**„BABEŞ-BOLYAI" UNIVERSITY, CLUJ NAPOCA**

**F A C U L T Y O F G E O G R A P H Y**

**DOCTORAL SCHOOL IN GEOGRAPHY**

**DEPARTMENT OF PHYSICAL AND TECHNICAL GEOGRAPHY**

# PhD THESIS

# THE UPPER AND MIDDLE BASIN OF RÂUL MARE. DENDROGEOMORPHOLOGICAL STUDY

SUMMARY

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**Keywords**: dendrogeomorphology, growth anomalies, debris flows, susceptibility, Râul Mare

# I. INTRODUCTION

## 1.1. Geographical position of the study area

The study site is represented by the upper and middle basin of Râul Mare, formed at the contact of four major morphological units (Retezat Mountains, Țarcului Mountains, Godeanu Mountains and Piule-Iorgovanu Mountains) (fig. 1). The main collector is the most important tributary of Strei River, draining an area of 380 km² which extends from an elevation of 480 m a.s.l. (Hațegului Depression) to 2509 m a.s.l. (Peleaga Peak).

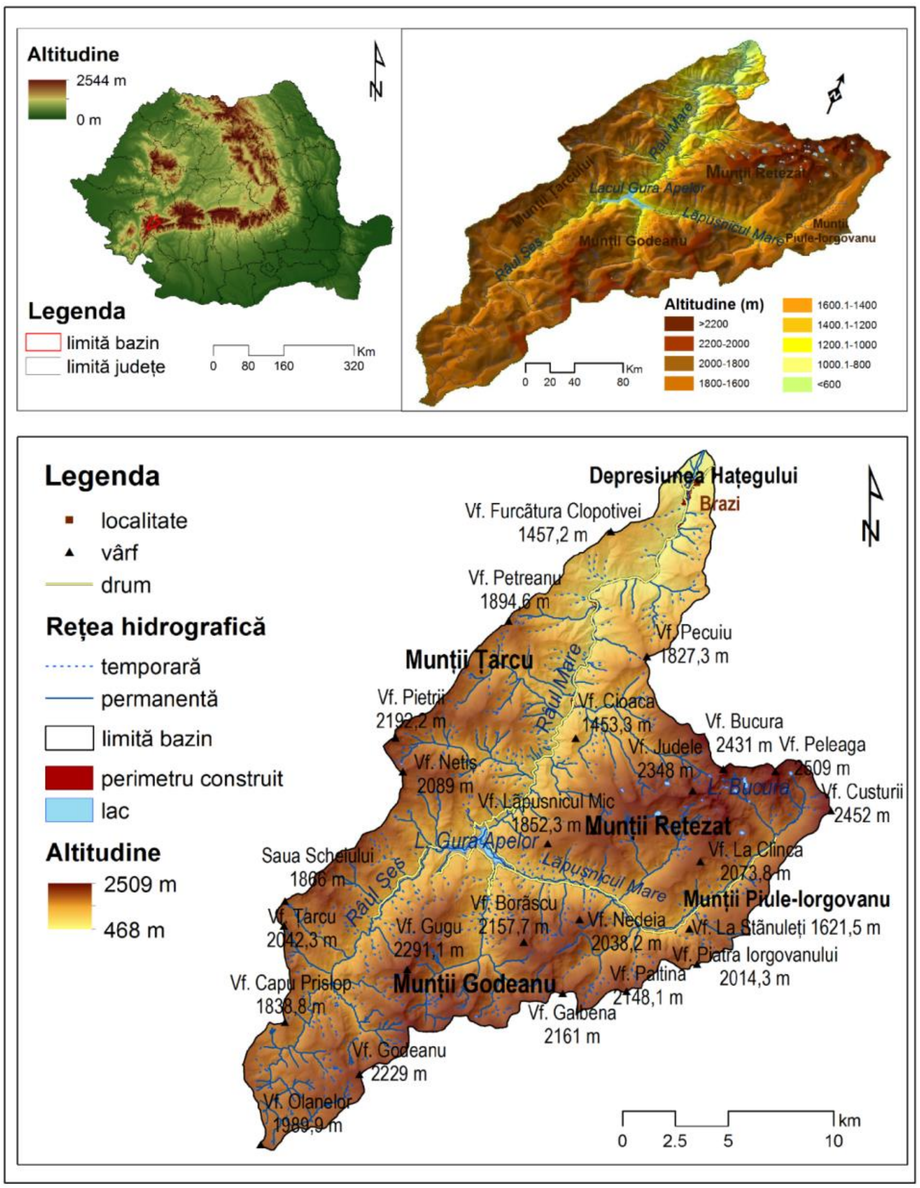


**Fig. 1.** Geographical position of the upper and middle basin of Râul Mare and the tridimensional model of the terrain surface

## 1.2. Motivation of the research subject and of the study area

The elaboration of a detailed assessment of the geomorphological processes which occur in the upper and middle basin of Râul Mare is very important because it presents an accelerated morphodynamics which is responsible for the manifestation of high energy discharge events that generate huge damages and even human loses. During the interval between 11 and 14 July 1999, there was an extreme event which affected the entire area of Râul Mare basin. On the night between 11 and 12 of July, there was registered a rainfall of high intensity (which locally exceeded 135 mm in 7 hours), which triggered debris flows on some torrents, affecting both the road infrastructure and the buildings. The debris flow that was formed on a small torrent located downstream of Gura Apelor Lake, rushed into Tomeasa colony causing 13 deaths and 21 injuries. The high number of casualties and the significant material damages demands and imperative necessity for a detailed investigation.

## 1.3. Research objectives

The main objective of this study is the spatial and temporal reconstruction of debris flows that occur in the upper and middle basin of Râul Mare using dendrochronological methods. The results can serve to complement and extend the existing database required for hazards and risk assessments. The reconstruction of the geomorphologica processes activity is based on the identification and interpretation of the growth anomalies found in the affected trees. Another objective of the study is to highlight the morphological and morphometric features which favor the manifestation of debris flows in this area. The assessment of the interdependence of the causative factors and the processes can be carried out in relation to the major weather events that marked the territory and other phyto-pedologic particularities. Another objective was a preliminary susceptibility assessment at a medium scale regarding debris flow activity for establishing the process spreading required for hazards and risk database.

# II. RETROSPECTIVE APPROACH OF THE RESEARCH HISTORY

# III. METHODOLOGICAL AND CONCEPTUAL ASPECTS

## 3.1. Conceptual aspects regarding the debris flow phenomen

### 3.1.1. The definition of the debris flow concept

The first study focused on debris flow was developed by Stiny in 1910, who describes a flood on a mountain stream in which at a certain moment, the amount of sediment carried by the flow increases causing the formation of a viscous mass with dynamic features similar to lava (Hungr , 2005). In 1978, Varnes includes debris flows in the category of mass movements which he describes as a rapid flow consisting of a mixture of solids, water and air that have a viscous texture. Later, in 1980, Aulitzky defines the process as a pulsating, viscous gravitational flow which is no longer dominated by the Newtonian laws of hydraulics and with potential velocities up to 30m/s.

Debris flows have been recognized and studied by a number of authors: Swanston (1974), Slaymaker (1988), Hungr *et al*. (2001), VanDine and Bovis (2002), Takahashi (2007) etc. In Romania, the term debris flow has only recently appeared in the literature and ti was only mentioned in some studies on natural hazards manifested in the montainous regions, without making a more detailed description of the process. Dendrogeomorphological methods were applied by Pop (2008, 2010, 2012), Ilinca (2010) and Chiroiu (2015b) to reconstruct debris-flows activity in mountainous areas. Also, Ilinca (2014) presents a characterization of debris-flows manifested in the lower basin of Lotru River, focusing on the triggering factors, velocity and morphology of the deposit. Currently, there is no unanimous accepted terminology regarding this process and there are several options for term translation: *curgeri de debris* according to Pop (2012) and Ilinca (2014) and *curgeri de grohotiș* according to Chiroiu (2015).

As we consider the term *curgeri de debris* as the most comprehensive we propose its use as the equivalent term of debris flow.

### 3.1.2. Classification of the mass-movements

Over time, there have been numerous discussions and debates regarding the terminology and the classification of the geomorphological processes based on various criteria, some of them more or less accepted (Beverage and Culberstone, 1964 Varnes, 1978; Hansen, 1984; Bradley and McCutcheon, 1985; Hutchinson, 1988, Pierson, 1986, Pierson and Costa, 1987; Sheko, 1988, Coussot and Meunier, 1995 Hungr *et al*., 2001). The main variables used to distinguish between debris flows and other similar processes are the triggering mechanism, basin characteristics, composition and proportion of solid fraction, velocity, duration, channel slope and the physical processes during flow etc.

From the consulted literature, we deduce that the amount of sediment gradually increases from normal flow with a certain amount of bedload to hyper-concentrated flows, debris flows, landslides and debris avalanches.

### 3.1.3. Characteristics

#### *3.1.3.1. Favorable triggering conditions*

Most of debris flows occur in small catchments characterized by steep slopes which are occasionally affected by extreme weather events such as high intensity rainfalls or rapid snow melts and substantial amounts of loose material. Also, debris flows can be triggered by the breakout of glacial or natural lakes as well as by the collapse of the man-made dams.

#### *3.1.3.2. The propagation of the process*

From the observations of some researchers regarding the Reynolds number is inferred that the analyzed process is part of laminar flows. The techniques and methods used to analyze landslides and water flow are not suitable for studying the dynamics of debris flows. The best method of analysis regarding the dynamics of debris flows can be found in analyzes of the fluid mechanics. The rheology, which describes the behavior of the fluid in response to shear stress is a function of: the relative proportion of water, sediments and air, the particle size distribution of the sediments as well as the physical and chemical properties of the particles (Johnson, 1970; Iverson, 1985). The velocity of the mass is determined by the relationship between the gravitational force and the resistance force.

#### *3.1.3.3. Deposit morphology*

The morphologic features of debris flow deposits are used to distinguish between basins affected by debris flows or flash floods/hyper-concentrated flows (Costa, 1988). Costa and Jarret (1981) describe debris flow deposits as being granular, poorly sorted and with unconsolidated terminal lobes and levees. VanDine (1985) describes deposits as unsorted materials consisting of layers of different sizes but predominantly coarse material which are mixed with sorted and sieved layers representing deposits of the normal flow.

#### *3.1.3.4. Frequency and magnitude*

The frequency and the magnitude of debris flows are closely related to the recharge rates with sediments of the transport channel and of the source areas. Catchments affected by debris flows must be recharged with material before a large event can reoccur.

The most important variables used to characterize catchments prone to debris flows are: the total basin area, the area which is actively contributing debris, active area index, total basin relief, elevation relief ratio, drainage density, zero-order ruggedness, mean basin slope and Melton index. Melton index was first used in studying the catchments in the southern part of the Canadian Rocky Mountains (Wilford *et al*., 2004). Based on this index there was determined catchments prone to flash floods and to debris flows (Jackson et al., 1987). The results obtained by Wilford et al. (2004) in the analysis of 65 catchments prone to flooding, debris floods and debris flows indicated the following: the debris flows occur in watersheds with a Melton index of over 0.6 while flooding occurs to values below 0.3. Therefore, values between the two thresholds (0.6 to 0.3) are attributed to debris flood-prone basins.

In order to estimate the magnitude, the maximum discharge is based on the changes in the morphology of the terrain (riverbed, channel slopes, cone) and on the presence of scars on the trunk of the affected trees. The height of these scars are used to reconstruct the maximum flow cross-sectional area. However, for a better estimation of the magnitude there should be used the total volume of the deposited material.

## 3.2. Dendrochronology and dendrogeomorphology

The variation of the parameters of growth rings of the trees and other features of the wood structure such as density of the cells are key indicators in deciphering the environmental conditions in which they grew. Therefore, the annual rings may be considered as an important database containing information about changes of the environmental conditions of a specific area, in a specific time in the past.

The dendrogeomorphology is the science that uses tree rings and their growth responses to date geomorphological processes responsible for the genesis and evolution of landforms. The term dendrogeomorphology (*dendron*- tree, *geo*-earth, *morphological*-form, *logos*-science) was introduced in 1971 by Jouko Alestalo. The impact of the processes on the tree is manifested both on trunks and roots and crown level. The pressuring forces determine certain morphological changes in the internal structure of the wood.

## 3.3. Anatomical features of the wood structure

Knowledge about the micro and macroscopic structure of wood and the influence of the internal and external factors is necessary when we want to decipher the dendrological alphabet and to identify the growth anomalies and their causes. If internal factors are related to hereditary characteristics of the species and the age of the trees, the external ones are related to the abiotic, biotic and anthropogenic factors.

### 3.3.1. Macroscopic structure of softwood

Tree's growth is manifested in all anatomical components - on stem, root and crown. The stem, which is the most useful part in dendrochronological investigations can be analyzed by using three different sections: the cross section, the tangential section and the longitudinal section (fig. 2). The longitudinal section of the stems shows the increase in width and height, being compared to an overlapping timber cones, each cone being formed in a growing season. The cross-section, which is also a dendrochronological sample allows the visualization of the macroscopic structure of the wood starting from pith to the bark (rhytidome). The annual growth rings and their parameters can be best seen in cross sections. The most important anatomical part of this section is the cambium layer, which serves to generate cells in the growing season for both inward part of the wood and bark. The annual ring represents all the cells formed in a growing season. The more favorable conditions at the beginning of the vegetation season cause the formation of larger diameter cells and thin walls arranged in a well-organized structure which is the earlywood. Towards the end of the growing season, when environmental conditions are more restrictive, cell structure changes, they appear more compacted with thick walls and smaller diameter and dark color which is called the latewood.

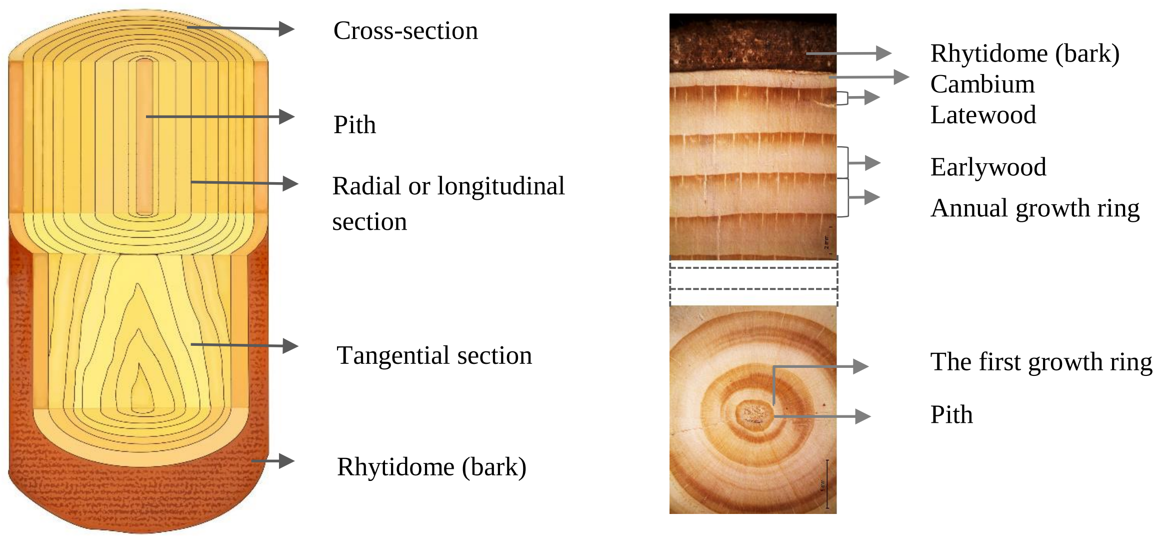


**Fig. 2**. The sections of the stem and the anatomical macroscopic structure of the spruce in a cross-section

### 3.3.2. Microscopic structure of softwood

Coniferous species are characterized by an overall homogeneous macroscopic and microscopic structure of the wood. The plant cells of the resinous trees are divided into prosenchymatic cells, consisting of axial tracheids, marginal tracheids and radial tracheids and parenchyma cells which are made up of longitudinal parenchyma cells, fusiform parenchyma, radial parenchyma and tangential rows of the transversal and longitudinal resin ducts (Lunguleasa, 2004). Of great interest to this study are the traumatic resin ducts, specific to conifers (fig. 3). In cross sections, these resin ducts appear as small dots with lighter and yellowish color. On the longitudinal section, the resin ducts appear as fine lines with different lengths parallel to the fiber direction. Not all species of conifers have resin ducts like yew or fir, but the latter can form traumatic resin ducts after an injury.

**Fig. 3.** Traumatic resin ducts visible in the cross-section of a spruce

### 3.4. Working steps

The interdisciplinary approach of this study required the use of a complex methodology that were borrowed methods and techniques specific to other areas of science. The proposed objectives greatly depend on respecting the methodological demarche and passing through all the working steps (fig. 4).

#### 3.4.1. Preliminary phase

The assessment of the particularities of the terrain must be completed by a detailed analysis of the study issues, contouring the main objectives and planning the working steps. In a first step, there were used different bibliographical sources, cartographic materials, specialized studies and expertises, to obtain as much information as possible for a detailed knowledge of the study area. Also, the procurance of a complete database allowed the application of the GIS techniques to obtain the thematic maps necessary for the study. Thus, the topographic maps 1: 25000 scale were used to vectorized the contour lines and elevation points based on which we obtained the digital elevation model (DEM). Also, based on the topographic maps and orthophoplans there were obtained the hydrological network, infrastructure, human settlements and other items of interest. The database was completed by other cartographic materials such as soil and geological maps 1: 200,000, orthophotoplans 1: 5000 and satellite images, atlases, Corine Land Cover Database etc.

THE DOCUMENTARY PHASE

Bibliographic sources, cartographic materials, archival records and other expertise

FIELD SAMPLING

Identification of the active geomorphological processes, establishing the sampling sites, sampling the trees and making the necessary measurements, terrain mapping

LABORATORY ANALYSIS

Prepairing the samples for analysis: mounting, drying, sanding and counting the tree rings, analysis and measurement of the rings with

INTERPRETATION OF THE RESULTS PHASE

Statistical analysis and interpretation of the results

FINALE RESULTS

Temporal and spatial reconstruction of the debris flows

**Fig. 4**. Working steps in the dendrogeomorphological studies

#### 3.4.2. Field step

The field step is the most important part of the study and mainly involves an expeditionary research of the terrain and establishing the representative study cases. The dendrogeomorphological investigations require appropriate sampling tools, working sheets for filling the characteristics of the sampled trees and other related measurements and a GPS to record the elevation points. During this step, there were organized several field campaigns both for exploring the terrain and for dendrochronological sampling and performing the necessary measurements.


**Fig. 5**. a) Sampling a tree using the Pressler increment borer, b) mechanical scar on the stem

The sampling was performed both by coring or taking cross sections and semi-transversal sections (wedges). The dendrochronological cores were collected using a Pressler increment borer which were mainly extracted from the trees located near the stream (fig. 5). The most common injuries found in trees which were affected by debris flow were: root burial or exposure, mechanical scars, tilting or curved stems and decapitation.

According to the procedure, all relevant information for the study was written on the working sheets for each sampled tree. The storage and transport of the cores must be done under appropriate conditions to avoid compromising the integrity and the quality of the samples. The mapping procedure was performed at a scale appropriate for the purpose of the study which emphasized the microforms and specific morphological features. For the spatial location of the features, there was used a GSP Magellan x600 Explorist while the measurements meant to complement the morphological characteristics of relief microforms were effectuated manually using the meter, clinometer and telemeter.

**Fig. 2**. The LINTAB measuring station and Leica stereo microscope

### 3.4.3. Laboratory analysis

In the laboratory, the samples were prepared and analysed according to standard procedure described by Stokes and Smiley (1968), Braker (2002) and Stoffel and Bollschweiler (2008). In a first step, 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 *(Time Series Analysis and Presentation, Rinntech, 2006)* (fig. 6). 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.

### 3.4.4. The analysis and interpretation of the results

At first, we analyzed the reference chronology in order to exclude the years when there were other non-geomorphological influences on growth. The most common growth disturbances found in the affected trees were: growth reduction or release, compression wood, eccentric growth rings and traumatic resin ducts. Sudden shifts from narrow to large rings and vice versa is a growth anomaly that can appear from many causes (fig. 7). The elimination of the competition around the trees that survived a major event will cause growth releases. Another type of growth anomaly is the compression wood that occurs due to longitudinal tensions in tilted stems (fig. 8). Compression wood has a different micro- and macroscopic structure and chemical composition, the lignin content is higher by 20-30% than the normal wood and therefore, has a different behavior to mechanical stress.

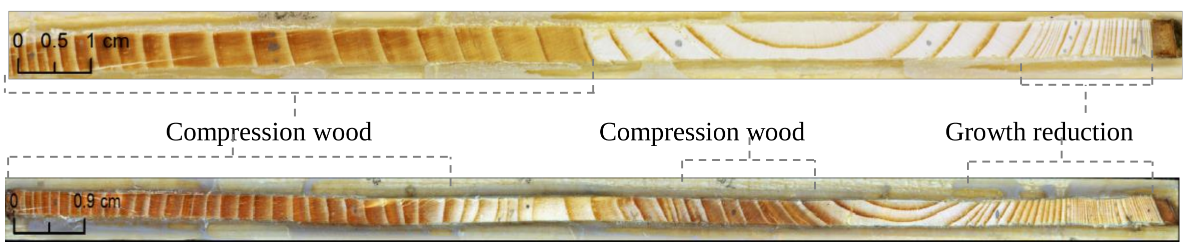


**Fig. 7**. Examples of compression wood

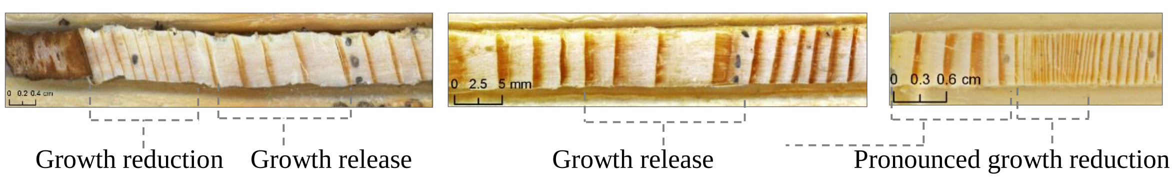


**Fig. 3.** The variation of the rings width

Of great importance for the reconstruction of the process activity are the tangential rows of traumatic resin ducts which appear within a growth ring or a succession of rings. If the tree is hit during the growing season, resinous tissue will appear after several days from the time of impact and the traumatic channels will be formed in about three weeks (Bollschweiler, 2008b).

## 3.5. Statistical dendrogeomorphological analysis and representation

The dendrogeomorphological reconstruction of the events is mainly based on the number of growth anomalies, so, based on their frequency. The responses of the trees are represented by the frequency index which can be calculated after the following formula:

$$It = \left( \sum_{i=1}^{n} (Rt) / \sum_{i=1}^{n} (At) \right) * 100$$

where*: It*= frequency index of growth responses in a given year; *Rt* = total number of trees that reacted in that year; *At* = total number of sampled trees (after Shroder 1978, Butler and Malanson 1985 Butler, 1987)

The increase of data accuracy by this method is based on optimizing the number of responses and on objective assessment of their intensity (Kogelnig-Mayer et al., 2011 Schneuwly-Bollschweiler et al., 2013 Corona et al. 2012, 2014). Over time, several threshold values have been used for the reconstruction of the geomorphological processes. Table 1 represents a retrospective of the limits and thresholds values used by some researchers in this domain. Debris flows generally affect smaller areas, unlike other processes such as snow avalanches or floods, so they can not be reconstructed using the same thresholds (Schneuwly-Bollschweiler et al., 2013).

Studies conducted in recent years have shown that using the number of reactions with their intensity and spatial distribution of the affected trees offer more satisfactory results (Schneuwly et al., 2009, Ruiz-Villanueva et al., 2010 Kogelnig-Mayer et al., 2011, Stoffel and Corona, 2014). The number and intensity of the reactions are shown by the weighted frequency index (Wit) used by Kogelnig-Mayer et al. (2011). The intensity of growth anomalies were classified into four categories - low intensity, moderate or intermediate, strong and obvious (mechanical injury and callus tissue) (table 2). Given that a tree can present several growth anomalies of different intensity, for example, intense traumatic resin ducts and moderate growth reduction there will be taken into account the anomaly with the highest intensity. The formula for the index calculation is shown below:

$$W_{it} = \left( \left( \sum_{i=1}^{n} T_i * 7 \right) + \left( \sum_{i=1}^{n} T_s * 5 \right) + \left( \sum_{i=1}^{n} T_m * 3 \right) + \left( \sum_{i=1}^{n} T_w \right) \right) * \frac{(\sum_{i=1}^{n} Rt)}{(\sum_{i=1}^{n} At)}$$

where: T*i* = number of trees showing mechanical injury and callus tissue, T*s* = number of trees with strong intensity reactions, T*m* = number of trees with intermediate intensity reactions, T*w* = number of trees with low intensity reactions, Rt = number of trees that showed growth anomalies in year t and At = total number of trees available for the reconstruction in year t

**Table 1.** Limits and threshold values of the minimum reactions used by other researchers in hydrological and geomorphological studies

| Researcher | Year | Process | Minimum threshold* | Tree species |
|---|---|---|---|---|
| Butler and Malanson | 1985 | Snow avalanches | 40% | Different coniferous species |
| Dubé *et al.* | 2004 | | 10% | *Thuya occidentalis* și *Abies balsamea* |
| Corona *et al.* | 2012 | | Flexible 5%-15% | *Larix decidua* și *Picea abies* |
| Lopez Saez *et al.* | | Landslides | 5% and ≥ 10 trees | *Pinus uncinata* |
| Corona *et al.* | 2014 | | I*t* ≈ 5% (GD ≥ 2) and 2,5% (GD ≥ 5) | |

| | | | | |
|---|---|---|---|---|
| Ballesteros-Cánovas *et al.* | 2015 | Flash-floods | ≥ 2 reactions | *Picea abies* și *Abies alba* |
| Mayer *et al.* | 2010 | *Debris floods* | I*t* ≥ 4% | *Picea abies* și *Larix decidua* |
| Stoffel and Bollschweiler | 2009 | Debris flows | >1 tree | *Larix decidua* |
| Bollschweiler and Stoffel | 2010 | | ≥2 trees | |
| Sorg *et al.* | | | ≥3 trees | *Larix decidua* și *Picea abies* |
| Procter *et al.* | 2012 | | | *Pinus mugo, Picea abies, Abies alba* |

*The minimum reactions was determined as follows: percentage (ex. 40% of the sampled trees showing growth reactions), by frequency index (It%) explained above and a minimum number of trees that have reacted or GD (number of growth anomalies)

**Table 2.** Classification of the growth anomalies on categories (Kogelnig-Mayer *et al*., 2011)

<table>
<tr><th rowspan="2">Growth anomaly</th><th rowspan="2">Criterion</th><th colspan="4">Intensity class</th></tr>
<tr><th>Weak</th><th>Intermediate</th><th>Strong</th><th>Very strong</th></tr>
<tr><td rowspan="2">Changes in width</td><td>(%)</td><td><60%</td><td>≥60%</td><td>≥60%</td><td rowspan="6">Obvious injury with calus tissue</td></tr>
<tr><td>Duration</td><td>≥ 2 years</td><td>< 5 and ≥ 2 years</td><td>≥ 5 years</td></tr>
<tr><td rowspan="2">Compression wood</td><td colspan="4">≥50% compression wood</td></tr>
<tr><td>Duration</td><td>≥ 2 years</td><td>3-5 years</td><td>≥ 5 years</td></tr>
<tr><td>TRD</td><td>Aspect</td><td>Compacted with space between</td><td>Compacted but not continuous</td><td>Very compacted</td></tr>
<tr><td>Calus tissue</td><td colspan="4"></td></tr>
</table>

However, we believe that the above thresholds and limits may be adjusted according to the availability of trees for sampling, the particularities of the process and the species used. Another important aspect to note is the delayed response of trees after the manifestation of an event. As noted by other researchers in their studies (Timell, 1986, Stoffel et al., 2010, Procter et al., 2012) growth anomalies such as wood compression, growth reduction or release and even traumatic resin ducts may appear only in the next year of vegetation. Delayed reactions have been also observed in this study where were used samples from the same species, close age and the studied processes usually occur in the growing season.

The spatial reconstruction of events is based on the spatial distribution on the terrain of the affected trees in a given year. Also, their distribution can be used as a key indicator when the number of the intensity of the reactions are not in compliance with a predefined threshold value. For example, if we have a small number of trees that have growth anomalies but are closed to each other (grouped) they may be included or took into consideration in the reconstruction analysis. In this respect, Schneuwly-Bollschweiler et al. (2013) recommends using Getis-Ord or Moran statistical spatial distribution index after Moran (1950) and Getis and Ord (1994). The spatial distribution of the major events that have marked a certain area can be seen at a regional level. In the study of snow avalanches, Germain et al., (2009) used the regional activity index (RAAIt). Also, the synchronicity index reflects the number of reconstructed events over the total number of the investigated studied cases.

# IV. PHYSICO-GEOGRAPHICAL INDIVIDUALITY OF THE STUDY AREA

## 4.1. Geological particularities

The upper and middle basin of the Râul Mare overlaps different morphological units ranging from 468 m a.s.l at Hațegului Depression to high mountains with altitudes above 2000 m a.s.l., formed in a geological unit with an extremely complex evolution. The territory is mainly built of Precambrian and Paleozoic metamorphic formations, Upper Cretaceous sedimentary deposits, Neogene and Paleogene-Miocene and Quaternary deposits (fig. 9). Retezat and Ţarcului Mountains are composed of crystalline schists of epizone that were cut by massive intrusive granites and granodiorites which form the Getic autochthonous (Niculescu, 1961). Godeanu Mountains are composed of crystalline schists of meso and catazone which also represents the Getic layer, located above the sedimentary layer and it's autochthonous (Niculescu, 1961).

The presence of superficial non-cohesive material deposits in small mountainous catchments plays a decisive role in the formation of debris flows. According to some researchers, deposits with depth ranging between 1 m and 2 m are most susceptible for debris flow triggering.

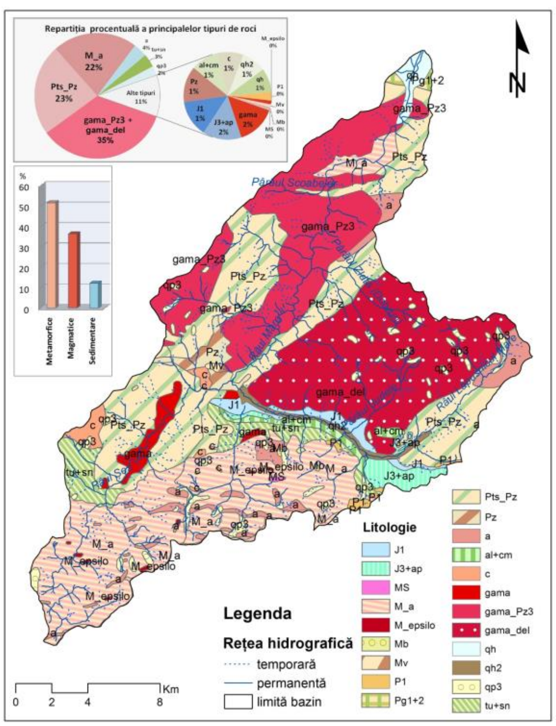


**Fig. 9.** The lithological map and the percentage distribution of the main types of rocks

Legend explanations:
**J1**- conglomerates, sandstones, clays, **J3+ap** - massive limestone, **MS**- metaserpentinites, **M_a**- mica and paragneiss, M_epsilo- pegmatites, **Mc**- meta-conglomerates, **Mv**- quartz sericit schists, sericite-chlorite schists, **P1**- conglomerates, sandstones, red shales, **Pg 1 + 2** - sandstones, conglomerates, gray and purplish clays **Pts_Pz**- crystalline schist, **Pz**- muscovito chlorite schists, sericite schists, quartzites, chlorite schists, **a**-, amphibolites, **al+cm** -limestone, marl sandstones, **alfa_pg1**- andesite, **c**- crystalline limestones, **cm** -sandstones, marl, **d**- sandstones, purple clays, granitoid gamma, gamma - granitoides, **gama_Pz3** - granite-granitoides, **gama_del** - granodiorite, **iota_Pz**- aplite, **Mb**- micaschist paragneiss, **pn-** gravels, sands, clays, **qh**-gravels, sands, gravels, **qh2**- sands and loamy sands, **qp3**- glacial deposits, silt, **to**- clays, sandstone, coal , marl, sandstone, **to+co** - marl with inocerami (layers of Deva), **tu+sn**- marl, sandstone, conglomerates, **vh+bs1**- sand, sand, volcanic breccias

### 4.2. Morphological and morphometrical particularities

#### 4.2.1. Morphometric particularities of the hydrological basin

Given that the area under investigation represents a hydro-morphological system, the variables used in the analysis are describing the current general state of the basin but also highlights some specific local features.

The length and width of the basin are morphometric elements of great importance for the calculation of the hydrological parameters. Also, the form of catchment basins is important due to the influence which it exerts on the timings of the concentration of runoff. The obvious asymmetry of the basin is also confirmed by the negative value of the asymmetry coefficient of -0.67, the right side of the basin occupying an area much larger than that left one. This is due to the adaptation of Râul Mare valley to the variability of the tectonics and structure conditions and to resistance of the rocks to either erosion or deformation. Regarding the hierarchy of the hydrological network, there is a maximum of five levels, the highest one being attributed to the main collector, Râul Mare. The catchment area is an important parameter in analysing the geomorphological processes such as debris flows. Theoretically, the greater the surface of the basin is the greater the amount of loose material. Also, the longer the transport channel is the more amount of sediments are available (Jakob, 1996). However, if the basin area is too large the debris flow is unlikely to reach the fan. In this study, the average area of the selected basins for debris flow assessment is 157.3 ha. Mountain areas have a considerable amount of poorly consolidated material due to intense weathering that are frequently entrained by runoff. Depending on the amount of sediments and other materials (woody materials), the flow can reach another level in terms of rheology and turn into mudflows, hyper-concentrated flows or debris flows. This greatly enhances the power of destruction of the processes having devastating effects on all structures and elements on his way.

#### 4.2.2. Morphometric particularities of the relief

The morphometric indicators and the quantitative aspects of the relief express in an objective and accurate manner the current status of the relief. The hypsometry is an indicator of the level of maturity of the terrain, slope reflects the potential morphodynamics while the fragmentation of the relief and the curvatures of the slopes indicate the lithological heterogeneity and the intensity of the fluvial erosion.

The hypsometric values are ranging between 468 m a.sl. (Haţegului Depression) and 2509 m in Peleaga Peak (Retezat Mountains) (fig. 10). The average altitude of 1581 m confirms the affiliation of the study area to the mountainous regions and the amplitude of 2041m indicates a high morphodynamic potential. This level difference which signifies an important source of hydraulic energy, was the main reason for building a hydropower station on the Râul Mare river.

One of the most important morphometric variables which has an important role in the manifestation of various geomorphological processes is represented by the slope. Most of the slopes of the basin are ranging between 17,1º and 31º which represents 43% from the total (fig. 11). Owning a significant proportion of 27%, the slopes ranging between 31,1º and 42º characterize the slopes of middle sector of Râul Mare but also most of the Lăpușnicul Mare and Râul Șes slopes. The 31º slope threshold represents the upper limit of stability of the talus materials while 42º limit corresponds to the lower limit of the freefall of these formations (Ichim and Bordeianu, 1970). Areas that exceed 42º value represent 7% from the total and correspond to the peaks areas but also and some sectors of the primary and secondary valleys.

Slope exposure is relative evenly distributed, only a slightly higher value of the slopes being orientated North-West. The caloric differences of the surfaces are more pronounced in the spring season when the snow melts faster if exposed to the south and east. Drainage density distribution in the basin reveals that the highest values of over 3km / km² are found in the middle basin of the Râul Mare (Netiș Stream, Bodu Stream etc) and at the headwaters of Râul Șes and in the middle and lower sectors of Lăpușnicul Mic and Mare (fig. 12). The lowest values, between 0.1 and 1 are representative for the interfluves or plateaus (erosion platforms of Borăscu, Râu Șes and Gornovița). Regarding the percentage distribution of the drainage density, the highest proportion of 37% is held by the class of 1.1 to 2 km/km². The fragmentation depth expresses the degree to which the fluvial processes conditioned by local or general levels shaped the existing relief. The fragmentation values of the analyzed basin are between 9.5 m/km² and 778.6 m/km² with an average of 407.6 m/km². The highest values are recorded in Râul Mare valley, in the lower basin of Râul Mare, Lăpușnicul Mare and Lăpușnicul Mic while the lowest values characterize the interfluves and the plateaus (Rades-Zlata Plateau). In terms of percentage, the largest proportion is held by values ranging between 400.1 and 500 m/km² which suggest a high relief energy over large areas.

The plan and profile curvature of the slopes is an expression of the local conditions under the direct influence of external factors which are shaping the earth surface. This morphometric parameter is very important for debris flow susceptibility studies, the concave surfaces being considered as possible source areas for the process initiation. The profile curvature influences the kinetic energy by accelerating the process in the convex portions and decelerating in the concave sections.

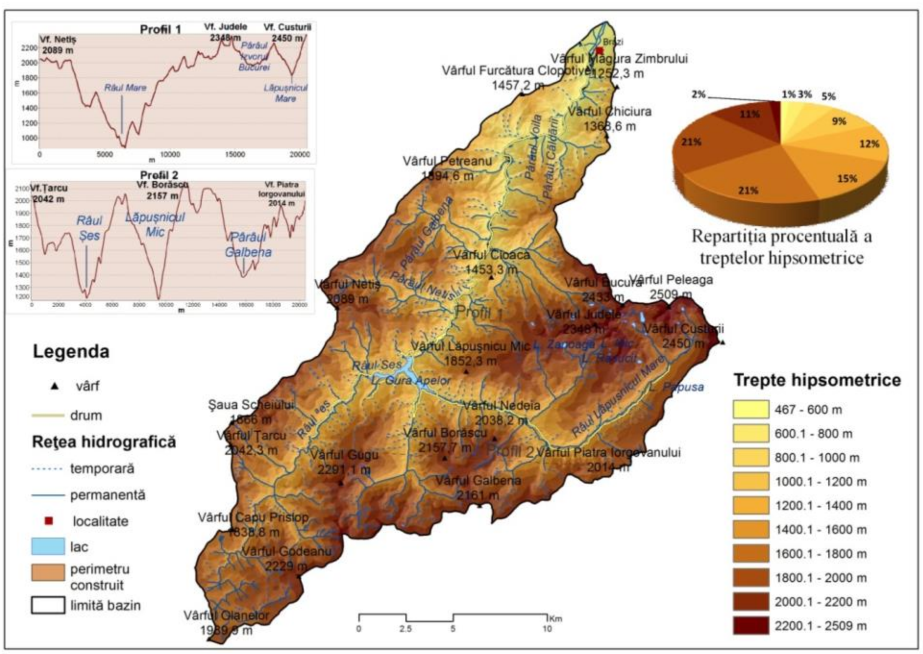


**Fig. 10.** The hypsometric map of the upper and middle basin of Râul Mare

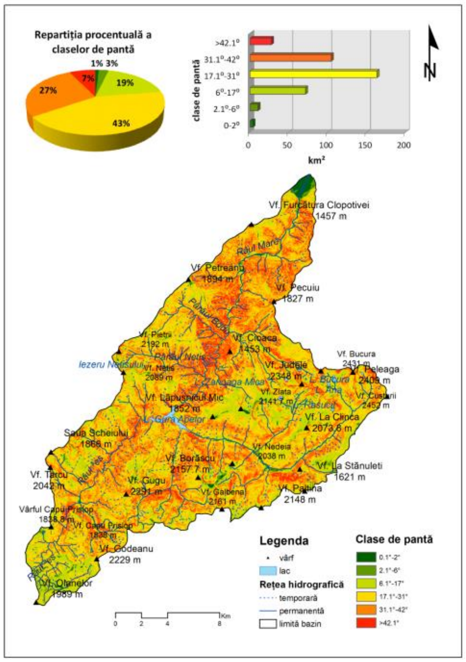

**Fig. 11**. The slope map and the percentage distribution of the slopes

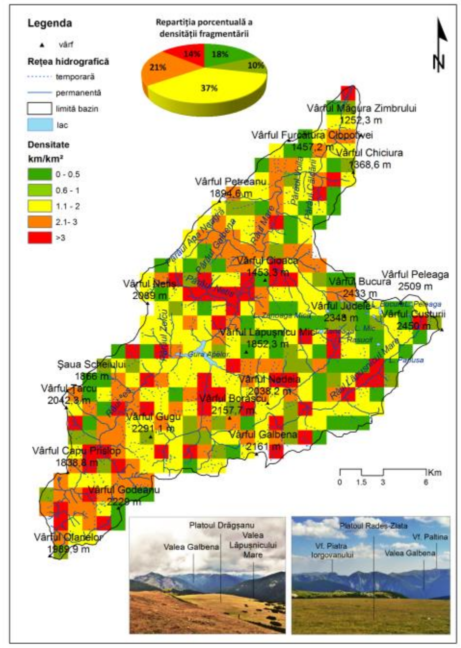

**Fig. 12.** The fragmentation density and the percentage distribution

### 4.3. Land use

The study area is covered by forests and shrubs in proportion of 69.5% while the rest is represented by subalpine meadows, bare rocks and other land use categories. The areas occupied by forest and shrubs are very important because the lack of vegetation would lead to an acceleration of the denudational processes. The higher the slope, the more accelerated the water flow and the power of erosion is. The most widespread soil types are the spodisols with 68.7%, formed under the coniferous forest or mixed with deciduous and in the subalpine and alpine meadows. The structure, texture and the depth of soil layer have repercussions on the ability of infiltration of water from rainfall and snowmelt. The difference between the permeability of soil horizons is very important for achieving a hydraulic gradient and for the initiation of the subsurface flow (Rădoane et al., 2001). The presence of forest cover contributes greatly to the stability of the mountains soils and protects against denudation (Stângă and Breabăn, 2005).

### 4.4. Climate

#### 4.4.1. Air temperature

The mean multiannual temperature has values between -0.5°C at the meteorological station Ţarcu (1961-2007 period), 7.4°C Gura Apelor station (period 1988-2012) and 8.8°C at Păclișa (during 1961 and 2001) (fig. 13, 14). The values of the mean temperature recorded on the aforementioned periods range between -1.8°C (1980) and 0.6°C (2002, 2007) at Ţarcu station, 7.7°C (1978, 1985) and 10.2 ° C (1994) Păclișa station and 5,2°C (2005) and 10.3°C (1994) Gura Apelor station. Regarding the monthly mean temperature, the lowest values are recorded in January, -2.43°C at Gura Apelor station and -2.6°C at Păclișa station, except Ţarcu meteorological station, where the lowest monthly mean temperature is recorded in February, of -8.6°C (fig. 15). In summer, the highest monthly mean temperatures are recorded in July at

Păclișa and Gura Apelor weather stations, with values of 18.8 ° C and 17.4 ° C respectively, while at the meteorological station Ţarcu is recorded in August 7.9 ° C.

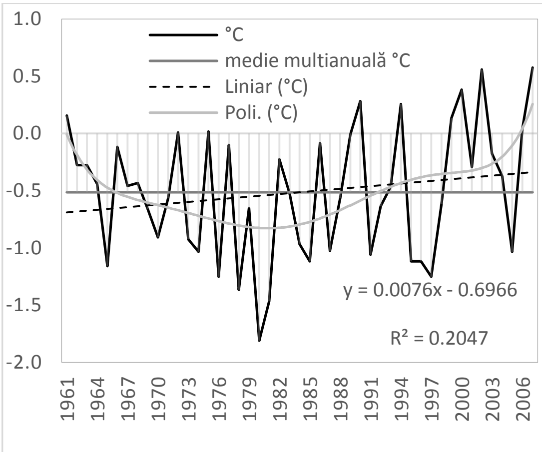


**Fig. 13.** Graphical representation of the multiannual mean of the air temperature and the evolution tendency at the metheorological station Ţarcu (1961-2001) (*source: ANM data)*

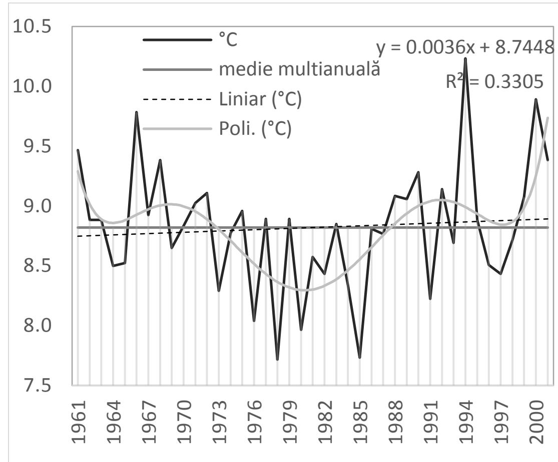


**Fig. 4.** Graphical representation of the multiannual mean of the air temperature and the evolution tendency at the metheorological station Păclişa (1961-2001) (*source: ANM data)*

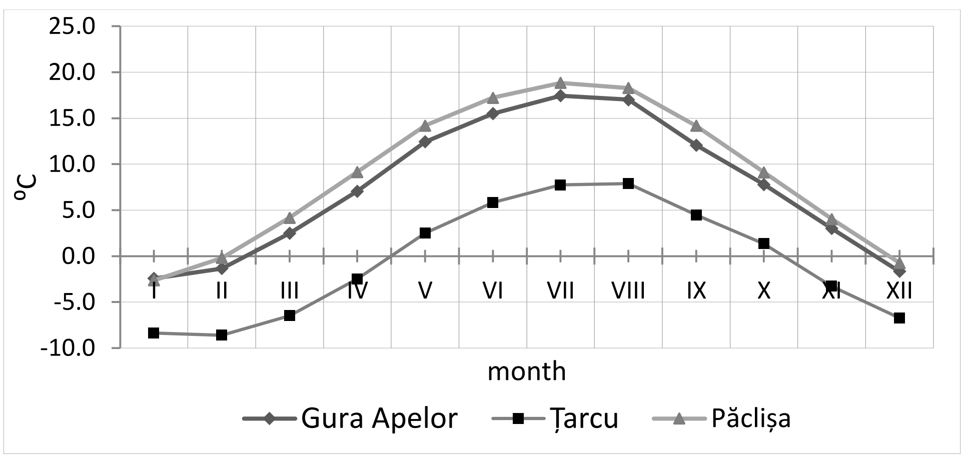


**Fig. 5.** Graphical representation of the monthly mean of the air temperature at the metheorological station Păclişa, Gura Apelor, Ţarcu (*source: ANM and SC.Hidroelectrica SA. data)*

### *4.4.1.1. Freezing and the freeze-thaw cycles*

The thermal amplitudes oscillating above and below freezing determines a phase shift of the free water inside the pores and cracks of rocks. The greater the amplitude the stronger the weathering process is. The range of oscillation of temperature above and below $0^{0}$C defines the freeze-thaw cycles. The monthly average number of the freeze-thaw cycles registered at Gura Apelor station calculated for the interval 2002-2011, indicates higher values at the end of winter and early spring (fig. 16). Most of the gelival cycles occur in March with an average of 20. The multiannual values of this parameter is 106, with a maximum number of 140 recorded in 2008 and a minimum of 70 cycles recorded in 2010.

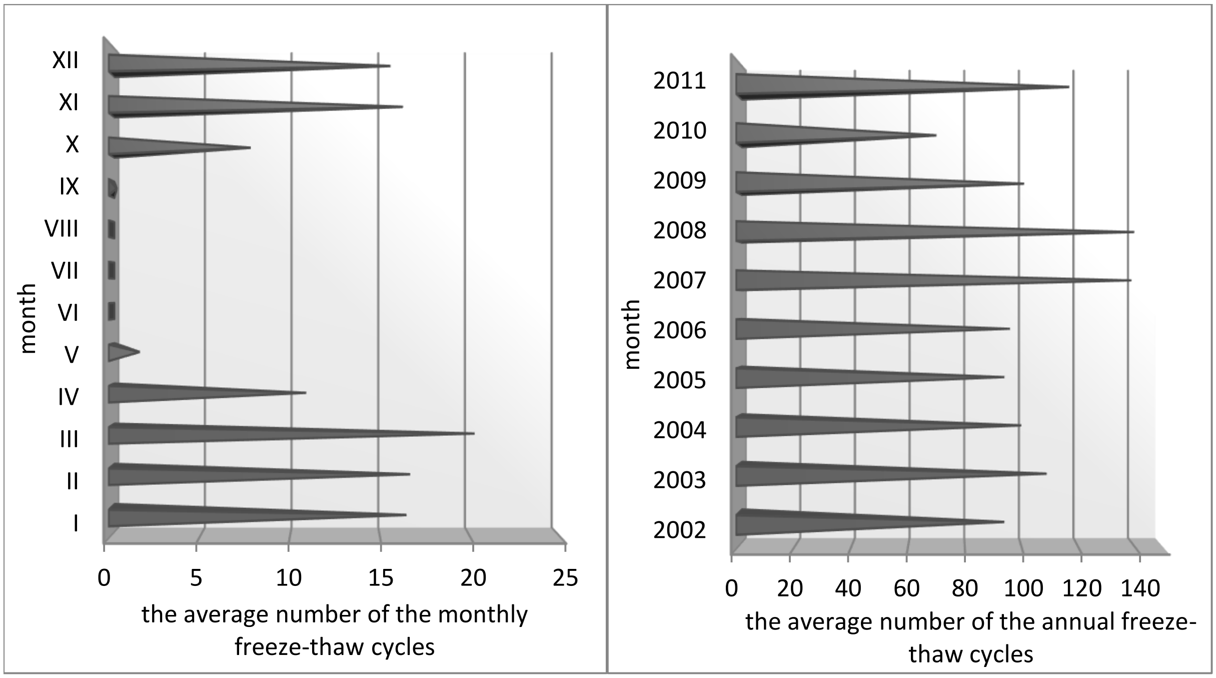


**Fig. 166**. The average number of freeze-thaw cycles registered at Gura Apei station (2002-2011) (*source: SC.Hidroelectrica SA*.)

### 4.4.2. Precipitation regime

The mean multiannual amount of precipitation calculated for the period 1961-2001 at the meteorological station Țarcu and Păclișa and 1999-2012 for Gura Apelor station are presented in the following table.

**Table 3**. The multiannual mean precipitation registered at the meteorologial stations Păclișa, Gura Apei and Țarcu *(source: ANM and SC. Hidroelectrica SA.)*

| Station name | Altitude | Analysed period | Mean multiannual precip. |
|---|---|---|---|
| **Păclişa** | 381 m | (1961-2001) | 566 mm |
| **Gura Apei** | 956 m | (1999-2012) | 1176 mm |
| **Ţarcu** | 2180 m | (1961-2001) | 942 mm |

Regarding the mean monthly amount of rainfall, the highest values are specific of the summer months for all analyzed stations (fig. 17). At Țarcu and Păclișa weather station the highest monthly mean of rainfall is recorded in June with 139.9 mm and 90.6 mm respectively, while at the the station Gura Apelor the maximum value is in July, of 148.4 mm. The lowest values are specific for February at the Păclișa and Gura Apelor stations (20.5 mm, 32.2 mm respectively) and March for Țarcu station (53 mm).

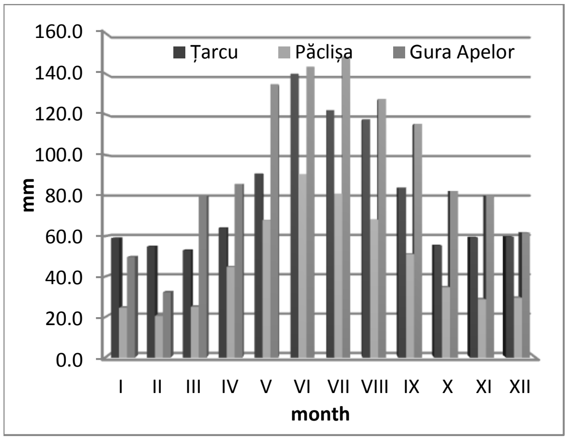


**Fig. 177.** The monthly mean precipitation registered at Țarcu, Păclișa and Gura Apei stations (*source: ANM and SC. Hidroelectrica SA.)*

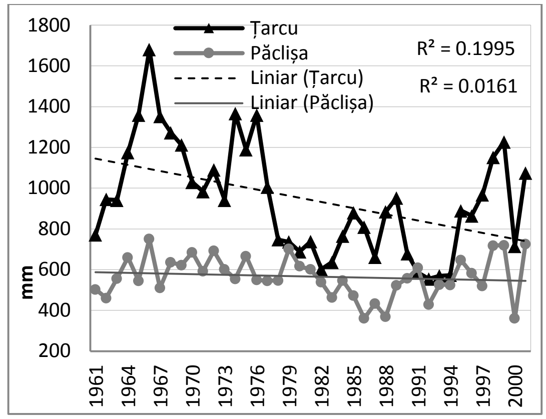


**Fig. 18.** The multiannual mean precipitation and the evolutionary tendencies registered at Țarcu and Păclișa stations (*source: ANM and SC. Hidroelectrica SA.)*

In order to see the evolutionary tendencies in what concerns the average amount of rainfall, we used the values registered at Țarcu and Păclișa weather stations, where the database is larger. According to the analysis, there is a clear descending tendency of the precipitation amount at Țarcu station, while at the Păclișa station this tendency is insignificant (fig. 18). Also, the amount of rainfall registered in one day is an important parameter in debris flows triggering. The amounts of the maximum precipitation fallen in 24 hours were analyzed at Gura Apelor station for the interval 1990-2012 (fig. 19). The highest value was recorded in 11.07.1999, of 136 mm. On average, the maximum amount of rainfall fallen in 24 hours is of 79 mm, the lowest value being recorded in 15.09.1998, of 36,4 mm.

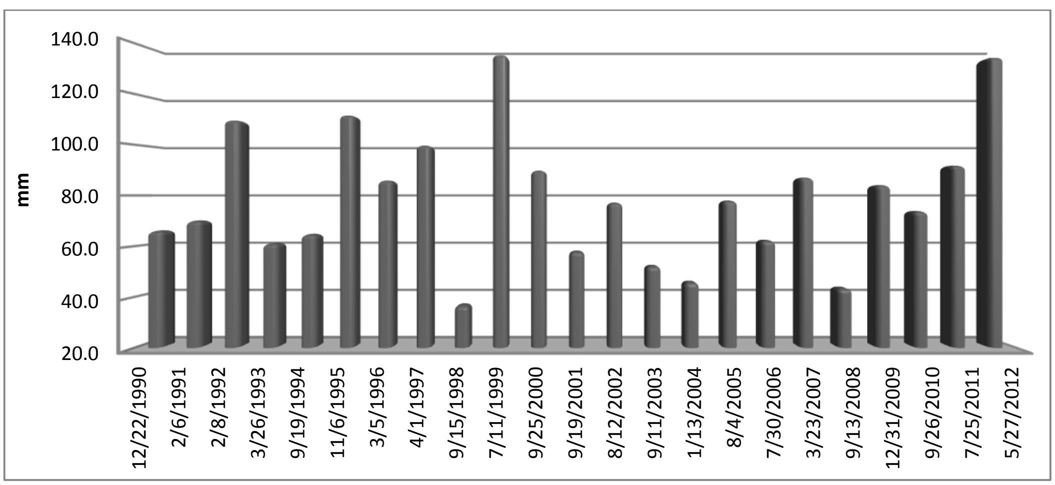


**Fig. 19.** The maximum 24 hours precipitation registered at Gura Apelor weather station (*source: SC. Hidroelectrica SA*)

The rainfalls falling in several consecutive days also play an important role in triggering the debris flow initiation. The saturation of the soil decreases the ability of the water infiltration and as a consequence, there is a faster response to runoff. Using daily rainfall data from Gura Apelor weather station, there were counted consecutive rainy days where there were recorded at least 2 mm (fig. 20). The 4 day of rain presents the greatest variance. If in most of the times there were only one or two cases, in 1999 there were seven such periods. The longest rainy period was 16 days when there were accumulated a total amount of 297 mm (May 2012).

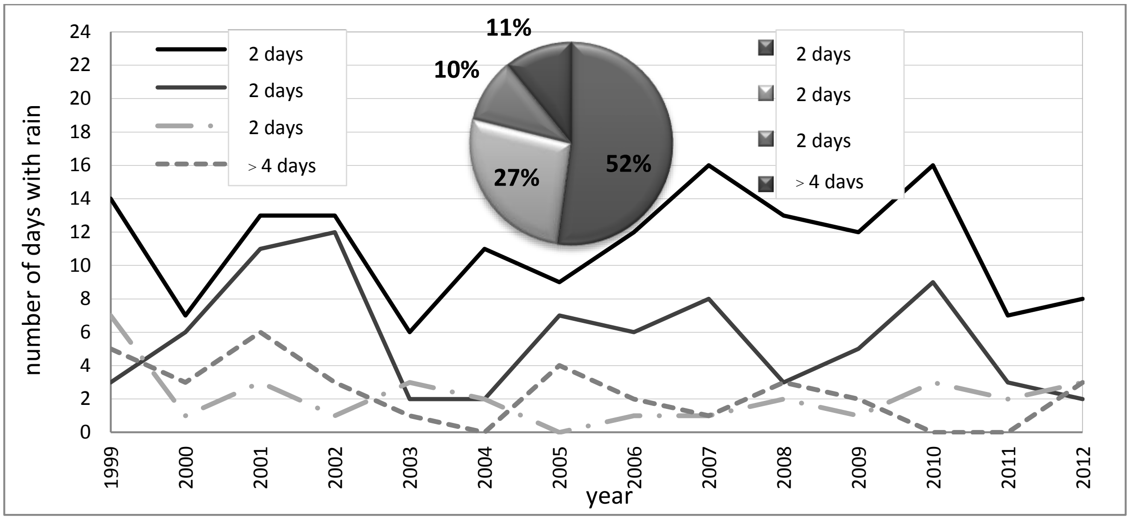


**Fig. 208**. Number of cases with 2, 3, 4 and above 4 days off precipitation (>2 mm/day) and the their frequency registered at Gura Apelor station (source: ANM and SC. Hidroelectrica SA.)

The implications of the climatic factors in the erosion of the land surface can be best seen through a few specific indices. The rainfall erosivity is visualised by the modified Fournier index which was calculated for all the three weather stations during the interval 1961-2001 for Păclișa and Țarcu station and 1999-2012 for Gura Apelor. The values varied between 39 mm and 234 mm, with an average of 72 mm at Păclișa, 111 mm at Țarcu and 165 mm at the Gura Apelor station. Also, the analysis of the Peltier diagrams offers an overview on the impact of the climate upon the relief. According to the chart, the examined weather stations are categorized into different morphoclimatic regions, suggesting boreal conditions for high mountain area, moderate for the lower regions and temperate for the northern part of the basin. Consequently, the mechanical weathering is strong mainly due to the intense freeze-thaw cycles while the chemical weathering has a more moderate character.

# V. THE SPATIO-TEMPORAL RECONSTRUCTION OF DEBRIS FLOWS USING DENDROGEOMORPHOLOGICAL METHODS

## 5.1. Study case number 1

The first 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. 21). 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 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 basin 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. 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. The studied torrent has a mean slope of 24°, most of the slopes ranging from 17° to 31°. Due to the steep slopes and impermeable substrates there is a fast response to heavy rainfalls. The forest standing on the cone and along the channel mainly consists of Norway spruce (*Picea abies* (L.) Karst.).

A detailed analysis of the morphometric parameters of the relief provides an objective view on the energetic potential of the basin and reflect the morphodynamic character of the geomorphological processes (table 4). The Melton index value of 0.83 indicates favorable conditions for debris flow occurrence. Also, of great importance is the active source areas that holds 1.66% of the total area of the basin. Most areas are located in the transport channel and in the upper part of the basin. For the weighted stability index, there was obtained a value of 2.3 which suggests a high degree of instability of the previously identified sources.

**Table 4**. The morphometric variables used in debris flow analysis

| | |
|---|---|
| Total basin area (km²) | 1,28 |
| Actively area which is contributing debris (km²) | 0,02 |
| Percetange of the active area (%) | 1,66 |
| Wieghted stability index | 2,3 |
| Total basin relief (m) | 940 |
| Elevation relief ratio | 0,5 |
| Drainage density (km/km²) | 3,2 |
| Melton index | 0,83 |
| Zero-ruggedness index | 0,39 |
| Mean basin slope (º) | 24º |

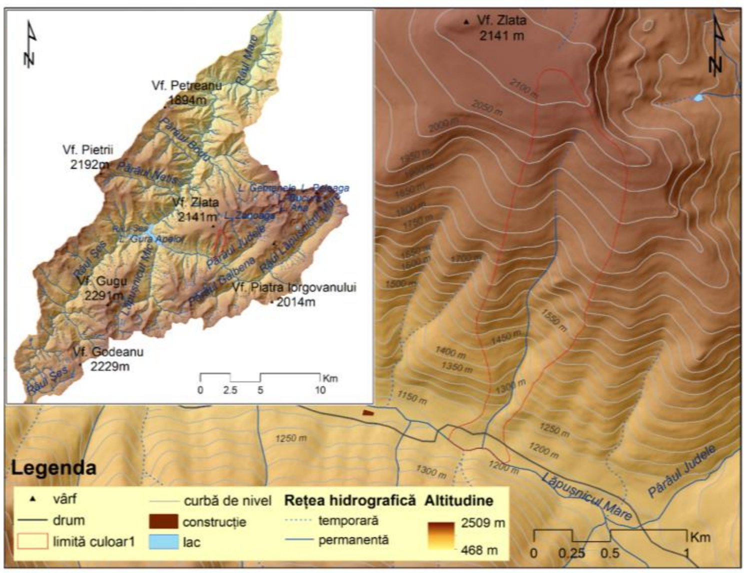


**Fig. 21.** Geographical position of the first study case

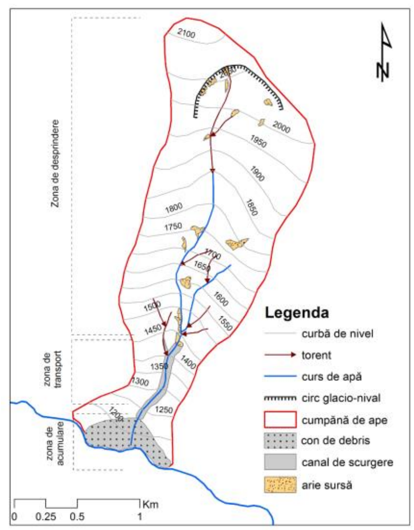


**Fig. 22.** Geomorphological scheme – study case number 1

### 5.1.1. Methodology

Using a Pressler increment borer there were extracted 136 cores from 68 affected spruces. All of the sampled trees exhibited obvious evidence of debris flow impact on the stem but also on the roots and crown. 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 the description of the disturbance type, its position, tree diameter, tree height and other useful information for the analysis. 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.

### 5.1.2. Results of the dendrogeomorphological analysis

The sampled trees have an average age of 62 years, the oldest one having 188 years while the youngest one is only 24 years old (fig. 23). The age structure of the trees shows that most of the trees are between 31 and 60 years. All sampled trees responded with different types of disturbances. In total, 608 growth anomalies were identified, the most frequently encountered being abrupt growth changes figured either by suppressed or released ring width 56% and 7%, respectively (fig. 24). Another 189 anomalies were formed in the form of tangential rows of traumatic resin ducts (TRD) (fig. 25), while compression wood (CW) was only occasionally found, in 26 cases, which holds 6%.

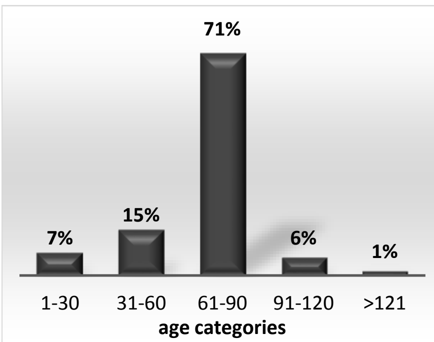


**Fig. 23.** Age categories distribution

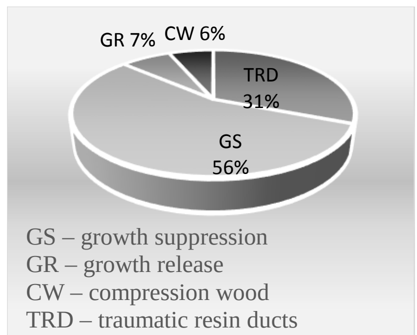


**Fig. 9**. Percentage of the growth anomalies

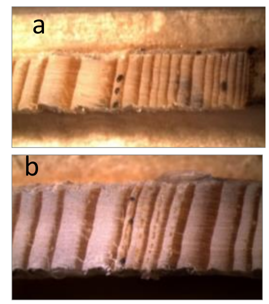


**Fig. 25**. a) abrupt growth reduction; b) TRD

Based on the growth anomalies identified there was calculated the frequency index of the responses for each year of the 1900-2014 interval (fig. 26). The highest values were obtained for 2000, 1952, 1950 and 1929 exceeding the value of 17%. The 10% threshold value of the frequency index was exceeded in 23 cases, the average calculated on the basis of at least one answer being of 7.6. Based on the number and intensity of the reactions there was also calculated the weighted frequency index was for the period between 1900 and 2014 (fig. 27). The average value of the index calculated for the years in which there were at least three reactions is 2.1 with a standard deviation of 6.1. From the values obtained for this index, we remarked the year 2000 for which there was obtained and index value of 47. The following values obtained, in descending order, only reach 7.3 in 1989 and 4.5 in 1929. The threshold of 1 is exceeded in 25 cases, but most of the values are between 1.1 and 2.

### 5.1.3. Interpretation of the results

The non-geomorphological influence on trees growth can be excluded through cross-dating which matches different parameters of the rings between trees from different locations on a common time period. As was noted in chapter 3, the identification of the marker rings both on the affected and reference chronology may indicate a climatic influence. In this case, the reference samples analysis revealed that 1989 is a marker year, most of the rings showing a significant reduction in growth.

The analysis of the growth anomalies identified in the 68 sampled spruces for this study case permitted the reconstruction of 15 events that occurred during 1920-2014 (fig. 28). The dendrogemorphological reconstruction before 1920 was limited by the young age of the trees, only two trees counting more than 93 rings. Based on the chronology obtained by this reconstruction we calculated the recurrence interval and the return period of the debris flows. For the period between the first and the last reconstructed event the recurrence interval varies between 2 and 10 years and a total number of 14 intervals. Using the recurrence interval achieved there was calculated a return period of 6 years of the process.

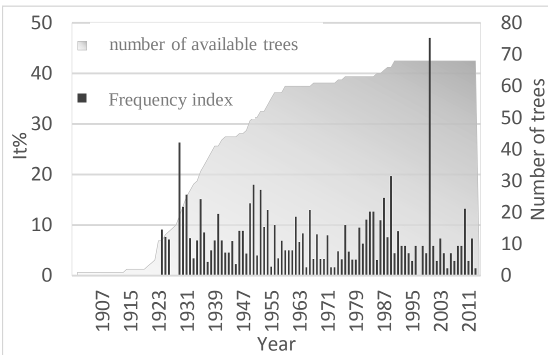

**Fig. 26.** Graphical representation of the frequency index and the number of the available trees

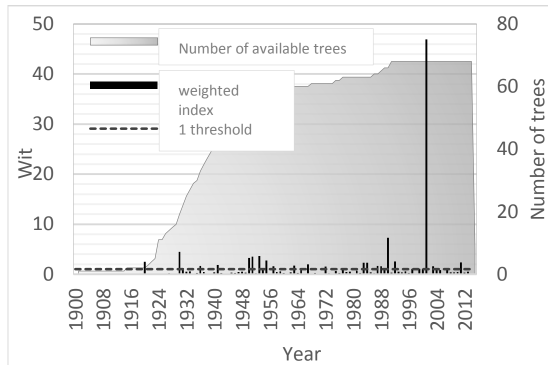

**Fig. 27.** Graphical representation of the weighted frequency index and the number of the available trees

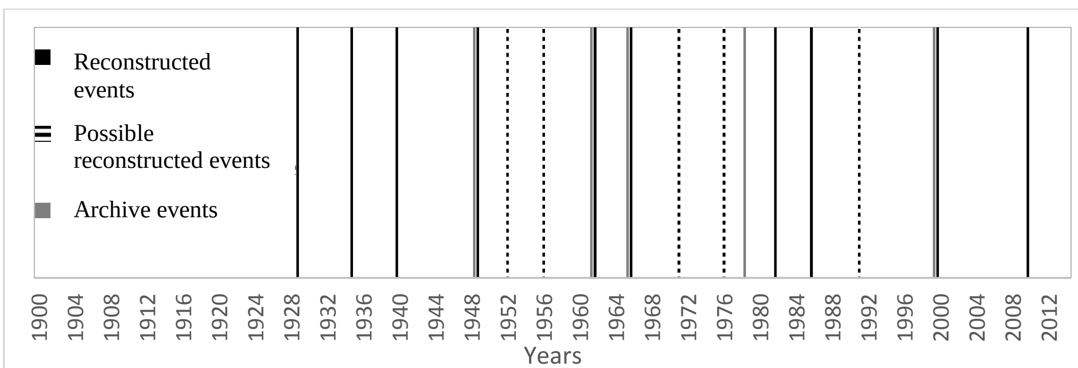

**Fig. 28.** The representation of the reconstructed events and the major events known from archive data

## 5.2. Study case number 2

The second study case (45°18'38.7"N 22°50'55.0"E) is located on the southern slope of Retezat Mountains (fig. 29). The main collector is a right tributary of the Lăpușnicul Mare River, which drains an area of 98 ha, extending from an elevation of 2030 m a.s.l. to 1331 m a.s.l. The torrent surface is mainly built of deposits of granodiorites 63.1%, while the lower sector crystalline schists dominate, accounting for 36.9% of total. The studied torrent has a mean slope of 26°, most of the slopes ranging from 17° to 31°. The steepest slope values which exceed 42° correspond to the slopes of the transport channel. The source areas which are part of the active area holds a percentage of 3.6%. Given the fact that most of the source areas are unvegetated, the weighted stability index of 3.4 indicates a high degree of the instability of those sources. Also, the relief amplitude of 699 m and the relief ratio of 0.6 indicates a potential energy (table 5).

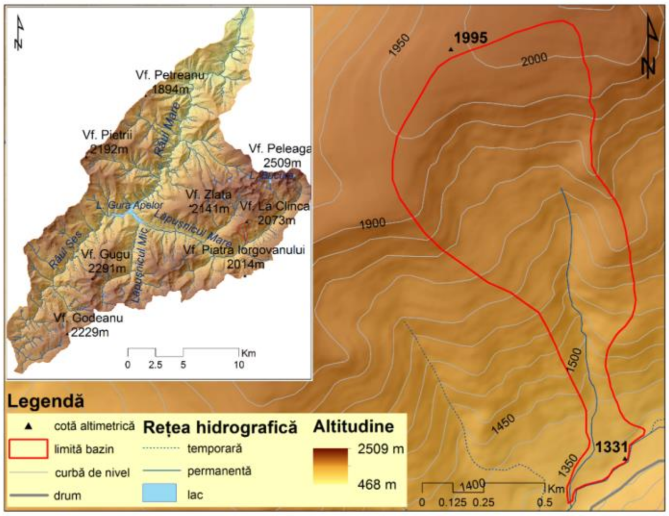


**Fig. 29**. Geographical position of the study case number 2

**Table 5**. The morphometric variables used in debris flow analysis

| | |
|---|---|
| Total basin area (km²) | 0,94 |
| Actively area which is contributing debris (km²) | 0,034 |
| Percetange of the active area (%) | 3,65 |
| Wieghted stability index | 3,4 |
| Total basin relief (m) | 717 |
| Elevation relief ratio | 0,6 |
| Drainage density (km/km²) | 2,82 |
| Melton index | 0.46 |
| Zero-ruggedness index | 0.48 |
| Mean basin slope (º) | 26º |

### 5.2.1. Methodology

Because of the large area where evidence of debris flow occurrences was found we separated the affected perimeter in three sampling areas. The first sampling area corresponds to the debris flow cone, where the trees are heavily affected (fig. 30). The second one corresponds to the area near the transport channel while the third one is located upstream the channel where a few old debris flow lobes were found. The trees located on the debris flow cone are mainly affected by burial while the ones bordering the transport channel present scars on the stems, root exposure or tilting stems. A number of 279 increment cores were extracted from 159 affected trees to which we add other 39 cross-sections and 1 wedge. The measurements effectuated for each tree were meant to complete the database necessary for the spatial reconstruction and for the estimation of the magnitude. In addition to this, 20 undisturbed *Picea abies* trees were sampled which have not been affected by debris flow activity or other geomorphological processes.

**Fig. 30.** Trees affected by the accumulation of sediments at the stem base and by root exposure

The sampling was carried out in several field campaigns that were collected both cores, cross sections and wedges from the affected trees. In total, 279 samples were collected from 159 trees presenting different types of injuries. The measurements of the each sampled tree were meant to complement the database necessary for spatial reconstruction of the process and to estimate the magnitude. To eliminate other non-geomorphological influence on growth, other 40 cores were extracted from 20 reference trees.

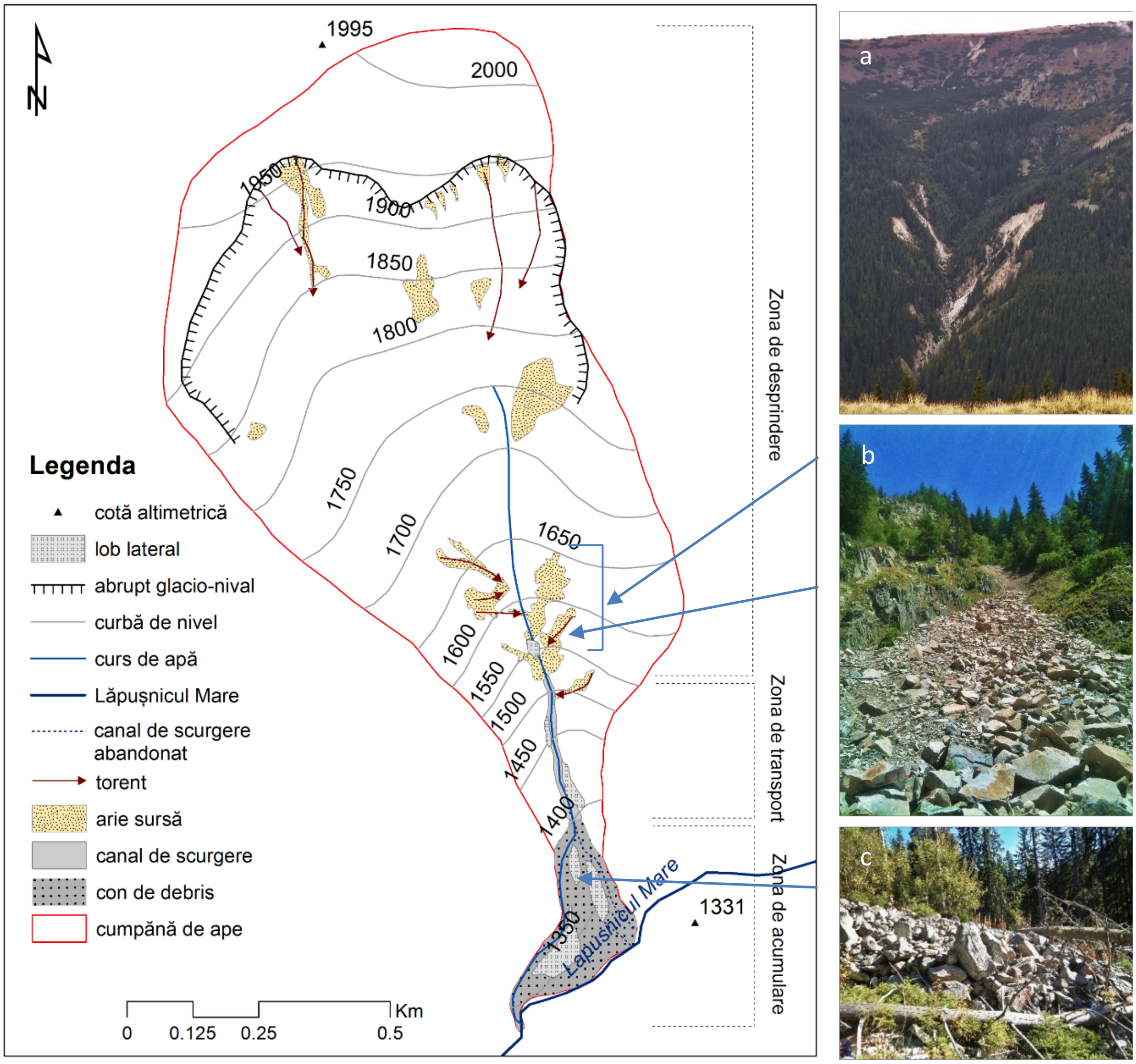


**Fig. 31.** The geomorphological scheme of the study case number 2: a) and b) the proluvial deposits and d) a debris flow lobe

### 5.2.2. The results of the dendrogeomorphological analysis

The sampled trees have an average age of 57 years, the oldest one having 125 years while the youngest one is only 15 years old (fig. 32). The age structure of the trees shows that most of them are between 31 and 60 years. The oldest trees occupy a small proportion of 4% only 5 trees reaching more than 120 years. All sampled trees responded with different types of disturbances. In total, 739 anatomical disturbances were identified, the most frequently encountered being abrupt growth changes figured either by suppressed or released ring width 46% and 12%, respectively (fig. 34). Another 32% anomalies appeared in form of tangential rows of traumatic resin ducts (TRD) while compression wood (CW) was only occasionally found, in 10% of the cases (fig. 33).

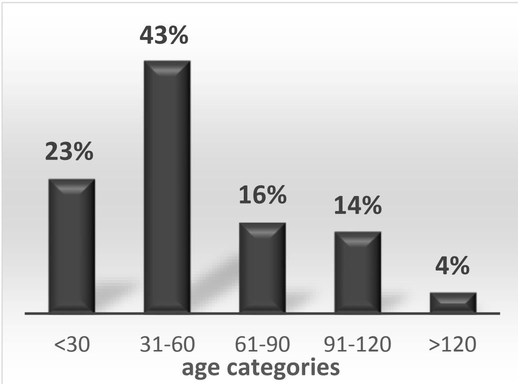


**Fig. 32**. Age categories distribution

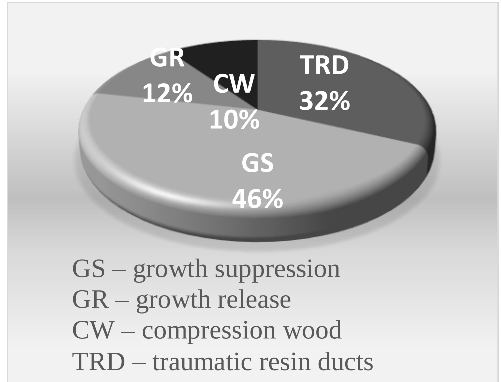


**Fig. 33**. Percentage of the growth anomalies

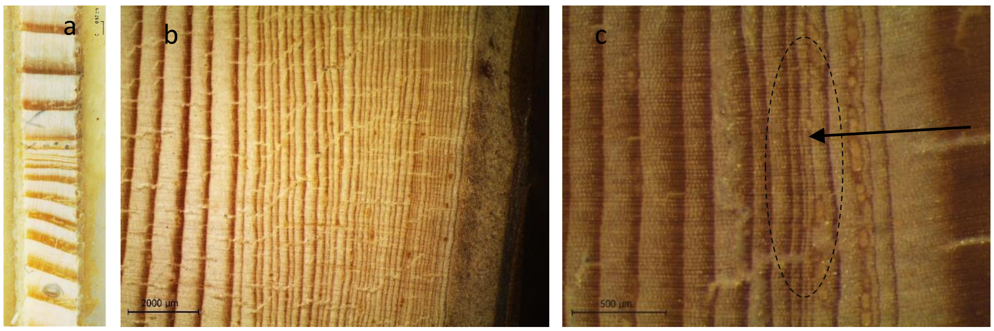


**Fig. 34.** Examples of growth anomalies:: a – narrow rings formed 5 years , b – narrow rings formed more decades, c – missing ring

The most numerous growth anomalies were identified in 1999-2001 with a total of 136 responses. The high number of the anatomical disturbances reflects the magnitude of the event and the high percentange of TRD in 2000 suggests that most of the trees reacted only in the next year of vegetation (fig. 35).

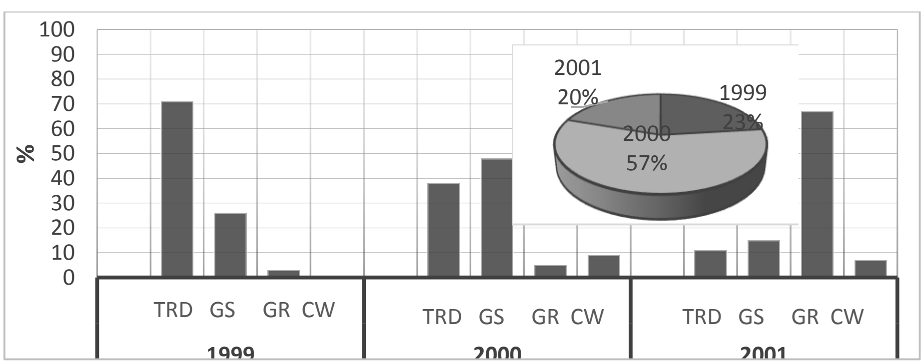


**Fig. 35**. The graphical representation of the main growth anomalies identified in 1999, 2000 and 2001 and the percentage of reactions in the three analysed years

Based on the growth anomalies identified there was calculated the frequency index of the responses for each year of the 1889-2014 interval (fig. 36). The average value of the index calculated for the years in which there was at least one reaction is 8% with a standard deviation of 6.5%. In the first part of the interval there were obtained high values but the number of trees was very low and also there were less than 3 reactions. The highest values were obtained for

2000 with a percentage of 53 %, 1999 with 22%, 1976 with 18% and 1951, 2010, 1969, 1941, 1954 with a percentage of 15%.

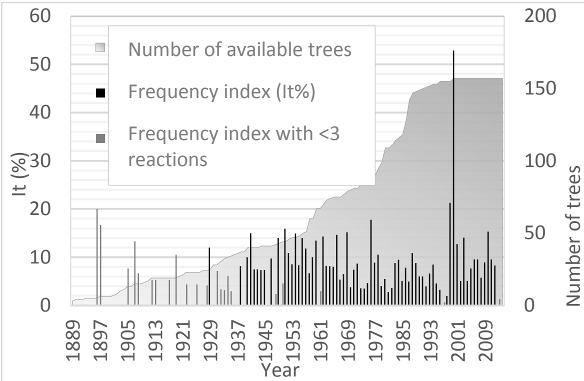


**Fig. 36**. Graphical representation of the frequency index and the number of the available trees

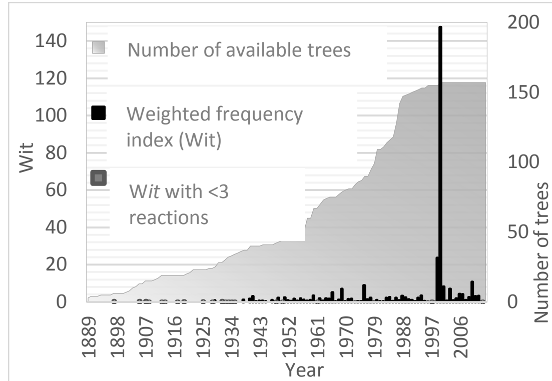


**Fig. 37**. Graphical representation of the weighted frequency index and the number of the available trees

Also, based on the number and intensity of the reactions there was calculated the weighted frequency index for the period between 1889 and 2014 (fig. 37). The threshold value of 1 was exceeded in 44 cases, but most of the values were between 1 and 3. The average value of the index calculated for the years in which there were at least three reactions was 4.4 with a standard deviation of 18. The highest value of 147.5 was obtained for the year 2000, from 83 responses, 32 being of strong intensity. Also, for the year 1999 there was obtained a value of 23.5, as there were only 4 evident reactions (of very high intensity).

### 5.2.3. Interpretation of the results

#### *5.2.3.1. Temporal frequency reconstruction*

The chronology of the reconstructed events begins only in 1929 when three reactions are identified, among which one being of high intensity. The analysis of the growth anomalies allowed the reconstruction of 19 events (fig. 38). For the period between the first and the last reconstructed event the recurrence interval varies between 2 and 9 years from which was obtained a return period of 5 years.

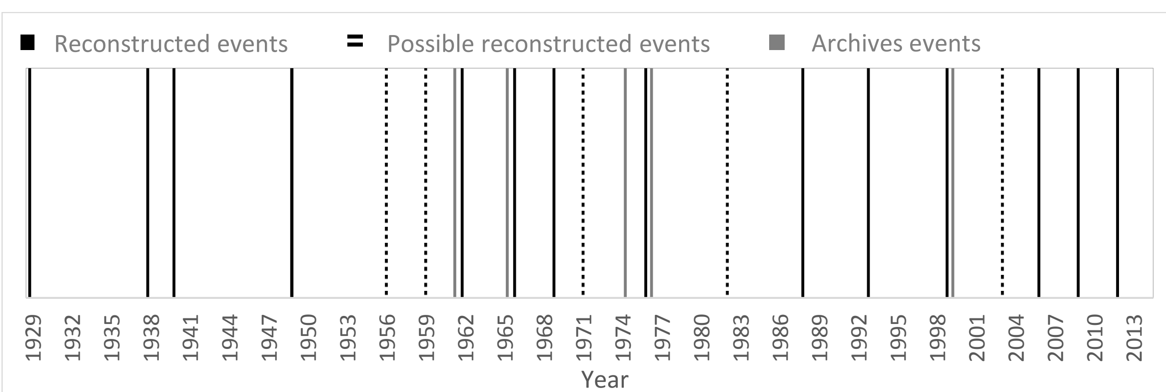


**Fig. 38**. The representation of the reconstructed events and the major events known from archive data

#### *5.2.3.2. Spatial frequency reconstruction*

According to the analysis, in the early twentieth century the debris flows had affected the upper and the right side of the current cone and then shifted to the left part which, nowadays, corresponds to an abandoned channel. In the last 30 years, they occur mostly on the right side of the cone, affecting the group of trees located near the confluence. In 1999, if it had not been for the forest areas which stopped the debris flow propagation, most certainly the Lăpușnicul Mare course would have been blocked. The consequences of this scenario is difficult to imagine given the fact that at the onset of the debris flow, Lăpuşnicul Mare River already had high discharge values both liquid and solid. The reconstruction of the process magnitude was difficult to establish because of the devastating effects of the event that occurred in the summer of 1999. The development in consequently years of strong reactions, often do not permit the identification of other new growth anomalies.

### 5.3. Study case number 3

The third study case (45º17'56" lat. N and 22º51'18" long. E) is located on the northern slope of Piule-Iorgovanu Mountains (fig. 39). The main collector is a left tributary of the Lăpușnicul Mare River, which drains an area of 244 ha, extending from an elevation of 2000 m a.s.l. to 1320 m a.s.l. The torrent surface is mainly built of crystalline schists and in the upper part of the basin there are conglomerates, sandstones, massive limestones etc. As for the slopes, the highest percentage is held by class ranging between 17º and 6,1º with 43%, followed by the class between 17,1º and 31º with a percentage of 31%. The steep slopes which are frequently exceeding 31º correspond to the slopes of the transport channel. 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. 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.

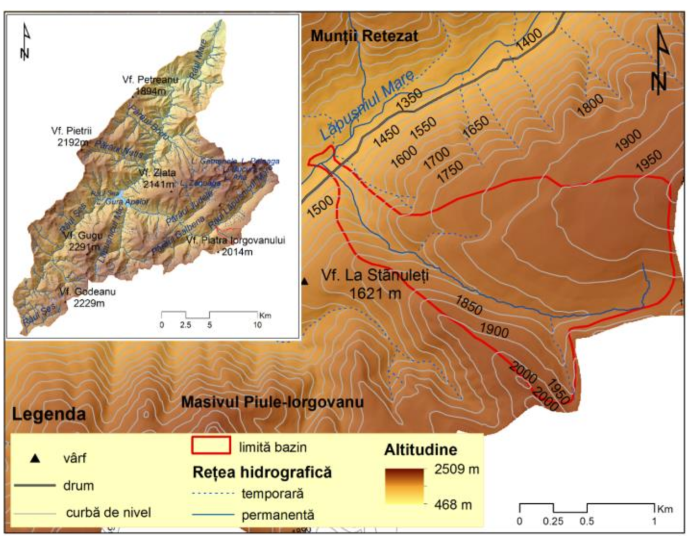


**Fig. 39**. Geographical position of the study case number 3

**Table 6**. The morphometric variables used in debris flow analysis

| | |
|---|---|
| Total basin area (km²) | 2,44 |
| Actively area which is contributing debris (km²) | 0,032 |
| Percetange of the active area (%) | 1,33 |
| Wieghted stability index | 2,9 |
| Total basin relief (m) | 717 |
| Elevation relief ratio | 0,5 |
| Drainage density (km/km²) | 2,82 |
| Melton index | 0,46 |
| Zero-ruggedness index | 0,72 |
| Mean basin slope (º) | 17,8 |

The source areas which are part of the active area holds a percentage of 1.33% (table 6). The most important source areas are located in the upper part of the basin and in the transport channel. Given the fact that most of the source areas are unvegetated, the weighted stability index of 2.9 indicates a high degree of the instability of these sources (fig. 40).

**Fig. 40**. Proluvial deposits accumulated at the bottom of the transport channel slopes

### 5.3.1. Methodology

Most of the trees located on the cone surface were strongly affected by debris flows, exhibiting various forms of disturbance such as mechanical scars, tilted or curved stems as well as root burial or exposure. The sampling step was carried out in three filed campaings in which there were collected cores as well as cross-sections and wedges. A number of 98 increment cores were extracted from 49 affected trees to which we add other 39 cross-sections and 1 wedge (fig. 41).

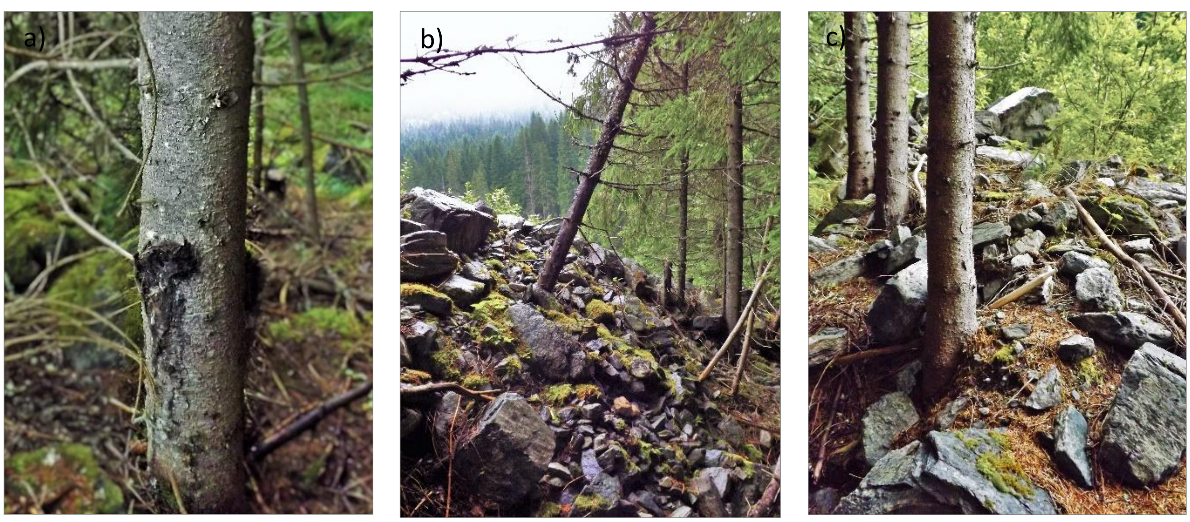


**Fig. 41**. Trees affected by debris flows: a) scars on the stem, b) tilted tree due to the pressure exercited by the deposits, c) deposits accumulated at the stem base

.

### 5.3.2. The results of the dendrogeomorphological analysis

The sampled trees have an average age of 55 years, the oldest one having 202 years, while the youngest one is only 16 years old (fig. 43). The age structure of the trees shows that most of the trees are between 31 and 60 years. All sampled trees responded with different types of disturbances. In total, 415 anatomical disturbances were identified, the most frequently encountered being abrupt growth changes figured either by suppressed or released ring width 45% and 10%, respectively. Another 30% anomalies were formed in the form of tangential rows of traumatic resin ducts (TRD), while compression wood (CW) was only occasionally found, in 15% of the cases (fig. 44).

Most of the reactions identified in this case were as in the others, in 1999 and 2000, with a total of 48 reactions (Fig. 46). Based on the growth anomalies identified there was calculated the frequency index of the responses for each year of the 1840-2014 interval (Fig. 48). The average value of the index based on the years in which there was at least one reaction is 6% with a standard deviation of 13.3%. The highest values were obtained for 2000, 1999, 1949, 1944 and 1935 exceeding the value of 20%. Based on the number and the intensity of the reactions there was also calculated the weighted frequency index for the period between 1840 and 2014 (fig. 49). The average value of the index calculated for the years in which there were at least three reactions is 3.2 with a standard deviation of 7. The threshold of 1 is exceeded in 29 years, but most of the values are between 0.5 and 1.4.

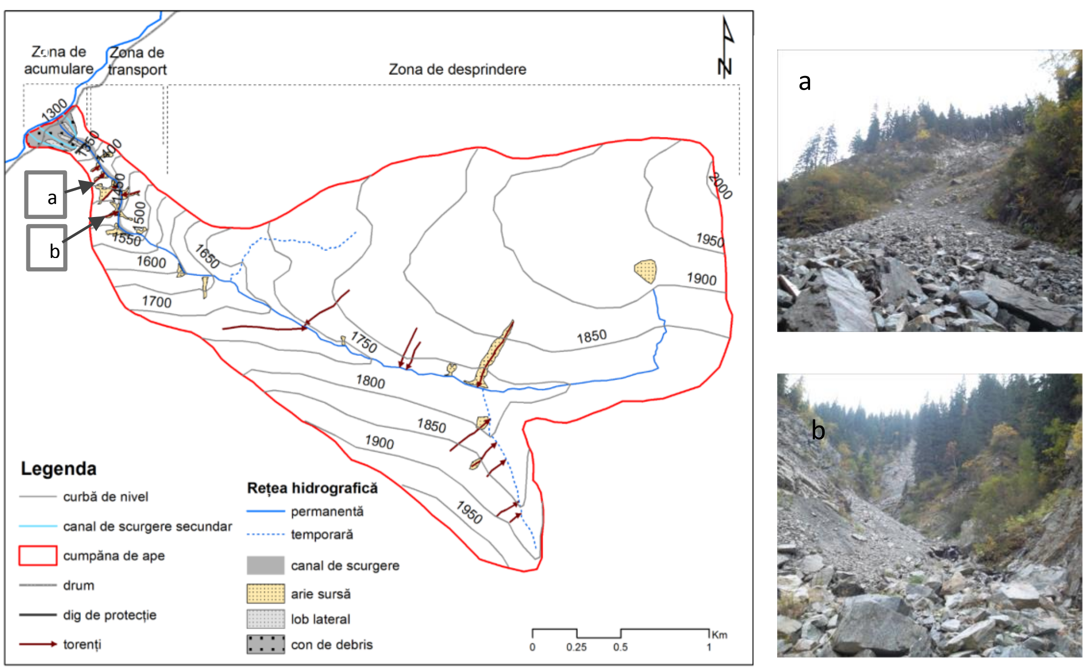


**Fig. 42**. The geomorphological scheme of the study case number 3 and the proluvial deposits located in the transport channel

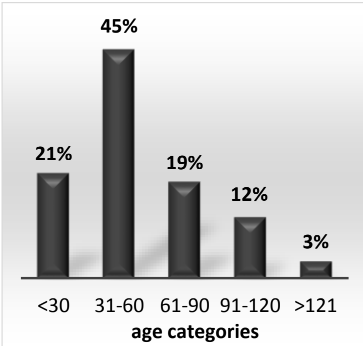


**Fig. 43**. Age categories distribution

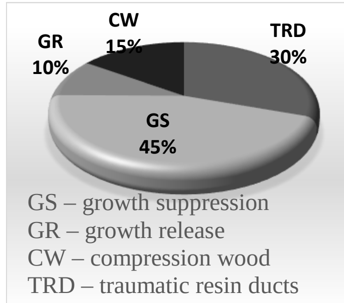


**Fig. 44**. Percentage of the growth anomalies

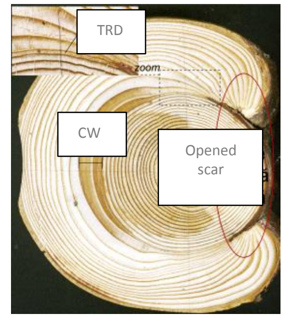


**Fig. 45**. Opened scar with TRD and CW in the opposite part

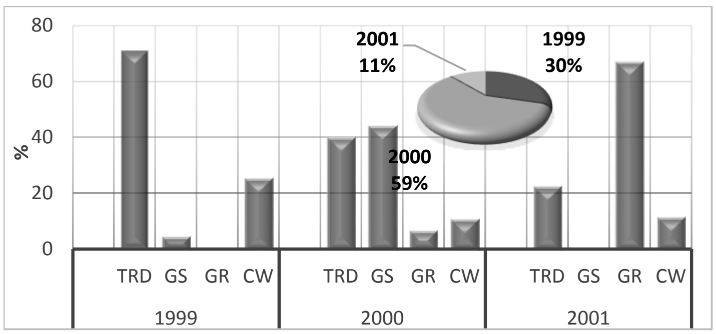


**Fig. 46.** The graphical representation of the main growth anomalies identified in 1999, 2000 and 2001 and the percentage of reactions in the three analysed years analizați

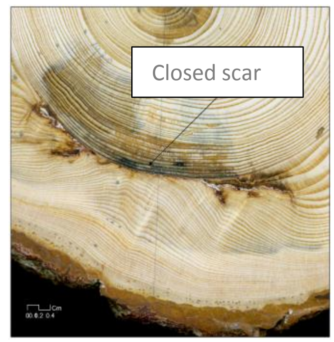


**Fig. 47**. Closed scar visible in a cross-section

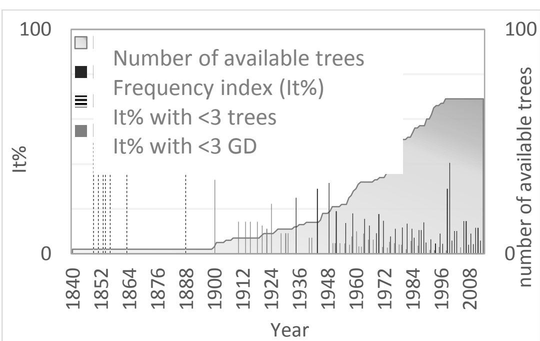


**Fig. 48**. Graphical representation of the frequency index and the number of the available trees

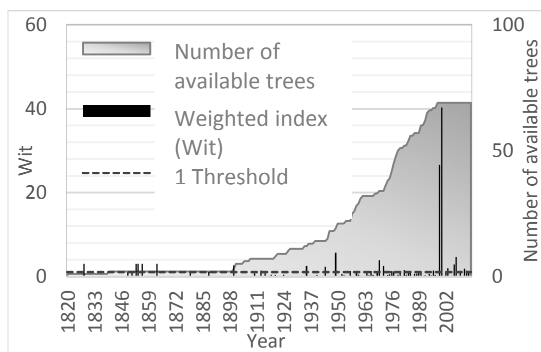


**Fig. 49.** Graphical representation of the weighted frequency index and the number of the available trees

### 5.3.3. Interpretation of the results

#### *5.3.3.1. Temporal frequency reconstruction*

The reconstruction of the events was based both on the number of growth anomalies and on their intensity. Given the low number of available trees prior 1940, the reconstruction started based on minimum 2 reactions. The chronology of the reconstructed events are presented in figure 50. The chronology of the reconstructed events by means of dendrogeomorphology allowed the calculation of the recurrence intervals and of the return period. Thereafter, for the reconstructed interval (1913-2011) the reccurrence interval varies between 2 and 22 years. The longest intervals correspond to the first part of the century when there were few available trees for the reconstruction. Based on this, there was calculated a return period of 6 years.

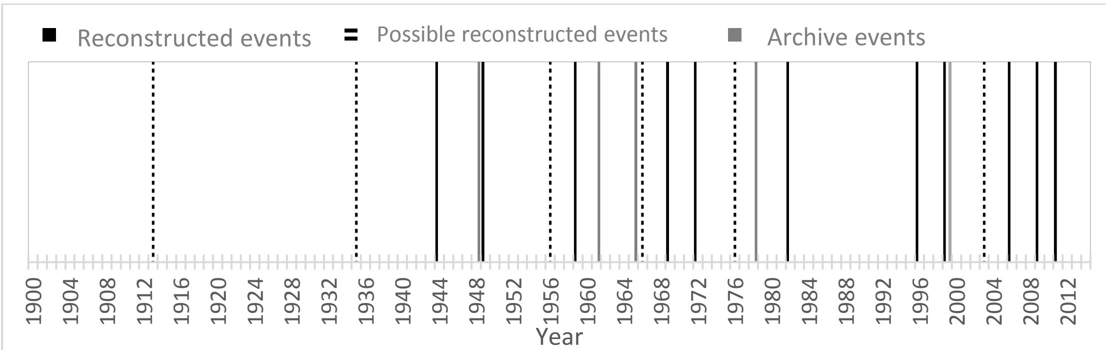


**Fig. 50.** The representation of the reconstructed events and the major events known from archive data

### *5.3.3.2. Spatial frequency reconstruction*

The spatial reconstruction of the events was accomplished based in the distribution of the affected trees and on the morphological changes identified in the field. According to the analysis, in the first part of the XX century the debris flows had affected a wider area while in the second part there is a concentration on the right side of the current cone. This fact can be explained by the construction of three dams in the lower part of the cone which were most certainly meant to hold the debris materials (fig. 51).

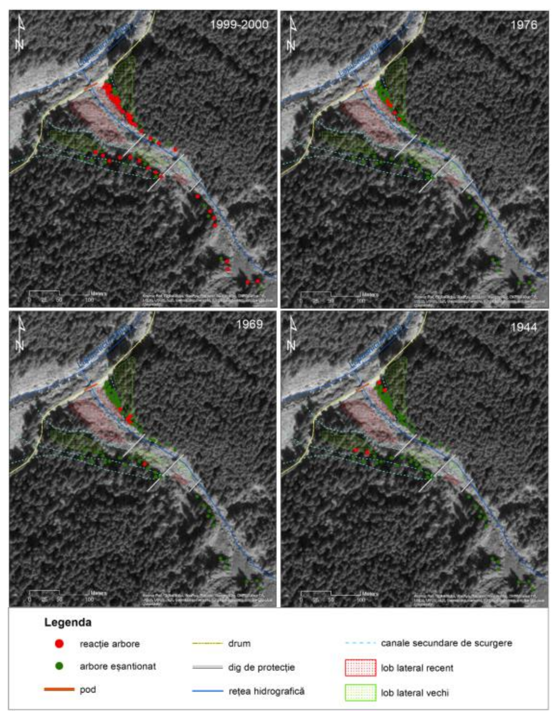


**Fig. 51.** Spatial distribution of the affected tress in 1944, 1969, 1976 și 1999-2000

## 5.4. The comparative analysis of the study cases

The comparative analysis of the three study cases reveals a high synchronicity of the events, resulting in five common events and another 11 registered in two study cases (fig. 52). The years that have been reconstructed events in all three study cases are: 1949, 1956, 1966, 1976 and 1982. The best correspondence of the events is between 2 and 3 study cases, most likely due to the small distance between them.

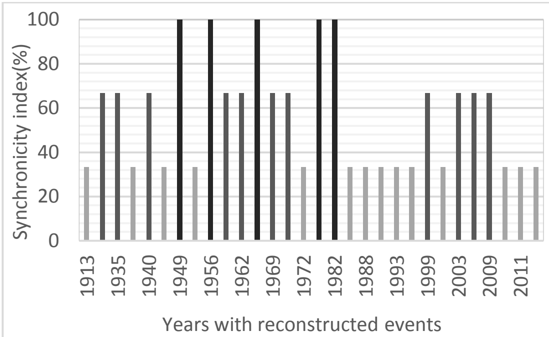


**Fig. 52**. The sinchronicity index of the events

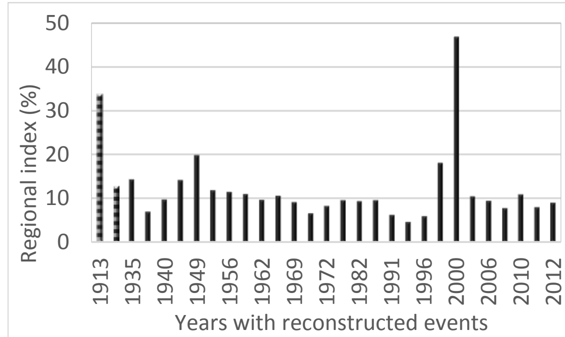


**Fig. 53.** Graphical representation of the regional index

The regional activity index reflects the abundance of responses of the affected trees in all three study cases and is directly proportional to the magnitude (fig. 53). The more growth anomalies the bigger the magnitude of the event. According to the reconstruction, the events from 1949 and 1999 occurred simultaneously on all three study cases and the overall analysis revealed a much higher magnitude of the events.

Also, the comparative analysis of the reconstructed events and the ones known from the archives reveals a good correspondence between the two data sets but highlights the delayed response of trees for some events that occurred towards the end of the growing season. Although most events were of hydrological and/or meteorological type, there were sufficient proves to sustain that, in some cases, these events were accompanied by geomorphological processes which significantly have increased the damages.

### 5.5. The analysis of the index threshold values used in dendrogeomorphological studies

Because of the necessity in standardizing the process of interpreting the results obtained from the dendrogemorphological analysis, some authors have adopted different threshold values. Increasing the precision of dating is based on optimizing the number of responses and on an objective assessment of their intensity. Until now, there have not been many concerns regarding the interpretation of the results but lately the implementation of some threshold values showed that there can be obtained more satisfying results (Kogelnig-Mayer et al., 2011, Schneuwly-Bollschweiler et al., 2013 Corona et al. 2012, 2014). In the present study, the reconstruction of the events was based on the number and intensity of growth anomalies identified in the affected trees. Starting from minimum 3 reactions and 3 trees available, there was established a sequence of events which manifested in the analysed study cases. This threshold value was also used by other researchers in debris flow activity reconstruction (Sorg et al., 2010 Procter et al., 2012).

The minimum threshold of 10% of the frequency index is commonly used in avalanche studies but, in this case, indicates a slight overestimation of the processes (fig. 54). On the other hand, the analysis showed that a minimum threshold of 40% provides an underestimation of the events, only the values obtained for 2000 in all three study cases being above this limit. To maximize signal from noise, in some studies, there were also implemented limit thresholds for the weighted frequency index. So far, there were used threshold values between ≥0.6 and 2. If the values above 0.6 clearly show an overestimation of the events, a 2 threshold value offers results much closer to the reality (fig. 55). In conclusion, adopting flexible threshold values in accordance with the number of available trees are more relevant for the reconstruction of debris flows in this area.

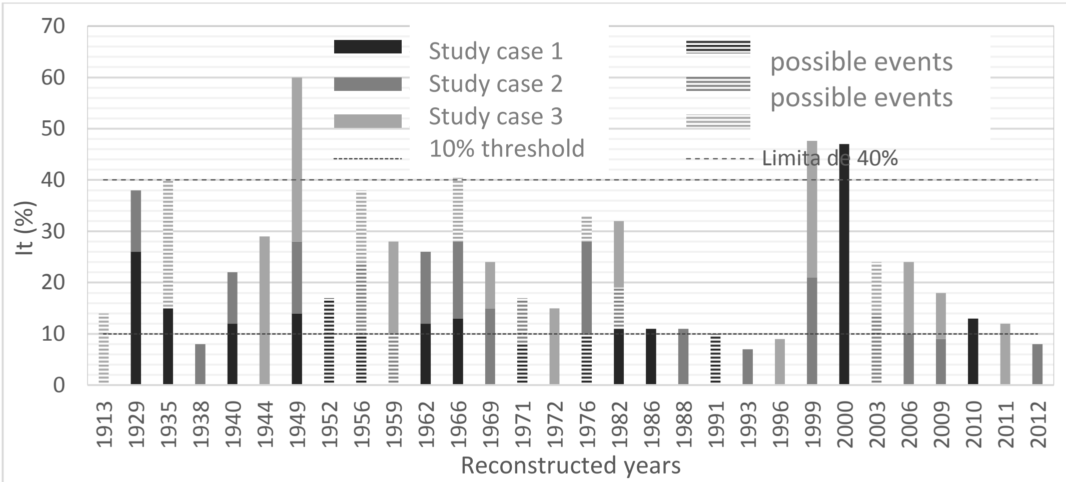

**Fig. 54**. The frequency index values obtained for the reconstructed events of the three study cases

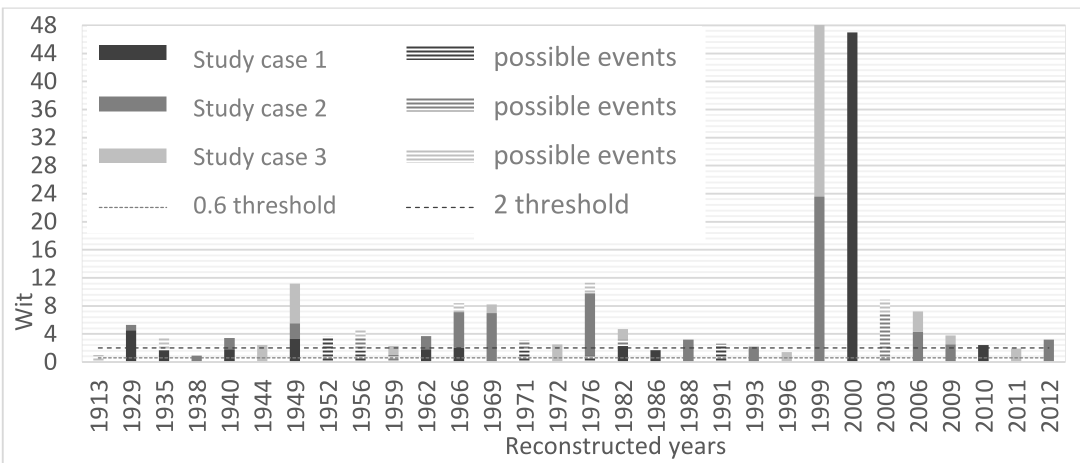

**Fig. 55.** The weighted frequency index values obtained for the reconstructed events of the three study cases

For the reconstruction of the geomorphological processes the precise dating of the growth anomalies is of great importance. Narrow rings, the missing rings or false rings represent the anomalies that generate the most confusion and errors. In order to minimize the errors, the rings must be compared to other rings from the same sample. In the dendrogeomorphological studies, the most frequently method used is the core sampling using an increment borer. The cores represent only a small part of the tree section, more precisely only 5 mm wide and 20-40 cm long. Therefore, the cross-sections which give the entire transversal section of the tree at a specific height are more useful for the analysis and significantly minimizes the errors. Also, many errors occur in dating the traumatic resin ducts (TRD). In the reconstruction process, is important to identify the first rows of TRD. As one can see in figure 56, the first row of TRD appears close to the wound while in the next years they are more developed. If the core is not extracted near the scar is possible that the first row of TRD to be missed. In this case, the time dating of the scar is wrong.

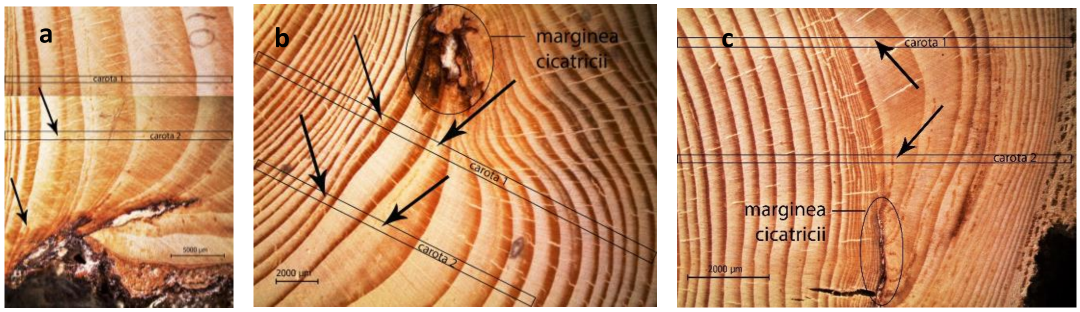


**Fig. 56.** Position of the traumatic resin ducts near the scar

# VI. DEBRIS FLOW SUSCEPTIBILITY

Susceptibility analysis of debris flows involves two main steps: the identification of the source areas and the estimation of the maximum runout distance. The source areas can be identified using different cartographic materials such as satellite images, aerial photographs or directly in the field. In other cases, there are used empirical methods which combines a number of factors considered crucial for source areas development.

In this paper, we obtained an assessment of debris flows susceptibility for Lăpușnicul Mare River basin using a spatially distributed empirical model. Flow-R model (*Flow path assessment of gravitational hazards at a Regional scale)*, developed by the researchers from Lausanne University, Switzerland, uses probabilistic and energetic algorithms in order to simulate the initiation zone and the spreading of debris flows.

## 6.1. Research methodology

Flow-R empirical model uses geomorphological and other user-defined criteria to identify the source areas of the debris flows. Subsequently, using flow direction algorithms and of the frictional laws it is obtained the propagation and the maximum runout distance of the process (fig. 57). This model does not offer any information on debris flow volume or mass, as this aspect proved to be really difficult to achieve especially over a large area. The input data which defines source areas are open to the user. Every cell of the grids is classified according to three possibilities: favourable when the initiation of the process is possible, excluded when the initiation is not possible or ignored when this parameter is not taken into consideration (Horton et al. 2013). According to this, a cell is considered a source area if is at least once favourable and never excluded.

In order to obtain source areas for this study site we used the following inputs: slope, flow accumulation and plan curvature to which we add a 10 m resolution digital elevation model. For locally analysis, there were included land use and predefined source areas. The maximum runout propagation is calculated starting from the source areas and uses flow direction functions and runout distance algorithms. For the flow direction, the programme uses several algorithms (D8, D infinity algorithms, Holmgren multiple direction method and its modified version, etc.) which control the direction of the flow. The modified Holmgren algorithm calculates the probability of the process to drift from a cell to the next eight cells (Baumann et al. 2011). The probability of a cell to be in debris flow path is a combination of the multiple flow direction algorithms and the persistence of the flow. Finally, the maximum distance of the debris flows is calculated on the basis of the frictional laws. As there is no information about sources mass, the kinetic energy which controls the spreading of the process uses energy balance, a friction loss function and a maximum velocity threshold (Park et al. 2013; Blahut et al. 2010).

The input data used in the general simulation are part of the continuous data. These are the most important variables introduced in the analysis in order to obtain the susceptibility map. But also, of great importance may be other factors such as land use or predefined source areas. To be included in the simulation, these data had to be accompanied by an XML file that includes the codes for each class, slope limit and the inclusion, ignorance or exclusion of each class which, remains at the user's choice. In this case, we used the programming language XML (Extensible Markup Language) edited in Notepad ++ based on which there were included classes of the land use and predefined source areas that were vectorized on the satellite images.

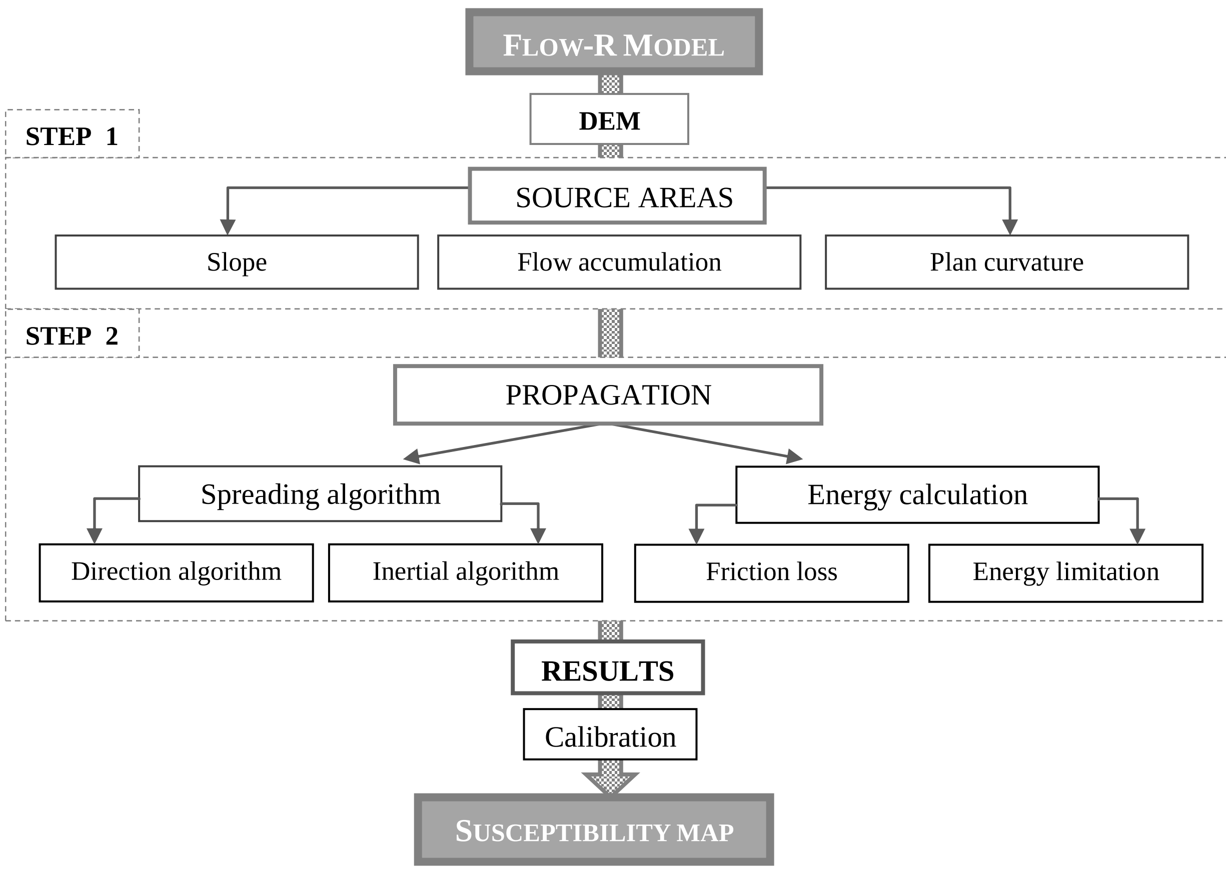


**Fig. 57**. Methodological scheme of the Flow-R model

### 6.2. The analysis and the validation of the results

In the general simulation, there were used only the continuous data, represented by the geomorphological parameters while for certain areas we also included classified data for land use and predefined sources. The predefined source areas were used to discover if there are important changes in the propagation of the process and in the maximum runout distance. Figure 58 shows that the predefined sources do not generate significant differences in terms of process spreading. Land use is also an important factor in susceptibility analysis of debris flows. Because in this study was used the Corine Land Cover database the results were not according to the reality. However, to verify the importance of this factor we vectorized the land use on a certain area on the satellite images. The results obtained were much improved, as there were excluded some forest areas while other areas important for source areas identification were included in the analysis ( fig. 59).

**Table 7.**Input parameters for source areas identification and for propagation calculation

| Input parameters for source areas identification | Criteria |
|---|---|
| Slope | Above 15° |
| Flow accumulation | Extreme events |
| Plan curvature | -2/100 $m^{-1}$ and -1/100 $m^{-1}$ |

| Propagation calculation | |
|---|---|
| *Spreading algorithm* | |
| Direction algorithms | Holmgren modified (1994) |
| Inertial algorithms | Gama 2000 |
| *Energy calculation - frictional loss function* | |
| Travel angle | 11° |
| Velocity | 6 - 15 m/s |

In the final map, the area susceptible to debris flows is represented by different probabilities of occurrence which gives a qualitative approach of the runout potential (fig. 61). The susceptibility map reveals a relatively homogeneous distribution of the processes in the territory. The areas with the lowest degree of susceptibility correspond to the upper basin of Râul Șes while the upper part of the Lăpușnicul Mare and he middle basin of Râul Mare present a much wider susceptible area. In total, the susceptible area covers a surface of 40.7 km² (10%).

We believe that the results of these types of simulations can be improved by introducing elements such as land use or predefined source areas. The condition is that the variables have to be as close as possible to the reality, therefore it is required a high-resolution data. A digital generalization of the field generates errors and misinterpretations of the results. A preliminary susceptibility assessment at a medium scale regarding debris flow activity is important for establishing the process spreading required for hazards and risk assessment databases. In addition, a better understanding of past and potential future debris flow occurrences is imperatively necessary, in order to take early measures and to prevent negative consequences.

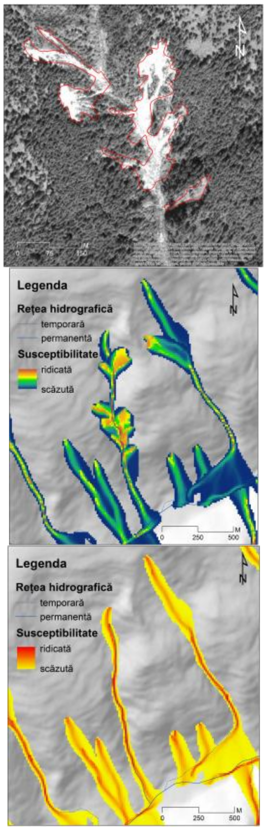


**Fig. 58.** a – source areas vectorised on the satellite images; susceptibility simulation based on source areas (b) and without predefined source areas (c)

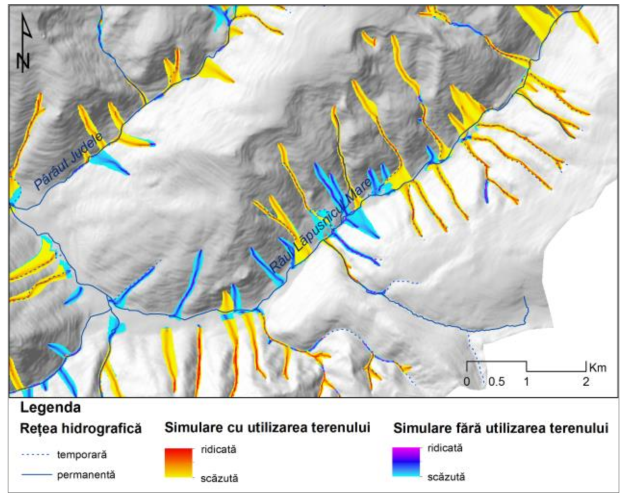


**Fig. 59.** Results obtained on land use. In the first simulation the results are obtained based on the land use vectorised on the satellite images while the second one is based only on geomorphological variables

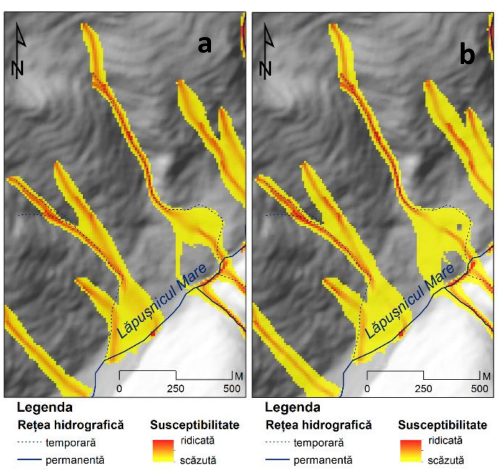


**Fig. 60.** Spreading results for: a)Holmgren modified algorithm with an exponent set to 4, b) Holmgren modified algorithm

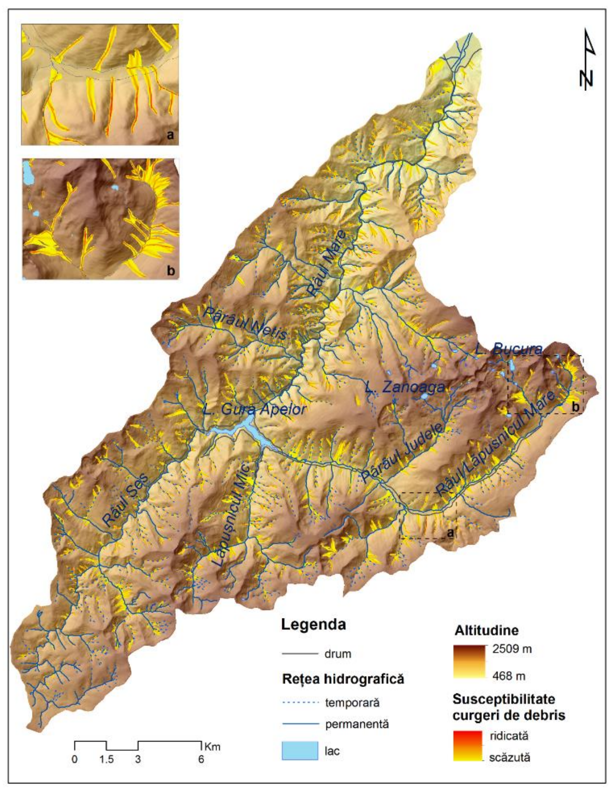


**Fig. 61**. The susceptibility map of debris flows in the upper and middle basin of Râul Mare. Rectangle marked with „a” represents a close-up of the channelized debris flows and the rectangle „B” shows the open slope debris flows

## VII. CONCLUSIONS

The interdisciplinary approach of the study highlights the interdependence of the geo components and the causative relationships between them. Any change made on one single component is transmitted to the others but in different forms and intensities. In this study, we focused on the interdependence and reciprocity relationships between the geomorphological processes and the biotic component, represented here by the forest.

In the first part of the study, there was carried out a detailed analysis on debris flows considering the favorable triggering conditions, propagation and deposit morphology. In Romania, there are only a few studies on this process despite the fact that there is a relatively high potential for debris flow occurrence, especially in high mountainous regions. The translation in Romanian language of the term is not unanimous accepted and therefore, we propose the term *curgeri de debris* as the equivalent of the term debris flow. In the second part of the study, we aimed to characterize the current state of the relief and to emphasize the parameters which favor the debris flows occurrences. The geographic individuality of the study area derives from the complexity of the geological, morphometric, climatic and anthropogenic factors as well as soil and land use. The reconstruction of debris flows activity in the upper and middle basin of Râul Mare was made using dendrogeomorphological methods. The dendrogeomorphological analysis reveals a moderate frequency and a different manifestation in terms of magnitude. The comparative analysis of the three study cases emphasizes a relatively high synchronicity of the events as there were 5 common events and another 11 registered in two of them. The total number of events reconstructed by dendrogeomorphological methods in this area reaches 30. Except for the possible event which was reconstructed for the third study case in 1913, the oldest event occurred in 1929. The comparative analysis of the reconstructed events and the archival records reveals a good correspondence between the two data sets but highlights the delayed responses of the trees which were affected by events that occurred at the end of the vegetation period.

Comparing the results of this analysis with the threshold values established by other researchers we observed that the reconstructed events were either overestimated or excluded. We, therefore, consider that the thresholds and the limits suggested so far should be adjusted according to the trees availability for sampling, the particularities of the processes and the species used.

The susceptibility map of the debris flow shows a relatively homogeneous distribution in the territory. The propagation of the process faithfully follows the channel paths of the permanent or temporary water courses, while the ones occurring on open slopes are present in the upper basin of Lăpușnicul Mare. For the debris flow susceptibility assessment in the investigated area there was used a specialized software called Flow-R developed by the Swiss researchers at the University of Lausanne.

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