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FREQUENCY OF FAST GEOMORPHOLOGICAL PROCESSES IN HIGH-GRADIENT STREAMS: CASE STUDY FROM THE MORAVSKOSLEZSKÉ BESKYDY MTS (CZECH REPUBLIC) USING DENDROGEOMORPHIC METHODS

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Abstract: High-gradient streams are localities with the most dynamic activity of geomorphological processes in medium-high mountains. This study of the frequency of floods and debris flows in a selected high-gradient stream in the Moravskoslezské Beskydy Mts was based on a dendrogeomorphic approach. It makes use of the most accurate methods applied in the dating of historic geomorphological processes. Individual events were reconstructed on the basis of the dating of various growth disturbances displayed in 99 samples taken from 56 predominantly broad-leaved trees.
As for the studied area, 26 years out of the last 113 years have been identified as years of rapid geomorphological processes. The frequency of the processes has been high above average since the 1970s. A majority of the events can be considered as flash floods. Debris flows, which can only be observed sporadically, originate due to the reactivation of old accumulation material that subsequently ends up re-accumulated on the alluvial fan at the mouth of a stream. A large number of events occur in connection with extreme short-term precipitation in summer months. In addition, they are affected by fast snow melting in spring, which has also been proved by intra-seasonal dating of selected events.

Keywords: dendrogeomorphology, high-gradient stream, debris flow, flood, Moravskoslezské Beskydy Mts.

1. INTRODUCTION

High-gradient streams represent places of highly frequent geomorphological processes in medium-high mountains such as the Moravskoslezské Beskydy Mts (Šilhán and Pánek, 2010). Apart from common floods related particularly to snow cover melting, the area is also sporadically affected by debris flows which endanger both the infrastructure and human lives, especially due to the culmination effect of these processes in the lower inhabited course of streams (Bollschweiler *et al*., 2011). The knowledge of the frequency of these processes is necessary for the prediction of the future trend of dangerous fast-moving geomorphological processes (Bollschweiler and Stoffel, 2010b).

The most accurate method used in zones where the streams flow through forested areas is dendrogeomorphology (Alestalo, 1971). High-energy processes can damage trees growing in the vicinity of streams. The reactions of trees to the damage can subsequently be

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identified they suffer and date relevant process with an accuracy of a specific season. Dendrogeomorphic methods have already been applied to study the frequency of debris flows (Pelfini and Santilli, 2008) and their spatial behaviour on alluvial fans (Bollschweiler *et al*., 2008), the frequency of debris floods (Mayer *et al*., 2010), and even floods themselves (Ruiz-Villanueva *et al*., 2010; Zielonka *et al*., 2008). A majority of dendrogeomorphic studies dealing with debris flows come from areas of high mountains, whereas medium-high mountains have so far been studied in connection with debris flows only rarely (Malik and Owczarek, 2009; Šilhán and Pánek, 2010). On the other hand, tree-ring analyses to study floods have mainly been applied in low-gradient streams (Gottesfeld and Johnson-Gottesfeld, 1990; Hupp and Bazemore, 1993).

The aim of this study is i) to reconstruct the frequency of fast-moving geomorphological processes (debris flows and floods) in a selected high-gradient stream in medium-high mountains, ii) to describe the behaviour and relations between both processes and iii) to identify major triggering factors leading to their occurrence.

2. STUDY AREA

The Moravskoslezské Beskydy Mts range between medium-high mountains with the occurrence of debris flows and floods (Šilhán and Pánek, 2010). The Moravskoslezské Beskydy Mts make a part of the thrust-and-fold belt of the Flysch Carpathians, which were tectonically formed as an accretional wedge and placed as nappes during the Miocene (Badenian) onto the Miocene foredeep and the basement of the Northern European plate (Menčík *et al*., 1983). The main landforms (steep north-facing escarpments) are affected by the monoclinal structure of the Cretaceous-Oligocene flysch bedrock (sandstones alternating with claystones and mudstones) slightly dipping (5°-20°) to the south and south-east (Menčík *et al*., 1983). Active high-gradient streams, which often copy the course of tectonic faults, are closely related to the steepest slopes affected by deep-seated slope deformations (Pánek *et al*., 2009). Unlike unlimited material sources of high mountains that are rich in intensive glacial and periglacial processes, debris flow material in these mountains comes from weathered Pleistocene layers of slopes or colluvia related to other slope deformations. The Moravskoslezské Beskydy Mts belong to areas with the highest precipitation totals in the Czech Republic and it is especially summer periods in which frequent short-term extreme precipitation events are recorded (even more than 100 mm/24 h) (Brázdil *et al*.; 2007). A majority of floods in Beskydian streams occur in spring months due to fast snow cover melting.

As a representative example of a high-gradient stream displaying the activity of fast-moving geomorphological processes was selected a nameless right tributary of the Satina stream on the NW slopes of the Lysá hora Mt (1 323 m) (**Fig. 1A**). It springs in the altitude of 840 m a.s.l. at the boundary of over-lying thick sandstone and conglomerate layers and under-lying predominantly clayey layers. The stream length from its spring as far as the mouth of the Satina stream in 600 m a.s.l. is 700 m (height difference 240 m, average inclination 19°). Wider vicinity of the lower stream course is built by a large accumulation of fossil debris flow. The whole stream basin is forested with prevailing species of common spruce (*Picea abies* (L.) Karst.), great maple (*Acer pseudoplatanus* L.) and European beech (*Fagus sylvatica* L.). The whole stream can be divided into 3 different zones (**Fig. 1B**, **2**). The first zone is found in the upper third of the stream with an average channel inclination of 35° and a few channel steps (a height of up to 1.5 m) (**Fig. 3B**). In this zone the stream has cut deep (up to 4 m) into the bedrock and there are several evident source zones of material. In the second zone, where the stream flows through a fossil debris flow accumulation, the channel is wider than in the first zone (up to 15 m) and debris flow material ends up accumulated in the form of stream bed and longitudinal levees which function as material sources for other debris flow. The lower boundary of this zone is formed by two 1.5-m-high artificial dams built in 2005. The lowest stream course, which corresponds to the third zone, is represented by an alluvial fan that is about 100 m long and highly asymmetric due to intensive lateral erosion of the Satina stream. The alluvial fan material consists of debris flow clasts of various sizes (up to 1 m), whereas its surface is formed by longitudinal, up to 2.5 m high levees and terrace-like forms along the active channel as remains of accumulation and erosional events. There is one active channel on the alluvial fan (**Fig. 3C**).

3. METHODS

Dendrogeomorphic research primarily requires high quality geomorphological mapping. During the geomorphological mapping of the study area at a scale of 1: 500, special attention was paid to erosional (channels, source zones) and accumulation landforms (stream bed accumulations, longitudinal levees). The map was completed with positions of sampled trees. Since the trees failed to be located using GPS, because of forests and steep slopes in the area, the position of the trees was determined by means of a laser rangefinder and a compass.

Unlike previous studies in the World, in which solely coniferous species were used in tree-ring analysis of floods or debris flows (Bollschweiler *et al*., 2008; Zielonka *et al*., 2008; Malik and Owczarek, 2009; Mayer *et al*., 2010; Ruiz-Villanueva *et al*., 2010), this study makes use of predominantly deciduous trees complemented with a few conifers. Samples for dendrogeomorphic analysis were taken (March, 2010) in two different ways. Trees displaying the signs of interference (injuries, tilting, stem burial; **Fig. 3A**) were sampled using a Pressler increment borer (max. 40×0.5 cm). Two cores

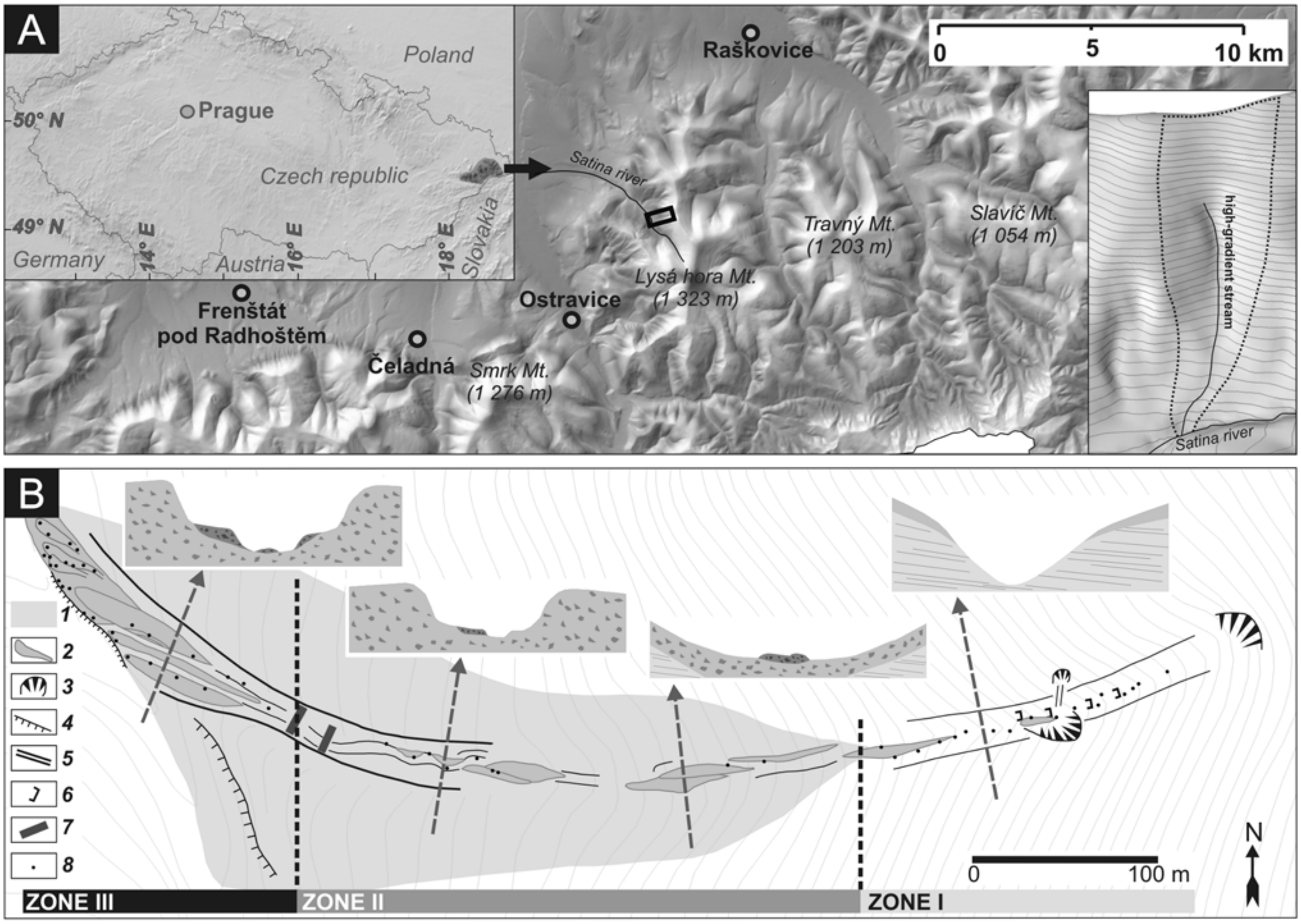

Fig. 1. *A – Position of the studied locality within the Moravskoslezské Beskydy Mts and the CR including marked basin boundary, B – Geomorphological map of the studied area containing a schematic drawing of cross profiles in selected parts of the stream (1 – extent of fossil debris flow accumulation, 2 – debris flow levee/lobe, 3 –source zone of material, 4 – erosional level, 5 – gully, 6 – level in the stream bed, 7 – anthropogenic dam, 8 – position of a sampled tree).*

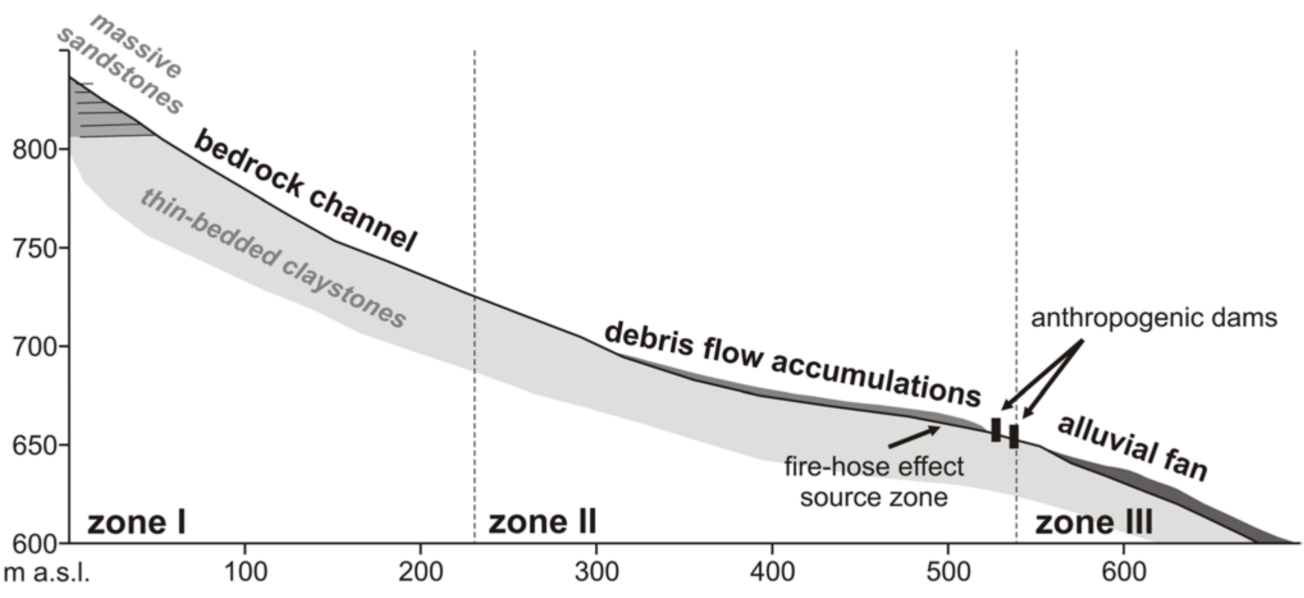

Fig. 2. *Longitudinal profile of the studied high-gradient stream.*

were taken from each tree: one in the direction of a process and the other one from the opposite side of the tree stem (upper side and underside of the stem; Shroder, 1978). The sampling took place either at the height of stem damage or stem flexion or as near as possible to the surface of material buried by the tree. The other sampling method consisted in extracting c. 2-cm-wide cross-cuts from both exposed roots and roots affected by previously occurring processes (**Fig. 3C**, **D**). In addition, 30 trees growing outside the reach of the studied processes were sampled in order to construct reference chronology representing normal growth conditions at study site influenced by climate (**Fig. 4C**) (10 trees – *P. abies*, 10 trees – *A. pseudoplatanus*, 10 trees *F. sylvatica*).

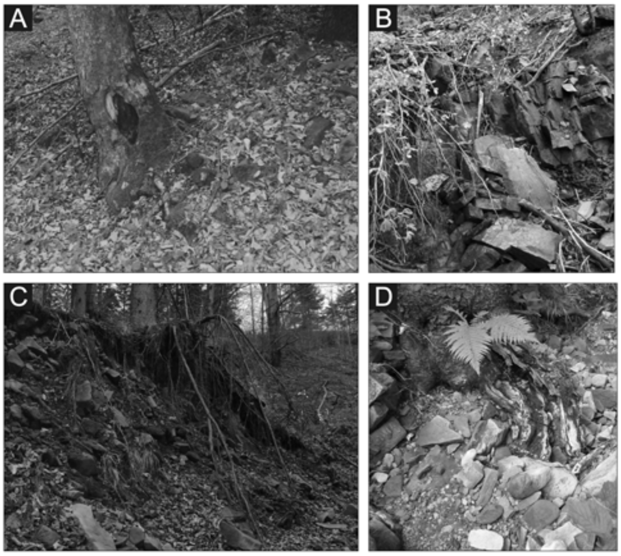

Fig. 3. *A – Scarred tree stem with a partially buried base on an alluvial fan, B – rocky stream bed showing a level in its upper section, C – exposed roots (*P. abies*) on the side of an active stream on the fan, D – damaged roots (*P. abies*) in the middle course of the stream bed.*

Sample processing and analyzing was conducted in accordance with standard procedures described by e.g. Stoffel and Bollschweiler (2008). The cores were left to dry, they were glued into woody supports, smoothed and polished. Tree-rings were counted and tree-ring widths measured with an accuracy of 0.01 mm using stereoscopic miscroscope, the TimeTable measuring device and the PAST4 programme (V.I.A.S., 2005). False or missing rings were identified on the basis of the reference chronology using a cross-dating method. Individual events were dated based on the identification of specific growth responses of trees to the geomorphological processes. Main reactions involved abrupt tree-ring growth suppression (as a result of a buried tree stem base or in case a tree became stressed in response to numerous impacts of moving material) (**Fig. 4A**), abrupt growth release (in response to the death of adjacent trees and lower competition between trees) (**Fig. 4B**), traumatic resin ducts (TRDs – a specific reaction of some coniferous species to mechanical stem wounding), formation of callous tissue (in response to stem or root wounding) and formation of reaction wood (tree's response to leaning in the form of asymmetric compensation growth on one side of the stem; compression wood by coniferous species formed on the underside of the stem, and tension wood by broadleaf species formed on the upper side of the stem) (Shroder, 1978; Stoffel and Bollschweiler, 2008). All increment curves were visually compared with reference chronology to eliminate possible errors caused by various events other than mass movement (e.g. insect outbreaks, windstorms, etc.). Cross-cuts made on tree roots were studied for the presence of callous tissue (Malik, 2006). The position of callous tissue within 1 tree-ring (Schneuwly

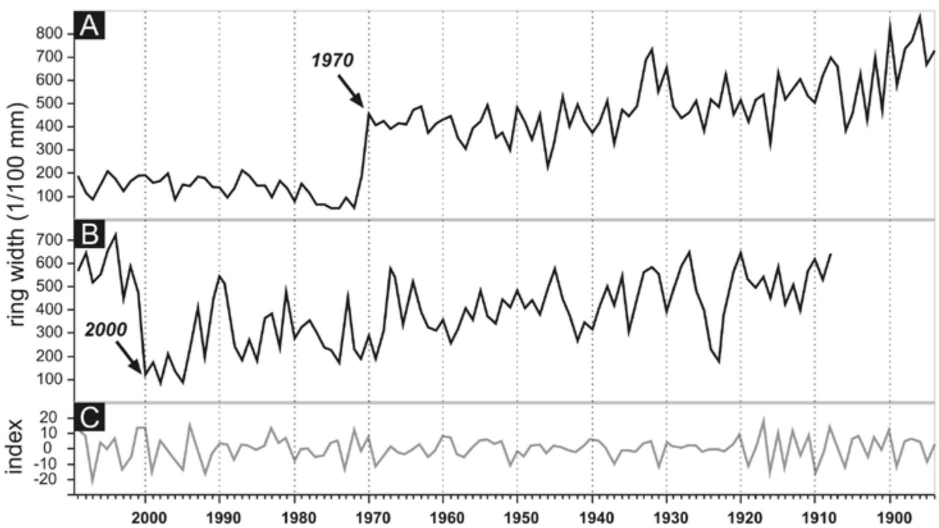

Fig. 4. *Representative examples of increment curves and their comparison with reference chronology (*A. pseudoplatanus*), A – abrupt growth suppression (1970), B – abrupt growth release (2000), C – reference chronology.*

and Stoffel, 2008) enabled intra-seasonal dating of the processes. In order to make sure the identified tree-ring width changes are results of geomorphological processes, only cases of abrupt growth suppression (>55%) and abrupt growth release (>200%) were considered to be reliable (Schweingruber *et al*., 1990). Moreover, only those growth changes that significantly differ from the reference chronology variations were considered as results of the impact of geomorphological processes (**Fig. 4**).

All dated growth disturbances (GD) were grouped into individual years, whereas the events were expressed by means of the 'event-response index' I_t calculated after Shroder (1978) as:

$$I_t = \frac{\left(\sum R_t\right)}{\left(\sum A_t\right)} \cdot 100\% ,$$

where R_t is a number of trees revealing GD as a response to debris flow or flood activity in year t and A_t is a number of sampled trees living in year t. With regard to variability in the number of trees affected by a process, two levels of certainty of the existence of dated processes were distinguished. Events occurring in years with I_t in the range of 5 to 15% are considered to be *probable* because although there is evidence supporting their existence, it is limited. On the other hand, events with I_t >15% are considered to be *certain*. With respect to the use of the I_t index, which is directly dependent on the number of sampled trees living in individual years (Sample Depth – SD), a reconstructed series of events was considered relevant only in case SD > 25%. To provide a better view of the trend in the number of events in time also frequencies per decade was included.

Analysis of potential meteorological triggering factors made use of data from a weather station on the Lysá hora Mt (1 323 m a.s.l.) situated at a distance of 2.2 km far away.

4. RESULTS

Trees were sampled in all the three mentioned zones. Together were 56 trees sampled. Most trees (30) were sampled on an alluvial fan in the third zone, while only 9 trees were sampled in the second zone and 17 trees in the first zone (**Fig. 2**). Average age of the trees was 92.9 years (STDEV = 26.5 years). The oldest tree had 144 rings (year 1865), while the youngest only 48 rings (year 1961) (footnote: number of tree rings after age correction due to reference chronology). Average age of conifers made 113.3 years (STDEV = 18.3) and in case of deciduous trees it was 83.9 years (STDEV = 24.8 years). The sampling included a total of 19 coniferous trees (33.9%) of *P. abies* and 37 deciduous trees (66.1%) of *A. pseudoplatanus* and *F. sylvatica*

Dendrogeomorphic analysis was carried out using a total of 129 samples, 30 of which had been taken from reference trees and 99 from disturbed trees. With regard to the 99 samples coming from disturbed trees, 86 cores were taken from tree stems and 13 samples from crosscuts made on tree roots. Details of the number of samples are given in **Table 1**. Within all the taken samples, 108 growth disturbances related to the activity of past floods or debris flows were identified. The most represented display was abrupt growth suppression (46.3%). This reaction was also most often observed in the case of deciduous trees. The second most frequent reaction was the occurrence of TRDs (17.6%), although only in the case of conifers. At the same time, as for the conifers themselves, this reaction was most represented. Abrupt growth release was identified in 14.8%, callous tissue in 12% and reaction wood in 9.3% of all the cases. Reaction wood was also identified only in the case of coniferous trees (compression reaction wood). Representation of individual growth disturbances related to individual wood species is shown in **Table 2**.

Evaluation of all the identified growth disturbances made it possible to reconstruct 26 events that took place between the years 1896 and 2009. However, with respect to decreasing SD (**Fig. 5A**), only events starting with the year 1900 can be considered as relevant. This period witnessed 7 certain events (I_t > 15%) (1929, 1939, 1949, 1960, 1970, 1985 and 1997) and 17 probable events (I_t 5–15%) (**Fig. 5C**). These events reached the highest I_t values in years 1970 and 1997 (both I_t = 25%). A debris flow event or a flood event thus occurs once every 4.4 years on average. Events that are considered to be *certain* repeat once every 9.7 years. In seven cases, was possible to determine an occurrence of an event with seasonal accuracy. Events occurring in the period before the be-

Table 1. *Number a type of samples from coniferous and deciduous trees.*

	trees	cores	cross-sections
coniferous	19	32	3
broad-leaved	37	54	10
Total	56	86	13

Table 2. *Number and type of growth disturbances identified in individual tree types.*

	trees	samples	growth suppression	growth release	TRD	reaction wood	callous tissue
Picea abies	19	35	15	6	19	10	3
Acer pseudoplatanus	21	37	22	5	0	0	5
Fagus sylvatica	16	27	13	5	0	0	5
Total	56	99	50	16	19	10	13

ginning of growing season (D – dormancy) took place in 1988 and 1992. On the other hand, events occurring in the period of summer wood formation towards the end of the growing season (L – late) took place in 1980, 1985, 2000, 2002 and 2006. The number and type of growth disturbances used in the identification of individual events is given in **Table 3**. **Fig. 5B** shows deviations of decadal frequencies of events from an average value in the period of 1896–2009 (2.17 events/10 years). The picture clearly shows two periods of distinct activity of processes. The number of events was much below average from the 1900s to the 1970s giving the lowest values in the 1950s and the 1960s, whereas the SD value was still high. Low values of the 1900s and the 1910s are related to a period of a considerably decreasing SD value. On the contrary, the values of decadal frequency were high above average from the 1970s to 2009 with higher values during the 1990s and the 2000s.

Fig. 6 shows a number of trees displaying growth disturbances in individual zones during all events. Most events (24) were recorded on the alluvial fan in the lower stream course within the third zone. It was also this zone in which growth disturbances were identified on the highest number of trees on average in relation with all the events. Most trees were affected in 1997 (8 individuals). Only 7 events were recorded in the middle course of the stream within the second zone. Besides one case in which 2 trees were affected, growth disturbances were always identified on one tree only. A total of 18 events were identified in the upper course of the stream within the first zone. Average number of trees revealing individual events is, however, lower than in the third zone. Maximum number of trees (4) was affected in 1970 and 1985.

Table 3. *Seasonality, types and numbers of growth disturbances identified in individual years.*

	season	growth suppre-ssion	growth release	TRD	reaction wood	callous tissue	total
2009		2	1				3
2006	L	1	1			1	3
2002	L	1	2	2		2	7
2000	L		1			2	3
1999		3	1				4
1997		5	1	3	1		10
1996		2	1				3
1992	D		1	1		1	3
1988	D	1				1	2
1985	L	1		1		4	6
1980	L		1	2		2	5
1977		4					4
1972		3		1			4
1970		5	2	2			9
1960		5	1	1			7
1953		2		2			4
1949		3		1	2		6
1940		3					3
1939		2	1		3		6
1932		1	1				2
1929		3			1		4
1924		1	1				2
1915		2					2
1903					2		2
1897				2	1		3
1896				1			1
Total		***50***	***16***	***19***	***10***	***13***	
%		**46.3**	**14.8**	**17.6**	**9.3**	**12.0**	

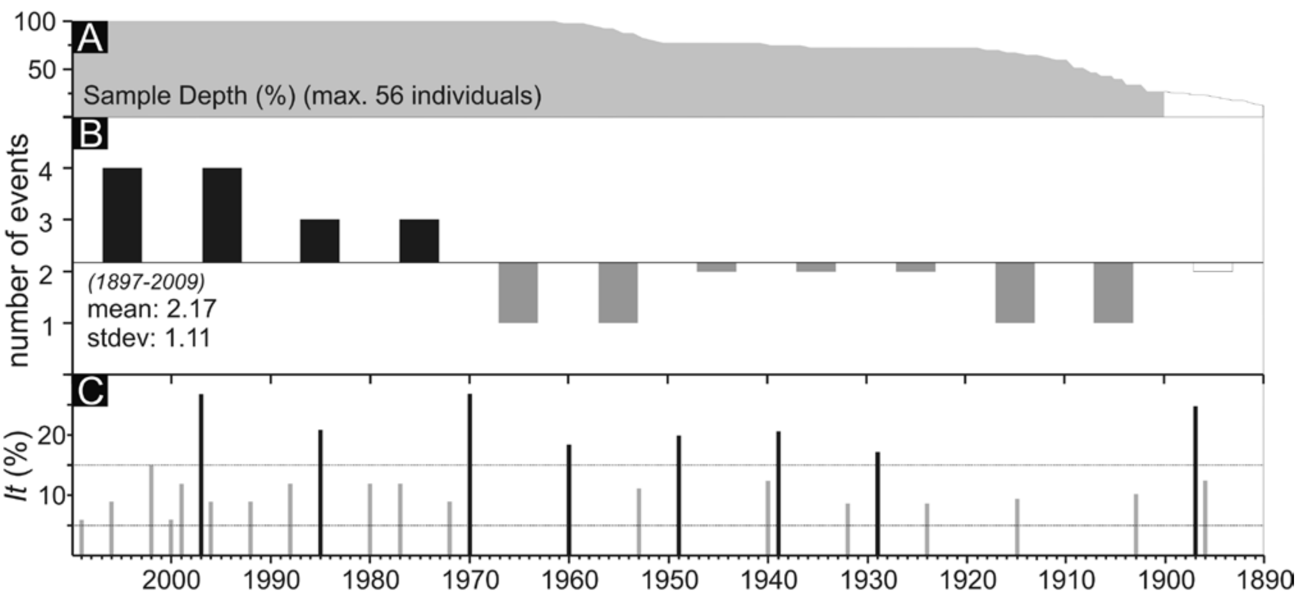

Fig. 5. *A – Progress in the number of sampled trees (Sample Depth; white area – SD <25%), B – deviations of decadal frequencies of events from the long-term decadal average, C – annual values of the* It *index incl. boundary values of* certain *(black bars) and* probable *events (grey bars) – dotted lines.*

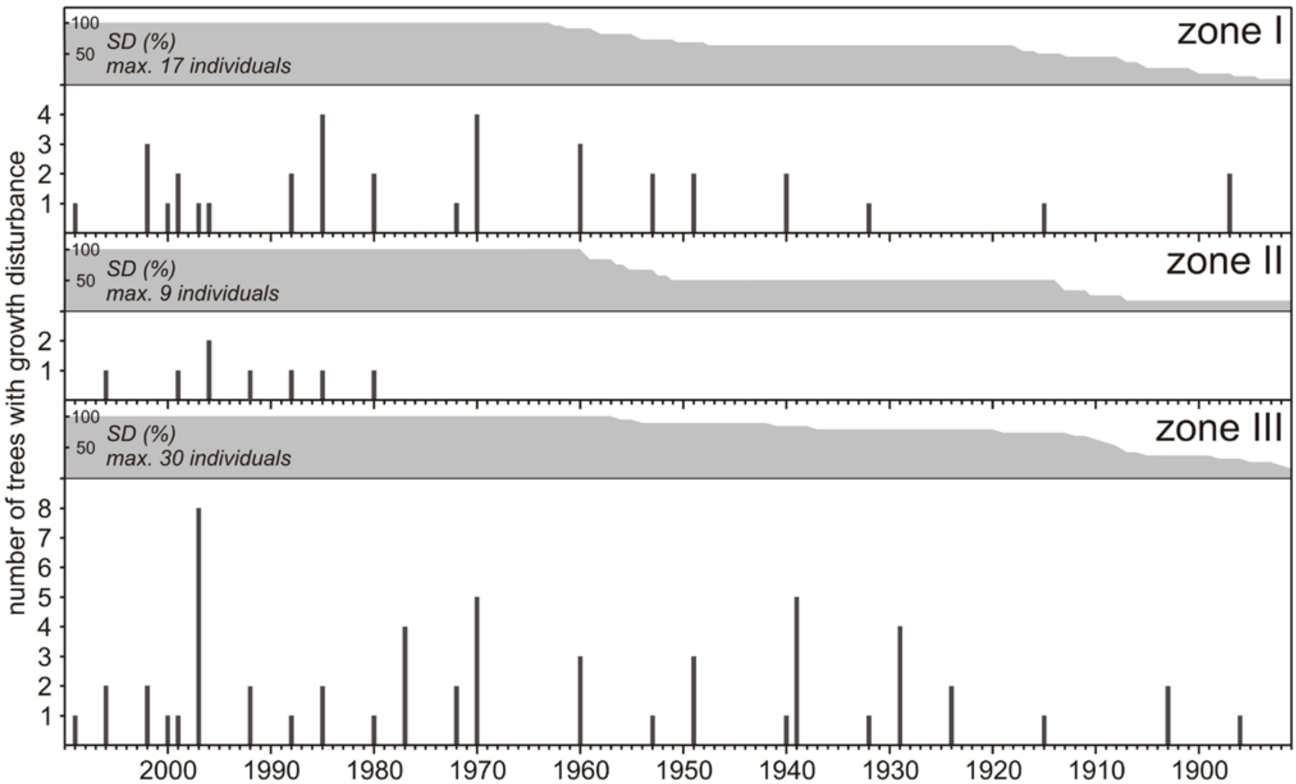

Fig. 6. *Number of trees displaying growth disturbances in individual zones of a high-gradient stream.*

Trees growing at the margin of the stream channel displayed exposed and dead parts of roots, which became manifested via abrupt growth suppression in ring series. On the other hand, two events during which material became accumulated on the alluvial fan were identified (in 1949 and 1997). There is one representative of *A. pseudoplatanus* in the lower part of the alluvial fan, which shows signs of stem burial in the form of adventitious roots at the height of ~1 m above the contemporary fan surface (**Fig. 7B**). Counting the tree-rings of the thickest (oldest) root and analyzing growth disturbances on cores was determined the year of burial to 1949. Dendrogeomorphic methods facilitate not only very accurate dating of the origin of geomorphological processes but spatial reconstruction of the evolution of landforms as well. The dating of growth disturbances on trees growing in individual erosional levels of the alluvial fan revealed at least 4 events during which the existing active stream channel underwent deepening (1939, 1972, 2006 and 2009) (**Fig. 7A**).

5. DISCUSSION

Analysis of 99 samples (86 increment cores and 13 cross sections) from 56 trees revealed 108 growth disturbances related to past flood or debris flow events. On the basis of these responses, it was possible to reconstruct 26 events of these processes starting with the year 1896. A benefit of this study is in dominant representation of deciduous trees (66.1%) in contrast to coniferous trees. The most important reaction of deciduous species to geomorphological events was abrupt growth suppression of tree rings. The same conclusion was also reached by e.g. Bollschweiler *et al*. (2011). TRDs and reaction wood occurred exclusively in connection with coniferous trees and it is particularly TRDs that may represent up to 70% of all identified growth disturbances (Perret *et al*., 2006). Low representation of TRDs in this study is caused by a small number of coniferous species in sample depth. However, positive influence of TRDs on the reconstruction of geomorphological processes was indispensable. Reaction wood facilitated the dating of almost exclusively older events that took place before 1949, which is most likely connected with the fact that the sampled trees were young at that time as well as small and easier to tilt. Another potential explanation suggests that events that caused the tilting of tree stems were much more powerful and dynamic than younger events.

The studies so far dealing with the processes in high-gradient streams have only used one-sidedly oriented methods. For example, reconstructing flood events, Zielonka *et al*. (2008) concentrated solely on scars found on stems of coniferous trees. Hrádek and Malik (2007) focused on more complex displays of deciduous trees

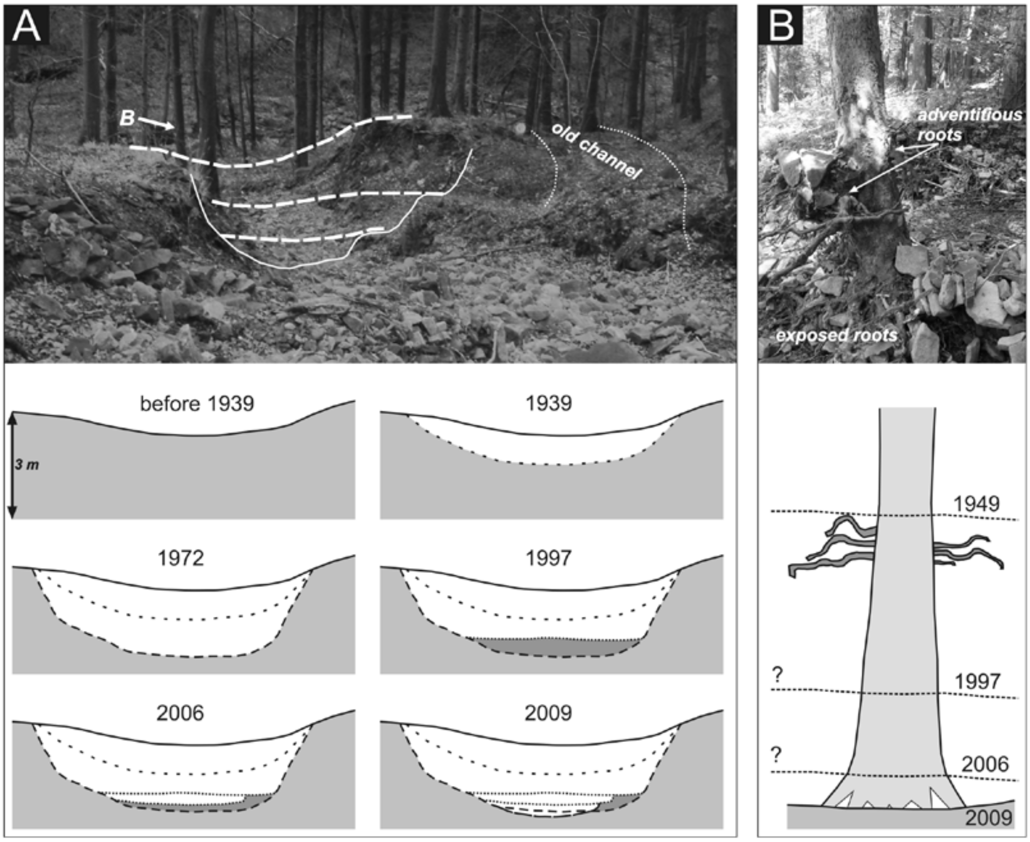

Fig. 7. *A – Reconstruction of erosional and accumulation events in an active bed on the alluvial fan at the mouth of the stream, B – tree (*A. pseudoplatanus*) with adventitious roots buried in 1949 with a few subsequent erosional events.*

when dating floods; however, the number of samples used was limited. Complex view of growth disturbances combined with statistic evaluation was brought by Ruiz-Villanueva *et al*. (2010); still, within a study of coniferous species only. On the contrary, analysis of floods and related accumulation events in low-gradient streams is often based on the analysis of adventitious roots (Hupp and Bazemore, 1993; Lehotský *et al*., 2010). This study tries to combine all the above mentioned approaches. Many dendrogeomorphic studies take advantage of statistic approaches in order to differentiate *certain* events from potential ones (Ruiz-Villanueva *et al*., 2010; Van Den Eeckhaut *et al*., 2009). In this study, two fixed limits were used in the reconstruction of individual events. Since the I_t index was used, maximum length of the reconstructed series was limited to 25% of the SD. Minimal values of the SD as a limit of the length of the reconstructed series of events was also used by Schneuwly and Stoffel (2008) or Šilhán *et al.* (2011). Another limit was represented by a minimal I_t value used to determine *certain* and *probable* events. Basically, it is modification of a quantitative approach used in the reconstruction of debris flows (Bollschweiler and Stoffel, 2010a).

The number and age of samples have a direct influence on the length of the reconstructed period as well as the I_t index of each event. Decadal frequencies of the number of events clearly reveal a distinctive period of a higher frequency of events (since the 1970s) and a period of below-average activity. Low values in the period of the 1900s and 1910s can be attributed to decreasing SD. However, since the 1920s SD has had little influence on such changes in frequencies. The causes of this little influence can only be a matter of speculation. One potential explanation is a change in triggering factors. Another possibility is identical frequency of processes but involving smaller events that affect a low number of trees (see e.g. Bollschweiler *et al*., 2008). Finally, what may be considered problematic is the methodology. The study of a large number of mainly older events was based on the identification of reaction wood. However, in case a tree trunk leans considerably, reaction wood can be found in a few successive tree-rings. If some events occurred within a few consecutive years, the response recorded in tree-ring series might be deleted because of the oldest event to which the trees reacted with the formation of reaction wood (Schweingruber, 1996).

An interesting figure is represented by the number of identified events in individual zones of the high-gradient stream. It is highly probable that the number of trees sampled in individual zones had a direct effect on the number of reconstructed events (correlation coefficient; r = 0.94). Still, some important facts need to be presented at this place. The first zone has a high longitudinal gradient and it is formed by a rocky stream bed. The source of material for debris flow transport is thus strongly limited. As a result, most events present themselves as increased water discharges of high velocity and dynamics. Debris flows, the volumes of which are highly limited, occur only occasionally. The second zone characterized by the lowest longitudinal gradient can be described as an accumulation zone of small debris flows from the first zone. Material accumulated here may, however, become reactivated (so-called "fire-hose effect"; Larsen *et al.*, 2006) at high water discharges and move down as debris flow further on in the third zone. Reactivation of the material of old debris flow accumulations is presently the most frequent cause of debris flow initiation in the Moravskoslezské Beskydy Mts (Šilhán and Pánek, 2010). Depending on the proportion of reactivated material and water, the processes manifest themselves on the alluvial fan either as erosional processes that deepen the active stream channel or as accumulation processes. Events occurring in the third zone in 1939, 1972, 2006 and 2009 can be considered floods and the events of 1949 and 1997 as debris flows with accumulation effect. In case of the other identified events, the character of the process could not be specified. Moreover, in 2005, two transverse constructions were built at the boundary between the second and the third zones in order to hinder sediment transport in the stream. Since that year no other accumulation events have taken place on the alluvial fan. Debris flow occurrence here is not only sediment-limited, but also transport-limited.

With regard to expected character of the processes, the analysis of potential meteorological triggering factors concentrated on the following aspects. A day with the highest precipitation amount has been selected from each year as an indicator of extreme precipitation. The occurrence of floods in high-gradient streams is highly affected by fast spring thick snow cover melting (Zielonka *et al.*, 2008). According to the authors, fast spring snow melt can be expressed as the so-called "melting index" that represents the difference between the values of April and May average temperatures. In this study, this factor has been completed with maximum snow cover thickness in the period of March-April. Results of the analysis presented in **Fig. 8** show that a majority of meteorological-data-supported events (15 out of 21) occurred in a year of extreme diurnal precipitation (which, in some cases, exceeded 200 mm/24 h; e.g. in 1972 and 1997). On the other hand, only 4 events took place during fast spring snow cover melting. In two cases (years 1988 and 1992), this assumption has been proved by intra-seasonal dating of events. Events intra-seasonally dated into the period of summer wood formation (1980, 1985, 2000 and 2002) were most likely induced by above-average summer precipitation occurrence. Events that took place in 1915 and 1977 may have been caused by both the above mentioned meteorological triggers; however, it is impossible to specify the concrete one without performing the intra-seasonal dating. On the contrary, neither potential cause can be associated with the origin of two events that took

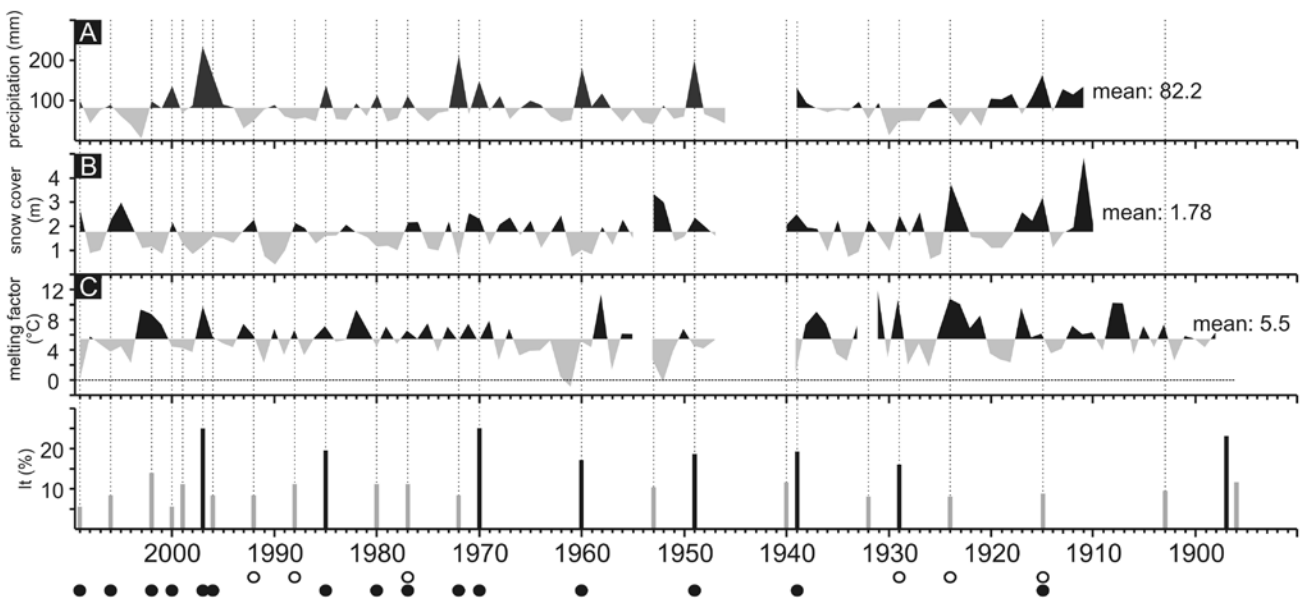

Fig. 8. *Comparison of identified events (It) with potential meteorological triggering factors of individual events, A – maximum one-day precipitation per year, B – maximum snow cover height in March-April, C – difference between average April and May temperatures, (white mark – correspondence of an event with the above-average melting index and, at the same time, the above-average snow cover thickness, black mark – correspondence of an event with the above-average one-day extreme precipitation total.*

place in 1953 and 1999, respectively. The lack of meteorological data hindered the specification of the origin of 5 events. However, the performed analysis shows that the most important factor controlling the occurrence of fast geomorphological processes in the studied high-gradient stream is short-term extreme precipitation. At the same time, absolute amount of extreme precipitation correlates strongly positively with the I_t index of individual events (correlation coefficient; r = 0.51).

6. CONCLUSION

Dendrogeomorphic analysis of 99 samples taken from 56 trees made it possible to reconstruct 26 events of fast geomorphological processes that have taken place in a selected high-gradient stream of the Moravskoslezské Beskydy Mts in the last 113 years. The reconstruction was based on a large number of deciduous trees that provided quality data and facilitated the reconstruction of events that would not have been identified in conditions of a limited number of deciduous trees.

Decadal evolution of the frequencies of events shows a significant increase in events in the last 40 years. Individual events that were identified are most likely flash floods. Debris flows occur sporadically, as a result of sediment-limited conditions of the basin. Debris flows in the lower course of the stream initiated by a “fire-hose effect” and manifested themselves by accumulation activity on an alluvial fan at the mouth of the stream.

Dominant triggering factor of the events is represented by short-term extreme precipitation events in summer months detected by dendrogeomorphic methods in e.g. 1980, 1985, 2000 and 2002 years. A secondary factor is fast spring snow melting observed in 1924, 1929, 1988 and 1992. This finding was proved by intra-seasonal dating of selected events.

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REFERENCES

Alestalo J, 1971. Dendrochronological interpretation of geomorphic processes. *Fennia* 105: 1-139.

Bollschweiler M, Stoffel M and Schneuwly DM, 2008. Dynamics in debris-flow activity on a forested cone – A case study using different dendroecological approaches. *Catena* 72: 67-78, DOI 10.1016/j.catena.2007.04.004.

Bollschweiler M and Stoffel M, 2010a. Tree rings and debris flows: recent developments, future directions. *Progress in Physical Geography* 34: 625-645, DOI 10.1177/0309133310370283.

Bollschweiler M and Stoffel M, 2010b. Variations in debris-flow occurrence in an Alpine catchment – A reconstruction based on tree rings. *Global and Planetary Change* 73: 186-192, DOI 10.1016/j.gloplacha.2010.05.006.

Bollschweiler M, Stoffel M and Schläppy R, 2011. Debris-flood reconstruction in a pre-alpine catchment in Switzerland based on tree-ring records of coniferous and broadleaved trees. *Geografiska Annaler A* 93: 1-15, DOI 10.1111/j.1468-0459.2011.00001.x.

Brázdil R, Březina L, Dobrovolný P. Dobrovský M, Halásová O, Hostýnek J, Chromá K, Janderková J, Kaláb Z, Keprtová K, Kirchner K, Kotyza O, Krejčí O, Kunc J, Lacina J, Lepka Z, Létal A, Macková J, Máčka Z, Mulíček O, Roštínský P, Řehánek T, Seidenglanz D, Semerádová D, Sokol Z, Soukalová E, Štekl J, Trnka M, Valášek H, Věžník A, Voženílek V and Žalud Z, 2007. *Vybrané přírodní extrémy a jejich dopady na Moravě a ve Slezsku* (Selected natural extremes and their impacts in Moravia and Silesia). Brno, Praha, Ostrava, Masarykova universita, Český hydrometeorologický ústav, Ústav geoniky Akademie věd ČR: 432pp (in Czech).

Gottesfeld AS and Johnson-Gottesfeld LM, 1990. Floodplain dynamics of a wandering river, dendrochronology of the Morice River, British Columbia, Canada. *Geomorphology* 3: 159-179, DOI 10.1016/0169-555X(90)90043-P.

Hrádek M and Malik I, 2007. Dendrochronological records of the floodplain morphology transformation of Desná river Halley in the last 150 years, The Hrubý Jeseník Mts. (Czech republic). *Moravian Geographical reports* 15: 2-15.

Hupp CR and Bazemore DE, 1993. Temporal and spatial patterns of wetland sedimentation, West Tennessee. *Journal of Hydrology* 141: 179-196, DOI 10.1016/0022-1694(93)90049-F.

Larsen IJ, Pederson JL and Schmidt JC, 2006. Geologic versus wildfire controls on hillslope processes and debris flow initiation in the Green River canyons of Dinosaur National Monument. *Geomorphology* 81: 114-127, DOI 10.1016/j.geomorph.2006.04.002.

Lehotský M, Novotný J, Szmańda JB and Fresková A, 2010. A suburban inter-dike river reach of a large river: Modern morphological and sedimentary changes (the Bratislava reach of the Danube River, Slovakia). *Geomorphology* 117: 298-308, DOI 10.1016/j.geomorph.2009.01.018.

Malik I, 2006. Gully erosion dating means of anatomical changes in exposed roots (Proboszczowicka plateau, southern Poland). *Geochronometria* 25: 57-66.

Malik I and Owczarek P, 2009. Dendrochronological records of debris flow and avalanche activity in a mid-mountain forest zone (eastern Sudetes – central Europe). *Geochronometria* 34: 57-66, DOI 10.2478/v10003-009-0011-7.

Mayer B, Stoffel M, Bollschweiler M, Hübl J and Rudolf-Miklau F, 2010. Frequency and spread of debris floods on fans: A dendrogeomorphic case study from a dolomite catchment in the Austrian Alps. *Geomorphology* 118: 199-206, DOI 10.1016/j.geomorph.2009.12.019.

Menčík E, Adamová M, Dvořák J, Dudek A, Jetel J, Jurková A, Hanzlíková E, Houša V, Peslová H, Rybářová L, Šmíd B, Šebesta J, Tyráček J and Vašíček Z, 1983. *Geologie Moravskoslezských Beskyd a Podbeskydské pahorkatiny* (Geology of the Moravskoslezské Beskydy Mts and the Podbeskydská upland). Praha, Ústřední ústav geologický: 304pp (in Czech).

Pánek T, Hradecký J, Minár J, Hungr O and Dušek R, 2009. Late Holocene catastrophic slope collapse affected by deep-seated gravitational deformation in flysch: Ropice Mountain, Czech Republic. *Geomorphology* 103: 414-429, DOI 19.1016/j.geomorph.2008.07.012.

Pelfini M and Santilli M, 2008. Frequency of debris flows and their relation with precipitation: A case study in the Central Alps, Italy. *Geomorphology* 101: 721-730, DOI 10.1016/j.geomorph.2008.04.002.

Perret S, Stoffel M and Kienholz H, 2006. Spatial and temporal rockfall activity in a forest stand in the Swiss Prealps – A dendrogeomorphological case study. *Geomorphology* 74: 219-231, DOI: 10.1016/j.geomorph.2005.08.009.

Ruiz-Villanueva V, Díez-Herrero A, Stoffel M, Bollschweiler M, Bodoque JM and Ballesteros JA, 2010. Dendrogeomorphic analysis of flash floods in a small ungauged mountain catchment (Central Spain). *Geomorphology* 118: 383-392, DOI 10.1016/j.geomorph.2010.02.006.

Shroder JF, 1978. Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. *Quaternary Research* 9: 168-185, DOI 10.1016/0033-5894(78)90065-0.

Schneuwly DM and Stoffel M, 2008. Tree-ring based reconstruction of the seasonal timing, major events and origin of rockfall on a case-study slope in the Swiss Alps. *Natural Hazards and Earth System Sciences* 8: 203-211.

Schweingruber FH, Eckstein D, Serre-Bachet F and Braker OU, 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia* 8: 9-38.

Schweingruber FH, 1996. *Tree rings and environment, dendroecology*. Wien, Haupt Verlag: 609pp.

Stoffel M and Bollschweiler M, 2008. Tree-ring analysis in natural hazards research – an overview. *Natural hazards and earth system sciences* 8: 187-202.

Šilhán K and Pánek T, 2010. Fossil and recent debris flows in medium–high mountains (Moravskoslezské Beskydy Mts, Czech Republic). *Geomorphology* 124: 238-249, DOI 10.1016/j.geomorph.2010.03.026.

Šilhán K, Brázdil R, Pánek T, Dobrovolný P, Kašičková L, Tolasz R, Turský O and Václavek M, 2011. Evaluation of meteorological controls of reconstructed rockfall activity in the Czech Flysch Carpathians. *Earth Surface Processes and Landforms* 36: 1898-1909, DOI 10.1002/esp.2211.

Van Den Eeckhaut M, Muys B, Van Loy K, Poesen J and Beeckman H, 2009. Evidence for repeated re-activation of old landslides under forest. *Earth Surface Processes and Landforms* 34: 352-365, DOI 10.1002/esp.1727.

V.I.A.S., 2005. Vienna Institute of Archaeological Science, Time Table. Installation and instruction manual. Ver. 2.1, Vienna

Zielonka T, Holeksa J and Ciapała S, 2008. A reconstruction of flood events using scarred trees in the Tatra Mountains, Poland. *Dendrochronologi*a 26: 173-183, DOI 10.1016/j.dendro.2008.06.003.