per landslide was 67.2, and the total number in no case fell below 40 trees. Combined with the chosen threshold parameters for defining a landslide event (5%), these numbers are sufficient to detect landslide events with minimal noise, according to an experimental study by Corona et al. (2014). However, even significantly lower numbers of analyzed trees have allowed effective detection of landslide events in the past (e.g., seven trees in the study by Clague and Souther 1982). Another aspect potentially affecting the reconstruction result is the variability in the age of the analyzed trees, which should be high (Stoffel et al. 2013), since trees generally show age-dependent changes in their ability to record landslide signals in their tree-ring series (Šilhán 2021). Also, in this respect, the dendrogeomorphic data used seem appropriate since the range of ages of the analyzed trees reached well over 70 years.

Although the research design set up was fine based on the above, one still needs to account for the limitations of the research method itself, which lie, for example, in the inertia of the duration of growth

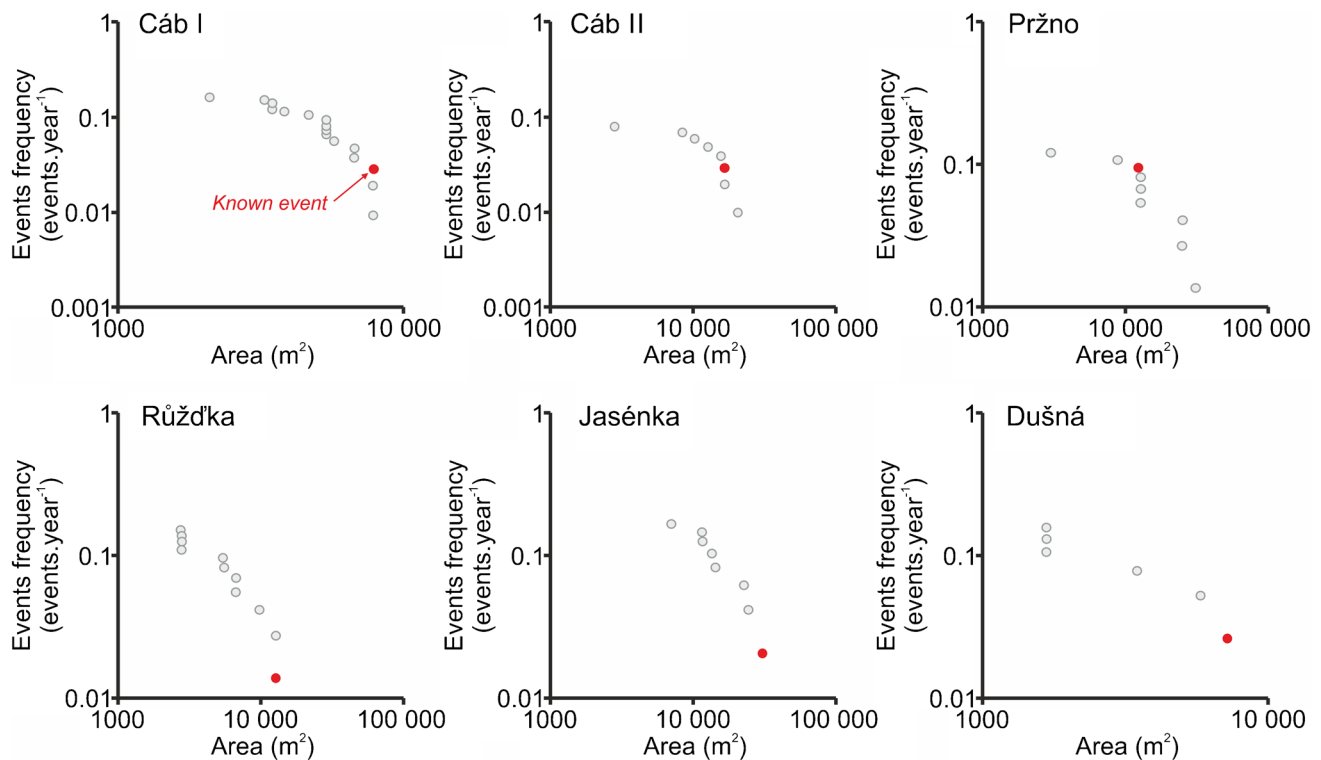


Fig. 7 Magnitude-frequency relationships of all analyzed landslides based on the reconstructed magnitude of the reactivated part of the landslide area and its chronological frequency

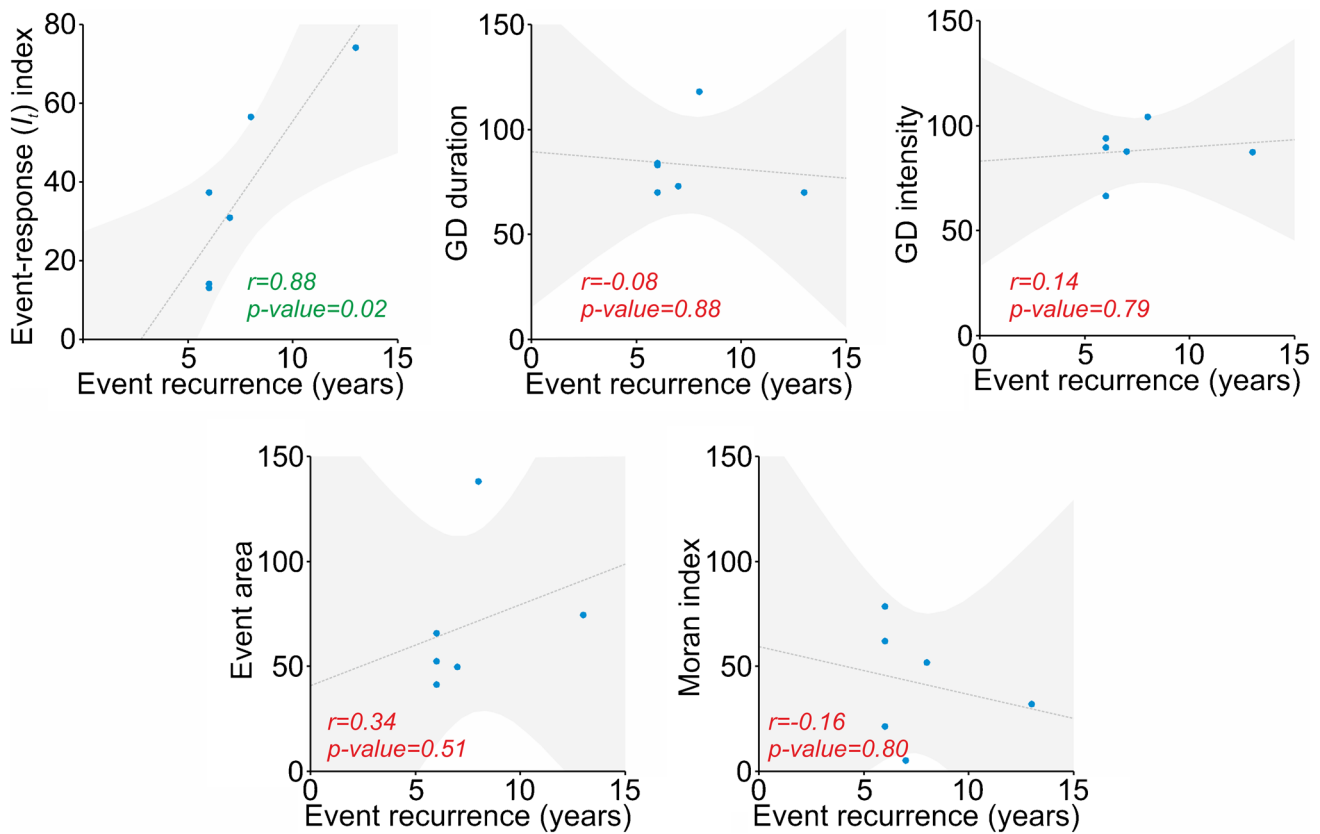


Fig. 8 Relationships between the mean values of the analyzed dendrogeomorphic parameters for each landslide and the frequency of reconstructed events (expressed using the recurrence interval)

disturbances (Corona et al. 2014). This is because both reaction wood and abrupt growth suppression do not occur in a single tree ring but over a period of several years (Lopez Saez et al. 2012). During this time, however, the tree is unable to record another landslide event, which may have a direct impact on the underestimation of the frequency of reconstructed landslide events. However, this effect can be at least partially ignored because it is a tree-level limit, and usually, only a limited number of trees respond during landslide events, leaving enough trees to record a possible younger landslide event.

Another limitation in dendrogeomorphic research of landslides is the size of the reactivations analyzed. Movements that are too small may not be able to affect the growth of trees, which thus have no reason to initiate a growth response. However, according to research by Šilhán and Stoffel (2022) or Šilhán et al. (2023), trees respond already to movements of units of millimeters, and therefore, undetectable landslide movements do not pose any risk. On the other hand, landslide movements that are too large can completely destroy all trees growing on the landslide (Stoffel and Bollschweiler 2008). However, in this case, it is possible to determine the age of the landslide event by the surviving trees growing in the vicinity of the landslide, as they respond to the removal of their competitors by growth release (Chalupová et al. 2020). The effect of total destruction of all trees may occur within the study area as described by Kirchner and Křeččí (1998) or Klimeš et al. (2009). However, within the study landslides, this effect can be excluded

due to the spatial distribution of tree age structure in all landslides, in which typical age gaps were absent.

A serious limitation of the dendrogeomorphic approach, which could theoretically affect the results of this study as well, is the presence of other types of slope movements than landslide (especially creep; Malik and Wistuba 2012). Intense creep may even simulate a landslide event or unrealistically increase its actual areal extent, thus affecting their spatio-temporal reconstruction (Fabiánová et al. 2021). However, this potential influence was already eliminated during field sampling, which excluded trees growing on steep parts of the slope where intense creep-type movements can be expected (Šilhán 2017b).

Evaluation of dendrogeomorphic parameters

The two parameters of the growth disturbance characteristics (duration and intensity) indicated the most potentially larger landslide events than historically known events. However, this applies only to some landslides (Pržno and Jasénka). However, it should be noted that these two parameters have only a proxy character (Šilhán 2017a), and it is not possible to estimate the extent of the affected area according to them. Nevertheless, according to the obtained results, it is clear that the selected landslide events on the Pržno and Jasénka landslides showed a greater degree of rotational movement of the landslide blocks than it was the case

in the historically known year 1997. Conversely, the parameter that directly indicates the extent of the area affected by landslide reactivation is the area assessed according to the methodology by Corominas and Moya (2010). In the case of this parameter, it again appears that some reactivations of the Pržno landslide were significantly larger in area than in the historically known year 1997. On the contrary, this was not confirmed for the Jasénka landslide but was found for the Cáb I and Cáb II landslides, which is a major difference from the parameters based on the GD properties. Thus, it can be concluded that some landslides experienced a large rotation of a small area of the landslide (Jasénka) and some experienced a small movement of a large area (Cáb I and Cáb II).

The indicator of the influence of the percentage of trees (I_t index) can show a high degree of correlation with the reactivated landslide area (Šilhán 2020) and therefore similar results. In the case of this study, this was true for the Pržno and Cáb II landslides; however, for the other four landslides, the percentage of living trees was significantly less affected during each reactivation. It is therefore clear that the results of this parameter can be strongly influenced by the spatial distribution of the trees analyzed, and it is therefore more accurate to focus on the results of the reactivated area reconstruction. This effect may also influence the results of the Moran index analysis, which in the case of this study should also be considered more as proxy information. Not all landslide events showed a tendency towards clustering, which may be due precisely to the uneven distribution of trees, but also to the inertia of GD. Analogous results to another proxy indicator (duration and intensity of GD) were again found for the Jasénka and Dušná landslide. In the case of the Pržno landslide, the results of the Moran index reconstruction confirm the results of the other dendrogeomorphic parameters evaluated.

The results of the dendrogeomorphic reconstruction also suggest direct impacts on M-F relationships, with half of the landslides appearing to be the largest historical landslide reactivation events with the lowest frequency over the study period. However, for the remaining landslides (notably the Pržno landslide), the historically known events were ones of the smallest and their frequency being significantly higher than that of the large reactivations. Thus, it appears that in half of the cases, the known events were indeed the largest in area (even though the movement was apparently small), and the other half of the landslides (Pržno, Cáb I, Cáb II) had larger events in years other than the historically known ones. The hypothetical rule that only the largest landslide events are in the historical record is only 50% valid in the case of this study. This study provides new insights into the problem of determining the M-F relationship, which should be taken into account in future research. Since the size and frequency of landslides are fundamental tools for assessing landslide hazard, the results of this study may impact landslide management and mitigation strategies, particularly in areas prone to landslide hazards. It is therefore recommended to use dendrogeomorphic methods in these areas to complement archival records, especially when defining magnitude-frequency relationships.

Conclusions

The aim of this study was to test a theoretical condition in which historically known landslide events are the largest ones, while smaller events remain unknown. To verify this, several tree-ring based

indicators were used to reconstruct the frequency and magnitude of past landslide events. Six landslide events were studied, and for each of them, the year of their historical reactivation was known. The selected tree-ring-based parameters in these years were compared with the dated years, which, however, were not historically known.

The tested parameters could be divided into two groups according to their immediate response to the landslide event parameters. The parameters that can be described as proxies (duration and intensity of growth disturbances) indicate that for half of the studied landslides, the known event was not the largest. However, these parameters, rather than the extent of the affected area, reflect the magnitude of the landslide movement (the rate of rotation of the landslide blocks). Conversely, a direct parameter expressing the areal magnitude of the landslide event indicated that landslides that had a magnitude of movement smaller than the known year affected but significantly larger area during reactivation. Thus, the landslides studied can be divided into three groups according to the results obtained. The first group is represented by two landslides for which the unknown events were smaller in area than the historically known event but with a larger magnitude of movement. For three landslides, the magnitude of movement was smaller, but the reactivated area was significantly larger than in the case of the known event, and for one landslide, it can be assumed that the magnitude of movement and the reactivated area during several of its reactivations were larger than in the case of the historically known event. Thus, this study clearly indicates that constructing an M-F relationship based only on historically known events may be burdened with inaccuracies that can lead to critical underestimation or overestimation of landslide hazard.

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Data Availability

Data will be available on request.

Declarations

Conflict of interest The author declares no competing interests.

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