Dendrogeomorphological reconstruction of past debris flow activity along a forested torrent (Retezat Mountains)

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Abstract. Applying dendrochronological principles and techniques in geomorphological studies proves to be a veridical method for spatio-temporal reconstruction of processes occurring in mountainous regions. Analysis of tree ring growth data provides valuable information on past geomorphic activity, especially where there is a lack of archival records regarding them. Trees affected by the manifestation of geomorphological processes reveal morphological and anatomical disturbances through which we can date and assess these former events.

This study is an attempt to reconstruct temporal debris-flows activity by determining and dating various ring disturbances as growth responses of the trees which have been affected by these processes. The study was conducted on a torrent located in the southern slope of Retezat Mountains. In this analysis we used 122 increment cores extracted from 60 Norway spruce (*Picea abies* (L.) Karst.) that allowed us to reconstruct more than a century of debris flow activity. Past events dated through tree ring analysis reveal a good correlation with meteorological and hydrological data recorded in the vicinity of the studied area. The results obtained can equally serve to complete the archival data regarding natural hazards specific to this area and to establish the frequency and the magnitude of the processes with a useful role in taking early measures so as to prevent negative consequences.

Keywords: dendrogeomorphology, temporal reconstruction, debris flow, anomalies, Retezat Mts.

1. Introduction

Debris flows are the most frequent kind of rapid mass movements occurring in the mountainous regions of the earth, except for avalanches (Strunk, 1991). Debris flows, as being described by Takahashi (2007), are massive sediment transport phenomena that manifest themselves in the channel of mountain streams, consisting of a large variety of solid material. In order for a debris flow to occur, there has to be a sufficient amount of loose rock and soil deposits (Bovis & Jakob, 1999) and a large amount of water. In addition to this, the morphometrical parameters of the area have an important role in debris flow triggering, as they usually occur in torrents characterised by steep slopes and high values of fragmentation depth (Slaymaker, 1988; Wilford et al., 2004).

In Romania, though there are some mentions about past debris flow occurrences (Bălteanu et al., 2004), only recently a few studies are concentrated on this type of mass-movements (Pop et al., 2008, 2010, Ilinca, 2009, 2014). The debris flows which occurred in Retezat Mountains area, caused a lot of damage to infrastructure (400000$ damages in 11-14.07.1999), determined negative ecological consequences and even fatalities (13 deaths registered in the last event).

The debris materials, formed mainly by rocks and boulders of all sizes, hit the trees adjacent to the stream drainage channel, causing them many disturbances (Fig. 4). Any mechanical disturbance causes morphological changes in trees cell structure (Schweingruber, 1996). After the event occurrence, visible scars and marks remain on the stem of the affected trees, all of the disturbances being recorded in the tree's growth (Alestalo, 1971). As it has widely been described in the literature (Shroder, 1980; Braam et al., 1987; Schweingruber, 1996, 2007; Strunk, 1997; Stoffel & Bollschweiler, 2009 etc.) the trees react differently, depending on the type of the disturbance (scars and marks on the stems, tilting of stems, uprooting, decapitation etc.) by formation of callus tissue, tangential rows of traumatic resin ducts, compression wood, growth release, growth reduction, etc.

Due to the high sensitivity to any geomorphological disturbance, tree species like Norway spruce (*Picea abies* (L.) Karst.), are considered extremely suitable for dendrogeomophological reconstruction. Using trees' reaction to physical injuries one can precisely date debris flow activity and assess the spatial extent of each individual event with annual or even seasonal resolution (Stoffel, 2008).

The main purpose of this study is to reconstruct debris flow activity by dendrogeomorphological methods on a small catchment situated on the southern slope of Retezat Mountains (Romanian Carpathians). In this study, 122 increment cores extracted from 60 Norway spruces (*Picea abies* (L.) Karst.) were used. It is very important to know whether the frequency of debris flows affecting an area is increasing or is stable over time, as this aspect determines what kind of measures should be taken in order to prevent negative consequences (Braam et al., 1987).

1. Study area

The study site (45°19’01.2”- 22°47’19.3”) is represented by a small catchment located on the southern slope of Retezat Mountains (Fig. 1). The main collector is a right tributary of the Lăpușnicul Mare River, which drains an area of 128 ha, extending from an elevation of 2100 m a.s.l. to 1160 m a.s.l., corresponding to the confluence with the Lăpușnicul Mare River. The torrent surface is mainly built of deposits of granodiorites, with the exception of the lower sector, where conglomerates with sandstone intercalations are dominant, forming the base for the depositional cone of the torrent (Fig. 3). At the elevation of 1550 m a.s.l. there is a structural breakout and a waterfall of 5 m, at the bottom of which there can be observed blocks of over 3 m in diameter. The forest standing on the cone and along the channel mainly consists of Norway spruce (*Picea abies* (L.) Karst.). The permanent stream flow of the torrent initiates at the elevation of 1850 m a.s.l., reaching the cone after 2.2 km where it flows into the Lăpușnicul Mare River.

The debris material which can be observed along the torrent stream is heavily fractured, starting from blocks of a few meters in diameter to fine sand that can be easily mobilised during heavy rainfall and incorporated in the debris flow mass.

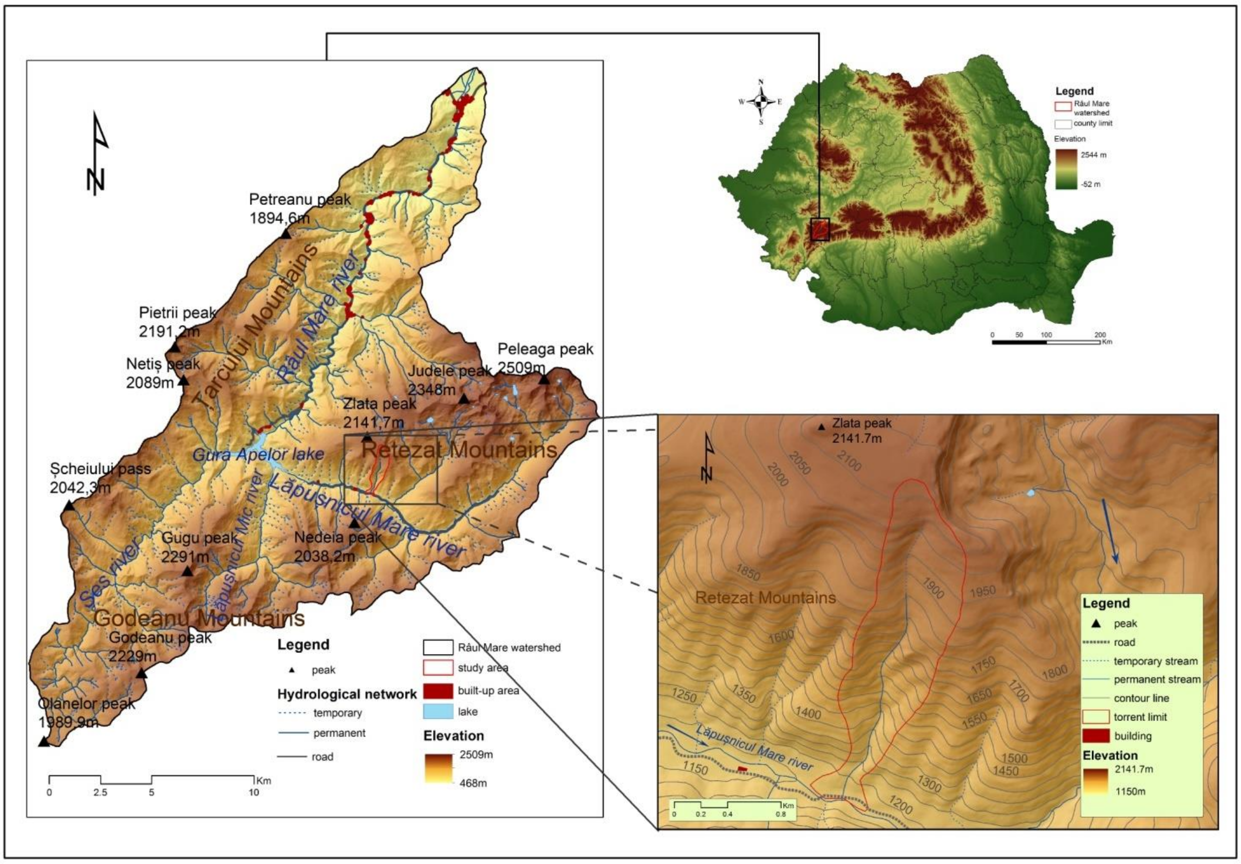


Fig. 1. **Geographical position of the study site**

The studied torrent has a mean slope of 24°, most of the slopes ranging from 17° to 31° (Fig. 2). Due to the steep slopes and impermeable substrates there is a fast response to heavy rainfall. The events which occurred in 11-14 July 1999 on almost all of Retezat Mountain’s torrents were triggered by intense rainfall during a period of three days (241 mm in 20.4 hours), causing enormous economic damages (≈ 800000 $) and 13 human life losses.

As it is a part of the Retezat National Park protected area, the study site has not been under a high anthropogenic influence. The torrent cone is crossed by the only access road to this area which connects the Poiana Pelegii site to the Gura Apelor Lake. After the event in 1999, many sectors of the road have been repaired and even moved and many streams were consolidated near the confluence (through deflection dam and reinforced-concrete frame constructions). In the lowermost part of the cone a small bridge was built as the road had been frequently destroyed by repeated debris flow events.

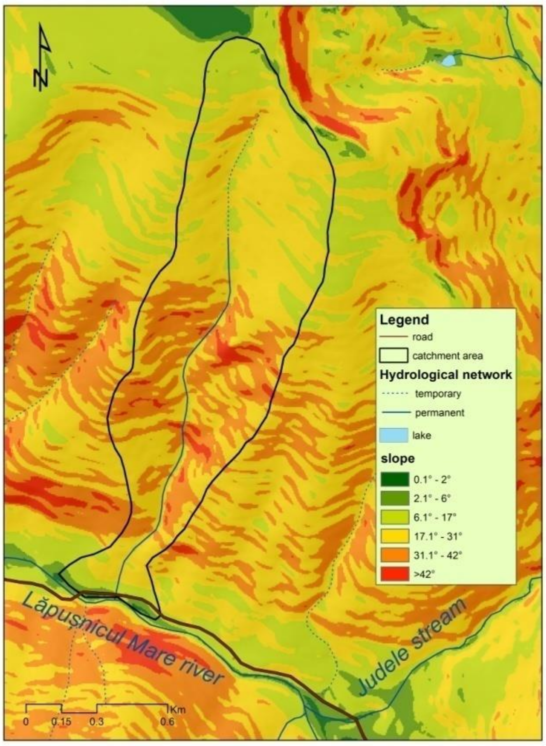
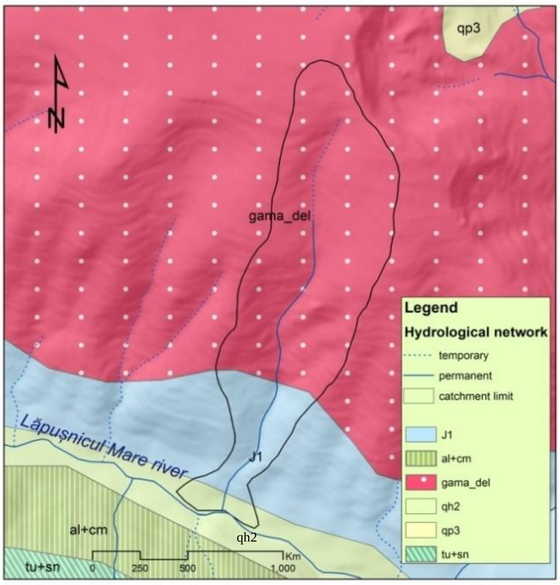


Fig. 2. **Declivity map of the catchment area**



J1- conglomerates, sandstones, clays; **al+cm** – limestones, calcareous-marls, sandstones; **gama_del** – granodiorites; **qh2** – gravels, sand, claysh-sand; **qp3** – glacial deposits; **tu+sn** – sandstones, conglomerates.

Fig. 3. **Geological map of the catchment area**

3. Methodology

In a first analytical step, we used different cartographic materials (topographic map 1:25000, ortophoplans 1:5000, etc.), field observations and other expertise, in order to gather detailed information about the study site. Based on the acquisition of a detailed database, the use of GIS techniques provided the thematic maps necessary for the analysis. For a more accurate representation of the geographical features and for a more precise observation of the value changes which arise in reality, the main morphometrical characteristics of the terrain surface were calculated based on a DEM with a 5 m resolution.

In addition to this, archival records were consulted to gain data regarding previous occurrences of major events at the study site or in the nearby area.

A number of 122 increment cores from 60 affected trees bordering the transport channel of the torrent were extracted in this study (Fig. 5). Using a Pressler increment borer, two increment cores were usually extracted per tree, except for the ones which presented multiple injuries. All of the sampled trees exhibited obvious evidence of debris flow impact on the stem but also on the roots and crown (Fig. 5, b and c). Most of them presented visible scars on the stem, especially on the waterside part. Two cores were extracted per tree, one close to the edge of the wound and the other on the opposite side of the stem. In the case of tilted trees, the samples were also taken from both sides at the height of the inclination. Moreover, for each sampled tree, additional data was gathered including description of the type of disturbance, its position, tree diameter, tree height and other useful information for the analysis.

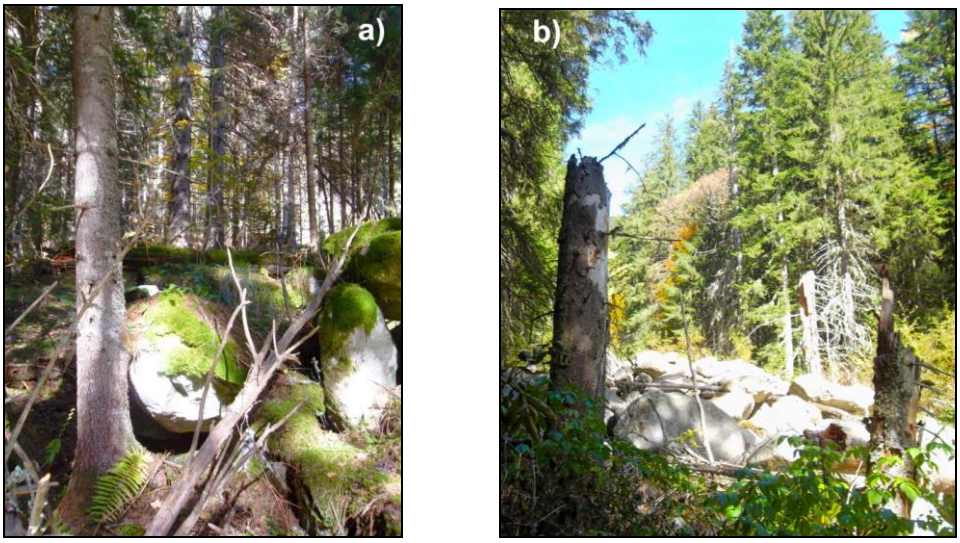


Fig. 4. **a) Damaged tree due to boulder impact;**
b) decapitated trees by mechanical impact and debris storage on the streambed

In addition to this, 20 undisturbed *Picea abies* trees were sampled which have not been affected by debris flow activity or other geomorphological processes. According to the procedure, the undisturbed trees were sampled at breast height, parallel to the contour line.

In the laboratory, samples were prepared and analysed according to the procedure described by Stokes and Smiley (1968), Braker (2002) and Stoffel & Bollschweiler (2008). In a first stage the samples were fixed on wood mountings, dried up and sanded in order to obtain a clear surface necessary for detailed anatomical observations. After counting the rings of each core, tree ring widths were measured with 0.001 mm precision using a LINTAB measuring station and TsapWin™ software. Growth curves of the affected trees were cross-dated with a reference chronology of undisturbed trees so as to obtain a normal growth condition of the investigated site. Afterwards, each sample was visually examined using a binocular microscope device in order to identify the growth anomalies and the year in which they appeared.

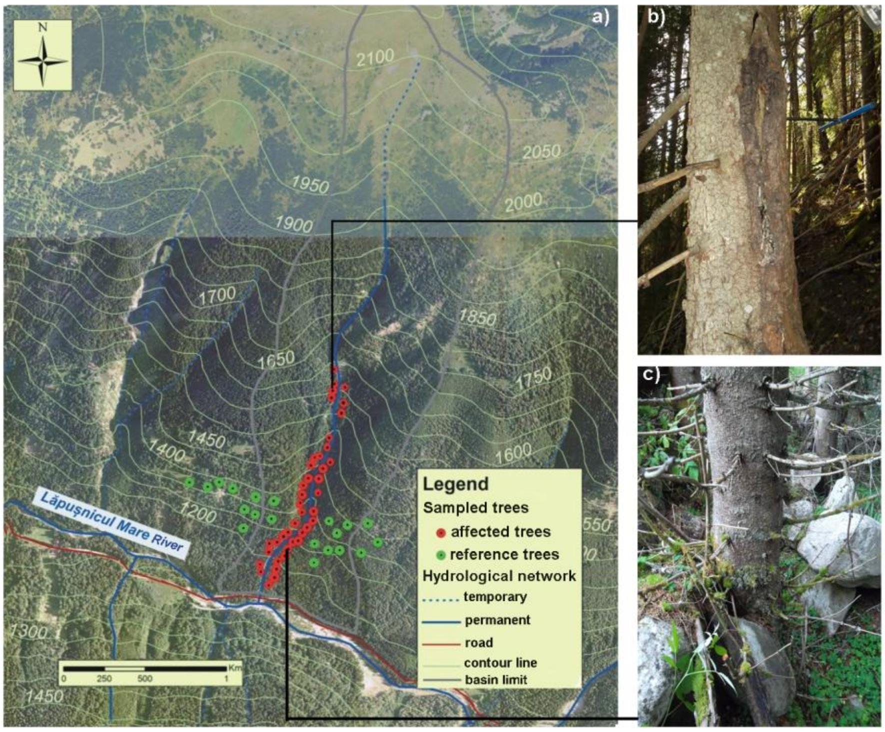


Fig. 5. **a) Position of the sampled trees; b) and c) - severe disturbances at the stem and roots level**

4. Results

The sampled trees have an average age of 76 years, the oldest one having 188 years, while the youngest one is only 28 years old (Fig. 6). The age structure of the sampled trees is heterogeneous and, therefore, we could not establish a spatial distribution of them. All sampled trees responded with different types of disturbances (Table 1). In total 556 growth anomalies were identified, the most frequently encountered being abrupt growth changes figured either by suppressed or released ring width in 316 and 42 cases, respectively. Another 172 anomalies were formed in the form of tangential rows of traumatic resin ducts (TRD), while compression wood (CW) was only occasionally found, in 26 cases.

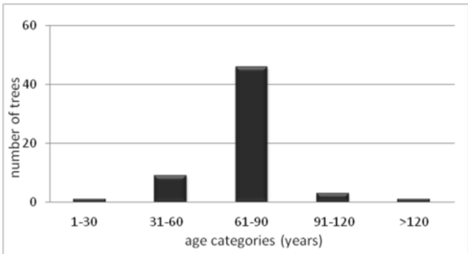


Fig. 6. **Representation of the age categories of the sampled trees**

Growth disturbances	total	%
Growth suppression	316	57
TRD	172	30
Growth release	42	8
Compression wood	26	5
Total	556	100

Table 1. **The total number of growth disturbances found in the sampled trees**

The event chronology attained through these reactions of the affected trees allowed us to reconstruct the following chronological sequence of debris flow occurrences in the investigated area. In 2000 a number of 30 trees reacted, from which there were 18 cases of tangential rows of traumatic resin ducts and 23 severe growth reductions. In 11 cases, the anomalies were both in form of TRD and in form of growth reduction. In the following 3 years another 49 anomalies were found. Another reconstructed year event was 1989, when 11 growth anomalies were encountered most of them being represented by growth suppression in 10 trees and traumatic resin ducts in 1 tree. Between 1962 and 1968, various types of anomalies such as traumatic resin ducts and growth reductions were identified in each year. This was considered a peculiarity, as in most cases after an event trees can react in the same year or in the following years, but not so far in time. In 1965 only 5 anomalies were discovered, but in the next year 10 anomalies were found. Also in 1961, 4 trees reacted through growth ring suppressions and compression wood. In the next 3 years, there were discovered in total other 15 reactions. In 1954, 7 trees reacted in form of 5 tangential rows of traumatic resin ducts (TRD), 1 growth reduction and 1 case of compression wood. Further in time, in 1949, 7 growth anomalies were discovered, mostly in the form of suppression wood, in 6 trees, 1 TRD and 1 case of compression wood. In the following year, 9 additional disturbances were identified, from which 7 cases of TRD and 2 suppression growths.

After almost a decade of reduced activity, in 1938, 5 trees presented TRD as growth anomalies. Earlier, in 1935, some growth anomalies were identified in the form of TRD in 6 cases and one case of growth suppression. Also related to this event can be considered other 7 anomalies found in 1936, from which 4 cases of TRD and 2 growth reductions. In 1929, 7 trees presented various forms of disturbances as TRD, growth suppression and growth release. To this event year the next two years can be also added, in which other 12 disturbances were found; in all 3 years in which trees reacted, in total 19 growth ring disturbances were counted.

As we go further in time, there are less available tree-ring data for the reconstruction, due to the young age of the majority of the sampled trees. The oldest disturbances identified were in 1866 via TRD, which continued to form even in the next year. Despite that, because of the limited number of trees available for the reconstruction, this year cannot be introduced in the review.

To this event chronology, another 3 events which might have been at a much smaller scale were added, as there were only few trees which reacted to them. Accordingly, the years 2010, 1992, and 1982 were also introduced in the analysis as there could be found some disturbances, many in the form of TRD and abrupt growth changes and a few cases of compression wood. In 2010, 6 TRD, 2 growth suppression and 2 growth releases were revealed as well as 4 other anomalies found in the next year. In 1992 and 1993, 13 anomalies were found, from which 4 TRD and one growth suppression for the first year and 4 TRD, 2 growth reductions, 1 growth release and one compression wood for the second year. In 1982, 8 anomalies via 7 growth suppression and one TRD were encountered, while in the next year 10 trees reacted by forming 7 growth reductions, one TRD, one growth release and one compression wood. In 1980, 7 anomalies were identified, out of which 3 TRD and 4 growth suppressions of the rings.

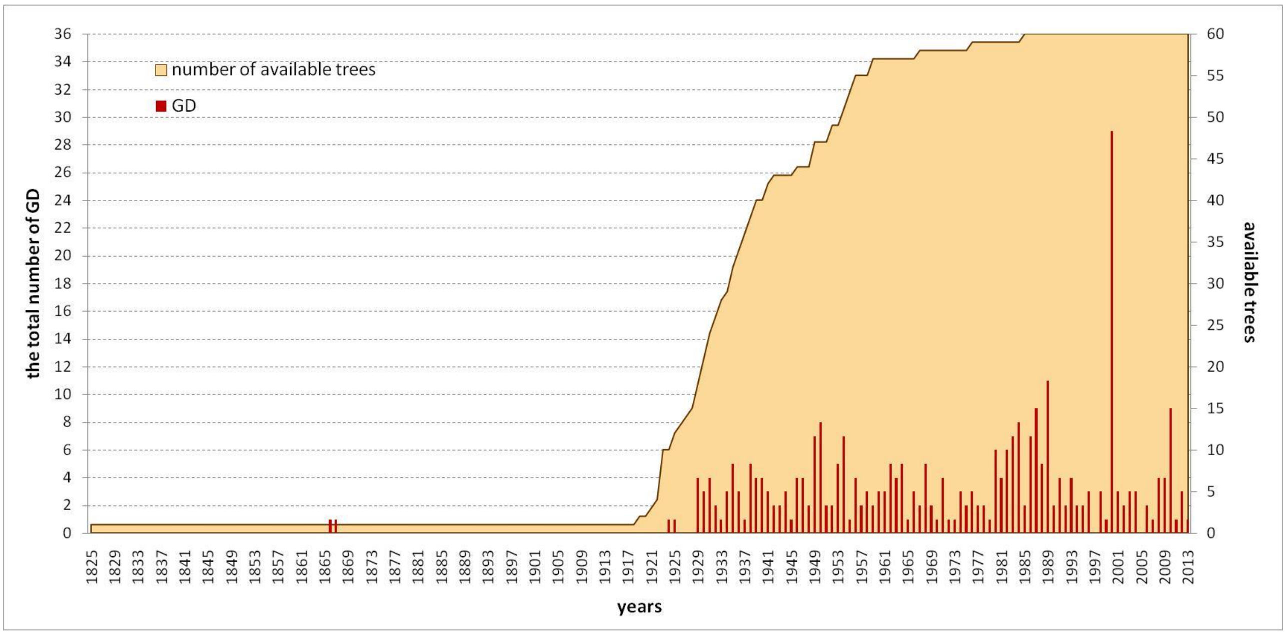


Fig. 7. **Representation of the total number of disturbances found in each year and the number of available trees**

The analysis of the 556 growth anomalies found in the 60 *Picea abies* sampled allowed the dating of 9 major debris flow events and another 3 of much smaller magnitude. The oldest event identified and introduced in the analysis was in 1929 and the newest occurred in 2010. As one can notice, debris flow activity is quite uniformly distributed, periods of repeated occurrences are followed by phases of no activity or at a much smaller-scale. According to Jakob *et al*. (2005), the channels of the torrents need to be recharged with debris supply in order to allow the debris flow development. Furthermore, the reconstruction of events dating prior to 1920 is limited by the absence of tree-ring data, due to the young age of the sampled trees.

5. Discussions

Using dendrogeomorphological methods for the temporal reconstruction of debris flow activity which regularly manifests itself on a torrent situated in the southern slope of Retezat Mountains, 9 major past events and other 3 smaller ones have been identified. The dendrogeomorphological reconstruction of debris flow occurrence was limited by the young age of the sampled trees and by the deprivation of other ones which were severely affected by rot or dryness. There were few trees which exceeded 100 years, the average age of the sampled trees being only 76. As a consequence, all the disturbances found prior to the 1920s could not be used in the assessment.

This temporal reconstruction has to be seen as a minimum frequency of past debris flow activity, as it depends on the probability of a tree being affected by the manifestation of a particular event in the past. According to this, only those trees which were directly hit by boulders and rocks transported by the mass-movement of the debris flow could react by forming different kinds of growth disturbances. Moreover, as debris flow magnitude decreases and the material remains in the channel, fewer trees can be affected and may, therefore, not be identified by dendrogeomorphological methods.

Comparing tree-ring data with local archival records one can notice a quite confident relationship between them. During the reconstruction period, six major flood events were registered which occurred in the vicinity of the studied area. Most of them were caused by massive amounts of rainfall of high intensity. The availability of a massive amount of loose rock, corroborated with the preponderance of steep slopes and a large amount of water make excellent conditions for the debris flow to be configured. Summer thunderstorms which are considered to be one of the main triggering factors of debris flows are frequently recorded in this site (135.8 mm in 7 hours, 11-12.07.1999). Earlier registered events in the neighbourhood area were noted in archives as they had caused major damages to infrastructure or even life losses. However, smaller scale events might not have been registered.

Tree-ring data coincide very well with archival records of the event which occurred in July 1999, but most of the trees affected then reacted only in the next year of vegetation. Given the high number of growth disturbances identified in 2000 to which another 49 anomalies found in the next 3 years of vegetation were added, one can deduce that the event had a high magnitude which caused severe damages to the riparian vegetation.

Between 1962 and 1968 there various types of growth anomalies were discovered in each year, which was considered a peculiarity due to the long period of reactions. As the available archival data were investigated for this period of time in what concerns debris flow or flash-flooding records in adjacent rivers, two major events were found, one in 07.09.1961 and another in 04.06.1965. As observed so far almost in every case, anomalies continued to be formed in the following years of vegetation after a major event. In the case of the event which occurred in September 1961, it is presumed that many growth disturbances of the affected trees appeared only in the following year, because the event manifested at the end of the vegetation period.

The last archival record found on flooding in the vicinity of the studied area was from 18.08.1948, when a major flood on Râul Mare River occurred. Related to this event might be the growth anomalies which were found in the next years of vegetation, in 1949 and 1950.

As additional archival data on major events occurring in this area could not be found, dendrogeomorphological methods may be the most precise and accurate way for dating geomorphological processes.

The trees which grew up near the streamline were either decapitated or eliminated, as their rotten and dry trunks and branches can still be seen in the channel or on the cone. Anthropogenic activity was not detected along the torrent channel, but some interventions have been observed in the lowermost part of the cone. After the event in July 1999, different protection measures have been taken, especially at the bottom of the torrent, so as to prevent the destruction of the road which crosses the cone. The bank of the active debris flow channel was reinforced at the apex of the cone, near the confluence with the Lăpușnicul Mare River. In addition to this, the road was consolidated and a bridge was built to protect it against any geomorphological or hydrological phenomena. Other necessary defensive works were not taken into consideration. In order to prevent the triggering of debris flows, the consolidation of sediment deposits needs to be considered as well as torrent bed reinforcements, dams and debris flow breakers, to hold back large boulders.

In conclusion, debris flow activity in the studied area appears to be rather influenced by meteorological events, as debris supply cannot be considered a limiting factor, due to the high availability of loose material. Therefore, particular characteristics of some weather events might trigger a debris flow. As it was pointed out by Armanini (2005), the concomitance of a period of successive rain events or an intense rainfall preceded by a long period of sediment saturation are favourable conditions for debris flow initiation. Unfortunately, this aspect decreases the predictability of this kind of phenomena, posing as a real threat to human safety. These processes have been causing many fatalities and economic damages and other negative ecological effects and, therefore, should not be underestimated.

6. Conclusions

The dendrogeomorphological analysis used in this study allowed the reconstruction of 12 events, covering almost a century. The study was conducted on a torrent located on the southern slope of Retezat Mountains. The results of this study reveal that the temporal reconstruction of past debris flows based on the interpretation of tree-ring data, coincide with archival records of meteorological and hydrological events. Since 1948, almost all of the event-years reconstructed through dendrogeomorphological means were confirmed by major events recorded in the archival data.

Despite the young age of the trees available for analysis, which limited the reconstruction of debris flow activity, the dendrogeomorphological method proved to be a reliable and valuable tool in the acquisition of data on former events at the study site.

The low predictability of debris flow occurrences, associated with their high destructive power, led to some unfortunate events which caused many economic damages and even human losses in Retezat Mountains area. Even if the event from 1999 led to the application of some measures which consolidated the torrents and the road, there are still some other actions that need to be taken into consideration. Smaller scale events manifesting within the channel are often neglected by the authorities. The temporal reconstruction of debris flow activity is important for establishing the process frequency required for hazards and risk assessment databases. In addition, a better understanding of past and potential future debris flow occurrences is necessarily imperative, in order to take early measures and to prevent negative consequences.

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