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USING OLD LANDSLIDE-DAMMED LAKES TO ASSESS SEDIMENT DELIVERY RATES IN SMALL CATCHMENTS – CASE STUDY: IEZER LAKE FROM THE ROMANIAN CARPATHIANS

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Abstract: The easternmost sector of the Eastern Romanian Carpathians (i.e. the flysch area) has a typical morphology, shaped mainly by gravitation-induced landsliding. The heterogeneity of lithological associations, in conjunction with structure, acts as the main cause of massive landsliding processes that affected the hill slopes across broad areas of up to 2-3 km^2, during certain stages of evolution of the relief. Whereas the majority of landslides are old and stabilized, the possibility for majors landslides still exists at present, like the case of the Cuejdel landslide in Stânișoara Mountains, which occurred in 1991. Despite the large number of landslides documented in the Eastern Carpathians, landslide-dammed lakes were formed solely in a fraction of these instances, and even fewer survived to the present; among these, Iezer Lake (dammed by the landslide which occurred in Iezer stream valley) has been thoroughly studied in recent years. Landslide-dammed lakes are regarded as local basins for sediment accumulation. Their significance for geomorphology and water engineering is considerably larger compared to man-made reservoirs due to their age (i.e. most are much older compared to reservoirs, therefore the assessment of sediment rates can be carried out for a longer timespan). In this study the sediment accumulation rate in the lake basin is inferred based on the modeling of the present-day and preexisting (i.e. prior to lake formation) topography. In terms of geographical location, the landslide, the lake and the entire catchment upstream are part of the Obcina Feredeu Mountains which overlie a highly folded substrate composed of glauconitic sandstones, compacted clays, variegated clays and sphaerosiderite clays, all of which favor landsliding. The lake is located at 931 m a.s.l. and stretches across 1.63 ha, of which ca. 0.88 ha were covered by paludal vegetation which grew from under a layer of 10 to 20 cm of water (in 2009, when the measurements were performed). Our research was initiated in 2009 when the Iezer landslide and lake basin were surveyed using a GPS and a total station. Based on this survey, the digital elevation model was generated. Furthermore, after scanning the site using a GPR and analysing the cross-sections of the initial valley, a model of Iezer valley prior to the lake formation was obtained. The actual volume of sediments accumulated in the lake basin was determined by overlapping the two topographical models, and the result was further related to the period of sedimentation and the area of the catchment. Consequently, the annual sediment delivery rate was determined, together with the observation that the annual sediment delivery rates in small catchments are lower compared to other areas pertaining to flysch.

Keywords: landslide, lake, sediments, silting, sediment delivery rate

1. INTRODUCTION

Major landslides occur on hillslopes pertaining to mountain ranges composed either of rocks which are resilient to erosion, but strongly affected by tectonics through cracking and faulting (Wilson et al., 2003, Weidinger & Korup 2009, Prager et al., 2009), or heterogenous sedimentary rocks susceptible to erosion due to their fine interbedding (Pánek et al., 2010, Migoń et al., 2010, Antinao & Gosse, 2009, Balescu et al., 2007, Margielewski, 2006, Micu, 2016). The flysch area of the Romanian Carpathians belongs to the latter category, as well as the flysch zones of the Ukrainian, Polish, Slovak and Czech

Carpathians (Prokešová et al., 2010, Pánek et al., 2007, Pánek et al., 2009, Bălteanu et al., 2010, Micu & Bălteanu, 2009, Margielewski, 2002, Margielewski & Urban 2002, Marschalko & Mullerova 2002, Krejci et al., 2002).

Gravitational processes involving mass movements typical for the Carpathian ranges are the result of deep-seated gravitational slope deformation (DSGSDs) (Crosta, 1996, Agliardi et al., 2001, Baron et al., 2004, Baron et al., 2005, Pánek et al., 2009).

The age of landslides can be determined using various methods based on the organic matter stored in sediments (Bertolini et al., 2004, Walker, 2005, Grimm et al., 2009), therefore special attention was granted to landslides which barred adjacent valleys resulting in the formation of landslide-dammed lakes which were subsequently silted completely or partially (Borgatti et al., 2007, Deplazes et al., 2007, Pánek et al., 2010).

Among geomorphic processes typical for the Romanian territory, landslides are specific for hilly and mountainous regions. In these areas they commonly leave a lasting mark on the landscape, and can occasionally result in the formation of landslide-dammed lakes. Iezer Lake from Obcina Feredeului is included in this category of lacustrine bodies and is reportedly one of the oldest of such lakes in Romania, according to studies. The landslide-dammed lakes from the Eastern Carpathians have recently been investigated by scentists with various backgrounds (geology, geomorphology, hydrology etc). The best known, as well as the most frequently investigated to date, is Lacul Roşu/ Red Lake from Haghimaş Mountains, where studies were carried out as early as the mid-19th century, soon after its formation (Schueller, 1838; Herbich, 1878) and continues to be studied to present (Mihăilescu, 1940; Pișotă & Năstase, 1957; Atanasiu, 1958; Preda, 1967; Bojoi, 1968; Pandi & Buzilă, 2004; Begy et al., 2009; Ilinca & Gheuca, 2011; Romanescu et al., 2013).

Moreover, Cuejdel Lake from Stânişoara Mountains, despite its young age (i.e. formed in 1991), was also subjected to various investigations (Ichim & Rădoane, 1996; Rusu, et al., 2002; Rădoane, 2003) and is currently the largest landslide-dammed lake in Romania.

Even though Iezer Lake from Obcina Feredeului is one of the oldest documented landslide-dammed lakes in Romania, due to its small size (1.62 ha in 2009) it was largely overlooked by researchers and only occasionally mentioned in the literature until 2009; however, it subsequently became a highly investigated site (Lesenciuc et al., 2010; Mîndrescu et al., 2010; Mîndrescu et al., 2012, Mîndrescu et al., 2016).

2. STUDY AREA

Iezer Lake is located at 931 m a.s.l. in Obcina Feredeului in the drainage basin of Sadova, which is a left-side tributary of river Moldova. The geographical coordinates are 47°36'12″ N and 25°26'52″ E (Fig. 1).

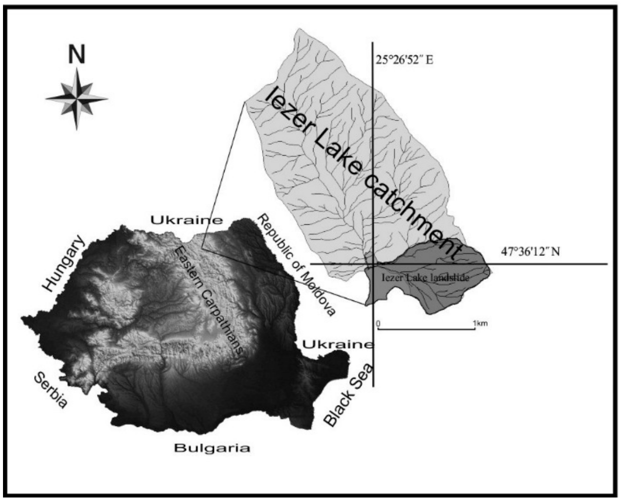

Figure 1. Geographical location of Iezer Lake in Romania

The earliest mention of Iezer Lake in historical documents dates back to 1594 (Mîndrescu et al., 2010), which attests to the fact that the lake already existed at the time. However, the factors which triggered the landsliding processes, as well as the exact period when these occurred, are still unknown.

After thorough research carried out at the site, a wood sample was extracted from the lake sediments at ca. 4m in depth. The calibrated radiocarbon age of the wood fragment is 1035 to 1176 yrs. (Mîndrescu et al., 2012). Assuming that the wood fragment originated in the tree logs displaced by the landslide which resulted in the formation of the lake, we may consider this to be the age of the landslide, as well as of the lake.

Based on this assumption, Iezer Lake likely formed between 839-980 BP, thus ranking among the oldest landslide-dammed lakes in Romania which are still in existence. Due to the lithological influence, the summits overlap almost entirely the assemblages of hard rocks which compose the thrust sheets, such as glauconitic quartz-sandstones, whereas saddles and valleys correspond to the more friable layers of schists and clayey-marly rocks. The morpho-structural conformity is high; landform shapes closely follow the structure, with parallel longitudinal summits and valleys typical in the central and western Obcina Feredeului which can be observed throughout this range. The main direction of the drainage, oriented southeastward, and the structural-lithological setting of the upper sector of Iezer valley is in consistent with the major geological structure of the flysch area. The main geomorphological traits of the investigated site are generated by the lithological variations and the small nappe-type structure of the Audia Nappe. In cross-section, Obcina Feredeului appears like a succession of hogbacks or a so-called „orogen cuesta" whereby the escarpment slope is oriented northeastward and the dip slope southwestward. Such dip slopes facing southwestward to Sadova and Iezer valleys, with slope gradients which often exceed 30° due to the hard and soft friable rocks interbedding can be rather unstable.

The formation of hogbacks is linked to the exaggerate folding of competent layers which eventually broke into the shape of reverse faults. Thus, the upper flank of each fold surpassed the reverse flank in sliding, reaching an abnormal contact with the upper flank of the next fold, and thus resulting in an imbricated small nappe-type structure of the normal flanks. The structurally-induced angularity is partially attenuated by denudation which resulted in slighly softened angles and summits, even though it does not alter the apparent youth of the relief. This impression is further enhanced by the drainage network which was unable to break through the main summit of Obcina Feredeului (Barbu, 1976).

Whereas the tectonics and geological structure directed the formation of major landforms in Obcina Feredeului, at the scale of Iezer Lake catchment, lithological associations acted as the main control in the dynamics of relief and the evolution of geomorphic processes that have operated in time.

In terms of morpho-structure, the Iezer site overlies the Audia Nappe (also known as the Black Shale Nappe) pertaining to the Eastern Carpathians.

2.1. Geological background

The petrographic formations from Iezer Lake area are Cretaceous and consist of pelitic, clayey-marly dark-colored sediments with interbedded hard siliceous glauconitic quartz-sandstones and variegated clays. The layers are arranged within the NE-oriented deeply folded thrust sheets. This type of structure is repeated eastward, where deposits are composed of similarly alternating layers of variable hardness and thickness (Fig. 2).

Stratigraphically, the outcropping deposits are composed of black shales and variegated clays. Black shales underlie the main summit of Obcina Feredeului which has the appearence of a raised section folded eastward over the Prisaca subunit, which in turn appears as a tectonically depressed section (Ionesi, 1971). Within the catchment of Iezer Lake black shales account for ca. 96% of the area. Black shale deposits consist of three members: the lower sphaerosiderite complex, the middle schist complex, and the upper glauconitic sandstone complex.

The sphaerosiderite complex appears in the shape of a 500 m-wide strip oriented southeastward. The friable lithology of this complex, consisting of black lutites interbedded with arenites and siderite limestones, has facilitated the formation and evolution of Iezer stream valley. The concentration of clay minerals is 54-68% for illite and 2.5-5.3% for chlorite (Papiu et al., 1975).

The schist complex outcrops on the right-side slope of Iezer valley at Pietrisului summit. In terms of lithology, this complex is composed of rock associations representing several leyers: lower clay-limestone, quartz-siltite, upper clay-limestone and silicolitic rocks. The concentration of clay minerals is 21-70% for illite and 0.8-7.5% for chlorite (Papiu et al., 1975).

The glauconitic sandstone complex outcrops on the left-side slope of Iezer stream valley and underlies the main summit of Obcina Feredeului. It consists of arenites, such as fine -and medium- coarse sandstones, 4 to 150 cm thick, closely interbedded with siltites and microrudites, as well as lutites (clay and siliceous clays). Arenite layers are prevalent in this complex, accounting for 70% of the total volume. The concentration of clay minerals is 56-71% for illite and 2.8-7.6% for chlorite (Papiu et al., 1975).

All the complexes of the Black Shale Formation have a common clayey sediment matrix, mainly illitic, that was overlaid by various lithological components, resulting in the formation of different types of rocks (Grasu et al., 1988).

The variegated clays outcrop in a NW-SE oriented strip with widths ranging between 100 and 150 m. Within the investigated perimeter, the variegated clays occur on the left side of Iezer Lake, in the lower third of the slope affected by landsliding. This formation is composed mainly of alternating red, green and even black clays, interbedded with thin layers of sandstones, marls and limestones (Grasu et al., 1988). This petrographic background indicates that in this area the geological substrate is favorable for landsliding, and this predisposition is further confirmed by the presence of landslide deposits which cover the catchment almost entirely.

2.2. Climate conditions

Both direct and indirect relationships have been documented between local climate conditions and landsliding. The direct control of climate over geomorphic processes is linked to the occurrence of intense and abundant precipitation, whereas the

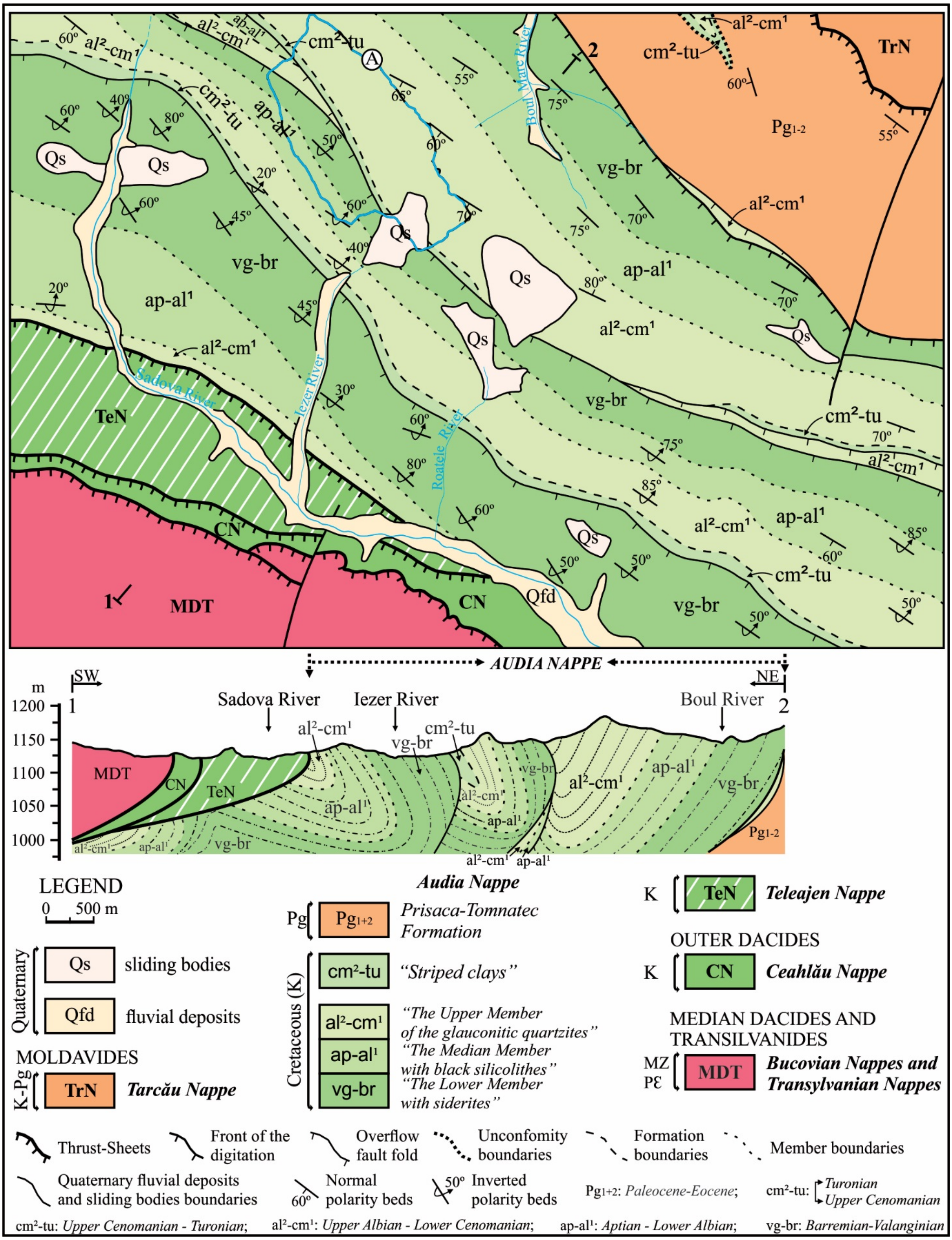

Figure 2. Geological map of the Iezer Lake area (acording Kräutner, et al., 1975; Săndulescu, 1984; Săndulescu et al., 1987). (A) Iezer Lake catchment

indirect relationship manifests through climate-controlled vegetation. The general traits of the climate in the northern Romanian mountains include lower mean annual temperatures and higher humidity. Our study area does not have any regular records of climate conditions, therefore we used climate data from the neighboring weather stations: Vatra Dornei (closest in terms of elevation to lake Iezer, 930 m a.s.l.) and Rarau (at higher elevation). The mean multiannual temperature is 5.1°C at Vatra Dornei (825 m a.s.l.), with monthly averages of -7.2°C in January and 15.8°C in July, and 2.3°C at Rarau (1536 m a.s.l.), with monthly averages of -7°C in January and 11.4°C in July. The absolute amplitude at Vatra Dornei is 71.1°C, with the lowest value of -36.5°C recorded in January, and the peak value of 34.6°C recorded in August, while at Rarau the amplitude is 57.4°C, with extreme values of -28.4°C and 29°C, respectively (Rusu, 2002; Lesenciuc, 2006). The mean multiannual precipitation is 715 mm at 950 m a.s.l. (Poiana Ițcani - Giumalău) and 909 mm at 1536 m a.s.l. (Rarau). For comparable elevation ranges, west and north-facing slopes receive larger amounts of precipitation compared to east and south-facing slopes by as much as 100 mm/yr. At Vatra Dornei the average monthly precipitation ranges from 25.5 mm in February to 103.4 mm in June. The highest amounts of precipitation ever recorded in 24 h are 260 mm at Vatra Dornei (in September) and 111 mm at Rarau (in June). The high amounts of precipitation falling over short periods of time can be a decisive factor for enhancing erosion processes within riverbeds and on slopes, as well as triggering landslides on slopes.

2.3. Vegetation conditions

The study area is part of a large forested area covered mainly by *Picea abies* occasionally mixed with *Abies alba*, *Pinus silvestris*, *Acer pseudoplatanus* and *Sorbus aucuparia*. The forests covering the catchment of Iezer Lake comprise of both stands which are currently being harvested, as well as compact wooded areas with *Picea* specimens more than 100 years old. On the right side of Iezer stream grow compact stands of young forest wihich have been planted 30-40 years ago. The vegetation of Iezer Lake consists of hydrophilic phytocoenoses pertaining to classes *Potameteapectinati*Klika in Klika et Novák 1941 and *Phragmiti - Magnocaricetea*Klika in Klika et Novák 1941. The main association is *Equisetetumfluviatilis*Soó 1927 which accounts for the largest part of the lake surface where the water is shallow (ca. 0,5 m) due to silting processes. The *Potametumnatantis*Soó 1927 association covers smaller areas where the water depth ranges between 0.5 and 2 m. The central part of the lake lacks vegetation due to the water depth. In the upstream sector of the lake where the silting process is more advanced the vegetation evolved towards hygrophilic and meso-hygrophylic meadows pertaining to the class *Molinio - Arrhenatheretea*R. Tx. 1937. Thus, the bank area where the substrate is more humid is covered by the hygrophilicphytocoenoses of the *Scirpetumsylvatici* Ralski 1931 association which gradually transition to the meso-hygrophylicphytocoenoses of the *Cirsiocani – Festucetumpratensis*Májovsky et Ruzicková 1975 association (Chifu et al., 2006). This transition is favored by the gently sloping terrain configuration which retains less humidity. In terms of land use, the silted area upstream of the present lake is currently a grassland which is managed in a manner typical to the mountainous region of Bucovina.

3. METHODS

The investigations on the study area were intiated in 2009 when the Iezer landslide body and lake basin were surveyed using the total station and a GPS. From the two ground control points (GCP) radiated with the GPS the actual measurement was performed by targeting the prism with the total station; the distance between the targeted points was 1-2 m, enough to highlight the details of the topography. Aside from the direct survey we employed cartographic resources (i.e. topographic maps, scale 1:5000, georeferenced in STEREO70, the official projection used in Romania) designed based on aerial photos dating back to 1981, from which we extracted the contour lines, the drainage network, lake contour and elevation points.

The GPR scans were performed in two successive stages, in June 2011 and January 2012, using a MalåRamac X3M with 100 MHz and 50 MHz shielded antennas (Fig. 3). The winter scan was necessary in order to survey the wet perimeter of the lake which was only reachable using an ice bridge. In the winter a total of 14 cross sections were made.

The cartographic materials were made using ArcGIS, Microsoft Excel and CorelDRAW X4 software. For rendering topographic details, generating current contours and drawing the level curves of the old lacustrine cuvette we used ArcGIS, and then, based on contours, the 3D models of the current and the old cuvette were made. For calculating the volume of the sediments submitted in the lake two methods were used:

1. Three-dimensional models for the current and the old cuvette were made, with the difference between the two models realised with TNTmips, then the result was exported as a txt file in Microsoft Excel and subjected to the Pixel Size Height method.
2. The volume for each cuvette (the current one and the old one) was transcribed into the 3D models, the difference between the two values being the very quantity of the sediment silted in the lake. The current

lake volume was also calculated, using two different software programmes, ArcGIS and TNTmips (as there is only a minor difference between them).

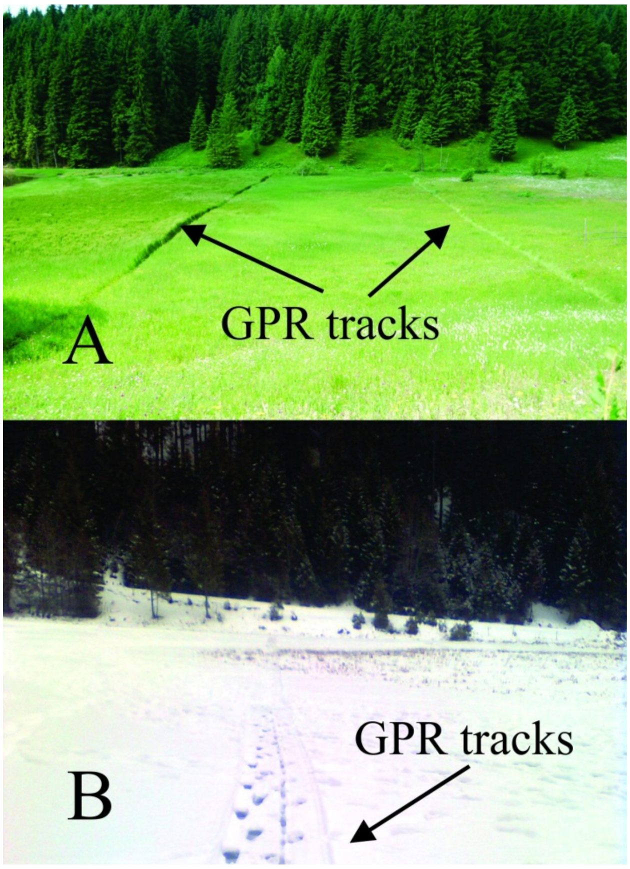

Figure 3. Traces left by the GPR antenna on the grass (A) and on the snow (B)

4. RESULTS AND DISCUSSION

The genesis of Iezer Lake is linked to the geomorphic activity of the western slope of the main summit of Obcina Feredeului where large landslides are a common occurrence. Among these, the Iezer landslide affected an area of 0.62 km^2, resulting in a complex micromorphology of the landslide body due to the displacement of a ca. 20 m-thick pack of mobile deposits and *in situ* rock (Fig. 4). The landslide body reached the base of the slope where it barred the valley of Iezer stream and led to the formation of a landslide-dammed lake (Lesenciuc & Gania, 2012).

The extent of the landslide is certified by the large amount of displaced material, its amplitude and high energy, which indicate that a number of conditions had to be met to generate such an imbalance. All these considered, it is likely that geological and geomorphic factors were the main triggers of the gravitational processes which eventually led to the formation of Iezer Lake.

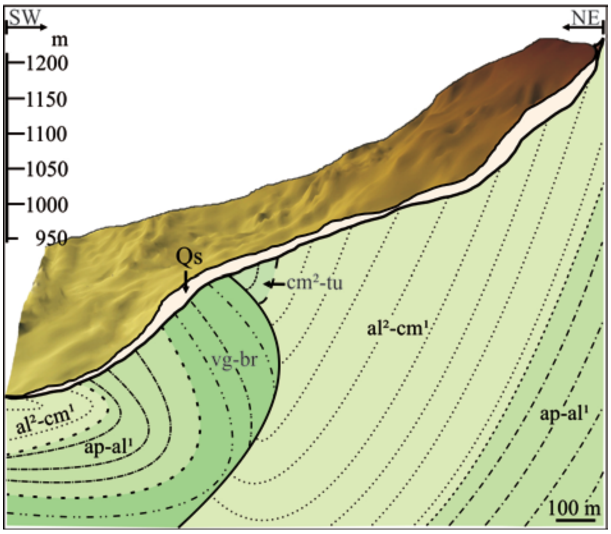

Figure 4. Iezer landslide cross-section (geological legend is found in figure 2). The folding and thrusting tectonic style enhances mass movements. The NE slope of Sadova Valley has a thrust sheets structure, represented by synclines with the normal flanc tectonically laminated. The synclines consist of layered deposits of Audia Formation and Variegated clays Formation. The lower half of the slope is sculpted on reversed synclines, converging towards SE and having strata dipping in the opposite direction as the slope (Azc. 20-50^{0}NE/20-85^0). The upper part of the slope is formed on normal synclines, with strata of the preserved flanc dipping in the same direction as the slope. The faults marking the edge of the thrust sheets are listric faults, and they frequently bring into contact hard, arenitic and silicolitic rocks with silto-lutitic deposits. This way, alternating rhythms of clayey-siltitic and arenitic-silicolitic rocks act as a factor enhancing the possibility of landslides and the transfer of materials to the lake cuvette. A first alignment which is important for the formation of sliding bodies is represented by the contact area between the reversed structures and the normal ones, and also the areas dominated lithologically by silto-lutitic materials, with interbedded arenitic, silicolitic and limestone materials.

The investigations conducted on recent landslides from the Eastern Carpathians reveal that the flysch area is currently affected by landsliding which occurs mainly at the base of slopes where substantial landslide deposits have accumulated (Surdeanu, 1986). In addition, the upper limit of occurrence of landslides is, at present, the 800 m a.s.l. elevation line on Bistrita valley in the flysch sector (Ichim & Surdeanu, 1973) and 900 m a.s.l. in the flysch mountains south of Obcina Feredeului (Ichim,1972, Ichim, 1979). Unlike contemporary landslides, which are typically small-sized and located mainly near the base of slopes (albeit there exceptions to this rule, such as Cuejdel landslide which occurred in 1991 in Stanisoara Mts as a major landslide which also generated a lake), the event which led to the formation of Iezer Lake involved a large landslide body of displaced material which affected the entire left-side hillslope of the valley and a landslide scarp located at 1237 m a.s.l. on the main summit of Obcina Feredeului. The landslide perimeter is 3.85 km, and the elevation gap is 337 m.

Therefore, this ranks as a major landslide similar to the events which resulted in the genesis of landslide-dammed lakes Cuejdel (1991) and Lacul Rosu (1837) in the Eastern Carpathians.

4.1. Reconstructing the evolution of the lacustrine basin

The use of GPR for the indirect analysis of superficial deposits and soils has produced conclusive results in several types of approacheswhich aimed to investigate the characteristics of alluvial, aeolian and marine deposits (Schenk et al., 1993, Tomer et al., 1996, Wyatt & Temples, 1996, Bristow & Jol, 2003, Neal, 2004, Tamura et al., 2008, Dickson et al., 2009, Rocha et al., 2013) or to identify certain tectonic structures or faults (Meschede et al., 1997, Maurya et al., 2005). The depth at which superficial deposits are transited by radar waves depends on the type of antenna employed and the physical and chemical properties of the deposits. When transiting through deposits with high electrical conductivity (including clays, salts, water etc), the penetration capacity of electromagnetic waves decreases as they are converted into electrical currents (Galagedara et al., 2003; Daniels, 2004; Lambot et al., 2004, 2006; Weihermùller et al., 2007). In this case we focused on the alluvial deposits accumulated in the lacustrine basin which formed behind the landslide which barred Iezer valley and we were particularly interested in scanning the differences between the stratification of alluvial and deluvial-proluvial-coluvial deposits (Fig. 5). Although the groundwater level is subsuperficial or in some instances there is a water body above the surface (in the case of the actual lake), we were able to delimit the preexisting morphological surface (i.e. prior to lake formation) based on the grain size differences between various types of deposits. Therefore we proceeded to reconstruct the configuration of Iezer valley prior to the formation of the lake.

An accurate reconstruction of the initial valley is achievable due to the lack of floodplain terraces in this sector, which only develop as the catchment size increases. For this purpose we analysed neighboring valley sectors pertaining to catchments with areas of ca. 4 km^2, similar to Iezer catchment (Fig. 6).

The results yielded by the analysis of valley cross-sections led to the conclusion that prior to the onset of lake formation the reach which currently hosts the lake was a narrow V-shaped valley sector whose slopes intersected in the stream channel. Using the total station we surveyed the entire sector surrounding the lake, including adjacent slopes, thus obtaining the 3D model of the current topography. Subsequently, using the GPR, we made14 cross section which covered the silted area of the lake as well as the current water body (Fig. 7).

The diagrams of the 14 cross sections were used to pinpoint the topographic location of the old valley profile prior to the formation of Iezer lake.

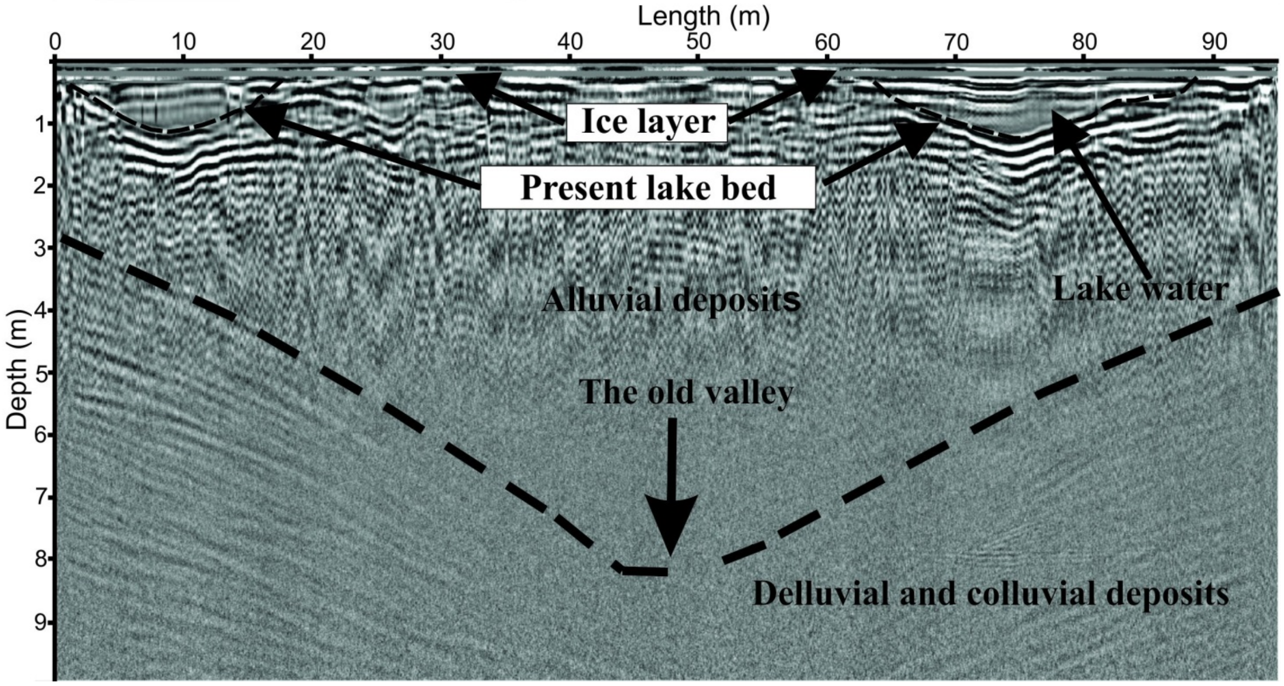

Figure 5. GPR diagram - transversal profile at the present-day limit of Iezer Lake

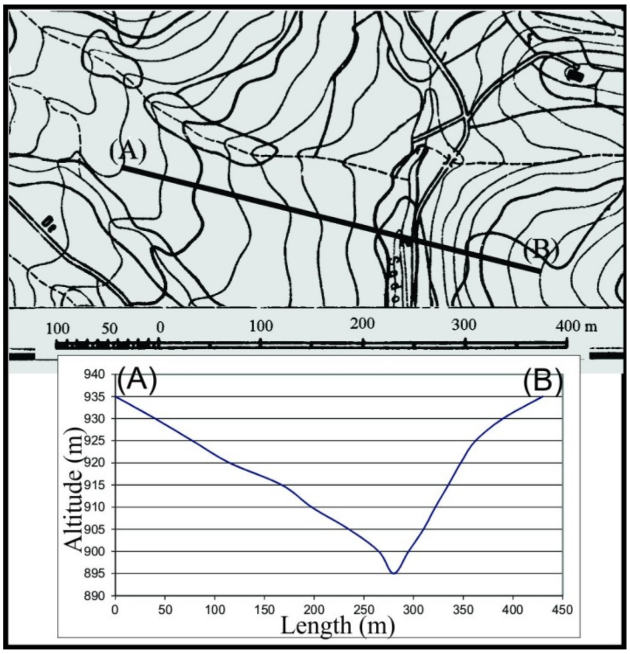

Figure 6. Topographic transversal profile of Sadova stream valley in the vicinity of Iezer valley

The transversal profiles identified on the GPR diagrams were related to the reconstructed longitudinal profile of the old channel thalweg of Iezer stream (Fig. 8). Thus, a 3D model of Iezer valley was built showing the initial configuration of the valley in the analysed sector prior to the barring which resulted in the formation of Iezer Lake (Fig. 9). Based on these scale-accurate models we determined the volumes of the two lacustrine basins (old and new) using as elevation reference the 937 m a.s.l. contour where the lake formed after the valley was dammed.

By determining the absolute elevation of the dam (937 m a.s.l.) we were able to estimate the initial area of lake Iezer (i.e. 5.2 ha), at which level the lake began to discharge water over the dam.

At peak level, the maximum depth of Iezer Lake was ca. 15 m located on the axis of the valley near the dam above the old stream channel thalweg. The volume of the lake estimated at maximum level after the damming of the valley was ca. 300400 m^3. Subsequently, the volume of the lake has continually decreased due to the joint action of two geomorphic processes typical for such lakes.

The first, and most significant, was the fluvial erosion exerted on the dam in the discharge area of the lake, that generated an incision in the dam which gradually dropped to the present-day level of the lake (931 m a.s.l.), thus leading to the drainage of a large part of its initial volume. This process of deepening the outlet into the mass of the natural dam evolved naturally until 1965 when the authorities intervened by building a dam and an overflow designed to maintain a certain level of the lake. The second major geomorphic process which impacted on the evolution of the lake is silting which caused a gradual decline in the volume of water.

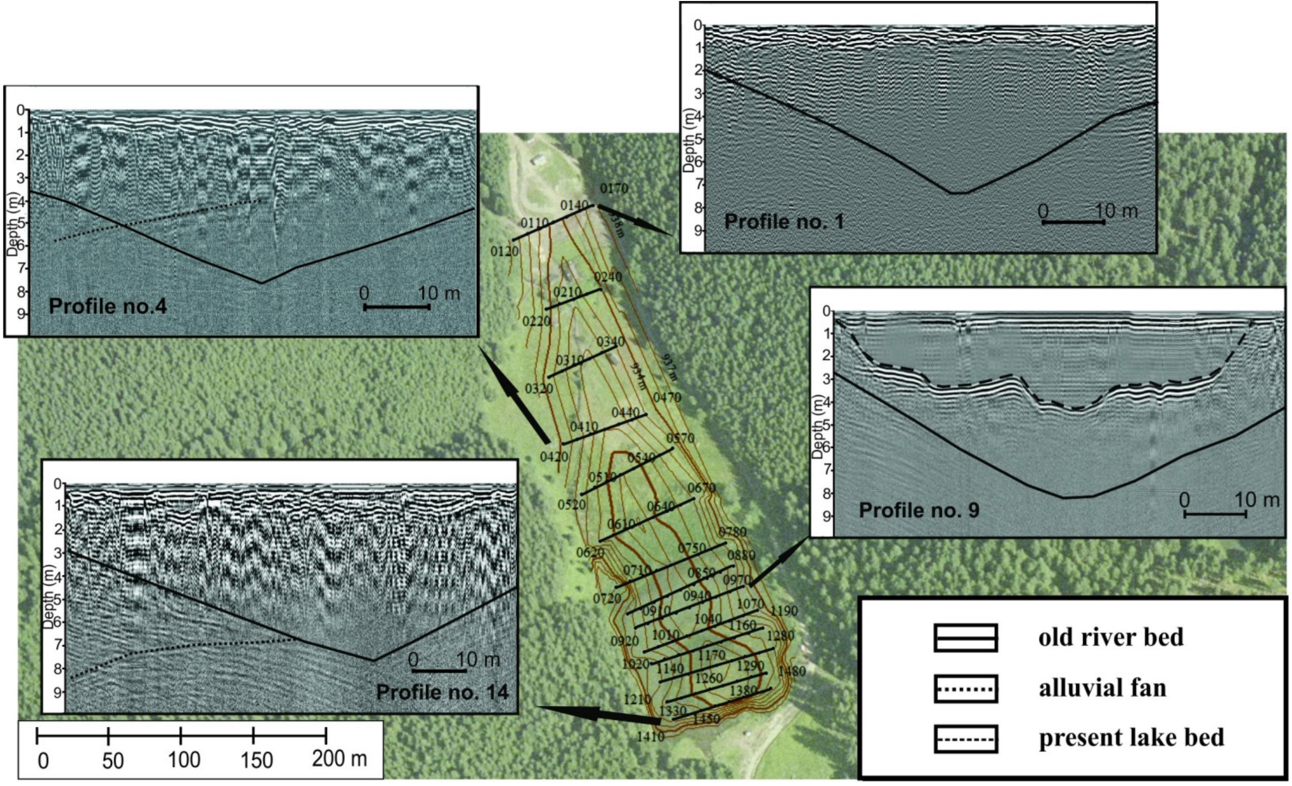

Figure 7. Position of the 14 GPR cross sections. Reconstructed transversal profiles and generated contours of Iezer valley prior to lake formation

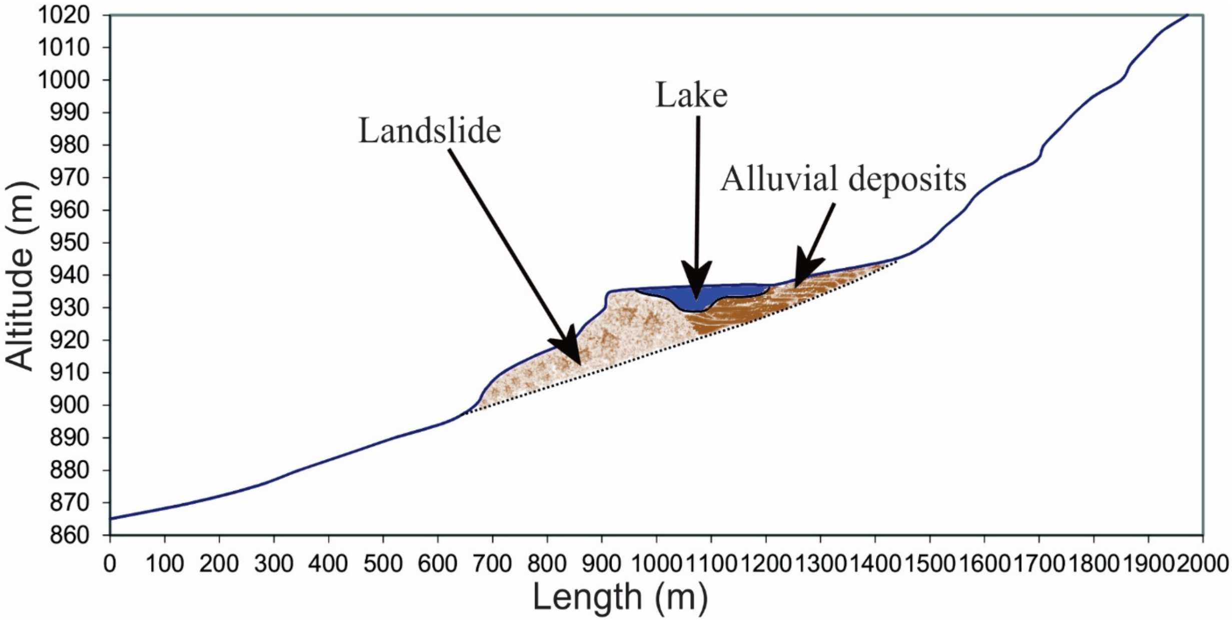

Figure 8. Longitudinal profile of Iezer valley channel thalweg

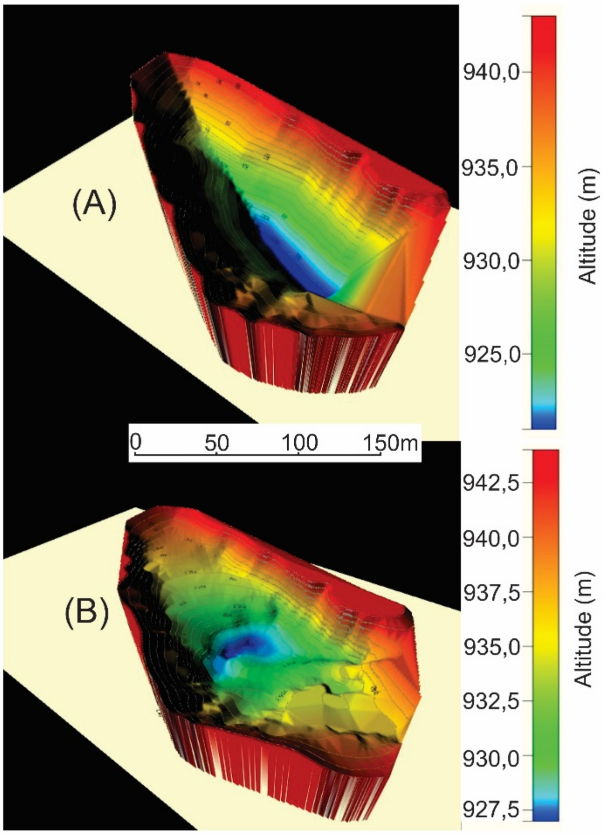

Figure 9. Digital terrain model. A. Iezer valley prior to lake formation (reconstructed based on GPR diagrams). B. Present-day valley in the perimeter of Iezer Lake (surveyed using the total station and GPS)

Unlike the fluvial erosion exerted on the dam, the sediment accumulation evolved undisturbed until 2014, without any human interference. However, the local administration of Sadova commune carried out excavations and dredging of the lake in order to convert it to a recreational area. We note the fact that all the field research was performed at the site was prior to these interventions, such that our data regarding the sediment volume were not influenced by the human interference.

4.2. The catchment, sediment accumulation / silting in the lake and sediment delivery

The geomorphological importance of Iezer Lake lies in the fact that it allows for the determination of the sediment accumulation rate in the lake basin (one of the longest known periods of evolution of a landslide-dammed lake from the Romanian Carpathians).

After the lake formed, the silting process evolved exclusively based on the input of alluvial material transported by the inlets or the colluvial materials derived from the areal erosion of the adjacent slopes. The geomorphological mapping of these slopes indicated that subsequent to the formation of the lake no additional landsliding occurred which would contribute to the sediment input.

The silting of the lake basin occurred gradually, as the sediment front advanced from upstream to downstream, thus reducing the aquatic area to 2 ha in 1981 (according to the topographic map, scale 1:5000) and 1.63 ha in 2009 (topographic survey). The sediment accumulation rate is closely related to the geo-morpho-hydrological traits of the catchment, which is no greater than 3.71 km^2. The analysis of the geomorphological system corresponding to a small catchment is very important, as various physical-geographical controls, such as precipitation, evapotranspiration or vegetation cover, are relatively uniformly distributed throughout the study area, while the differences are introduced by some morphometric characteristics of the relief. Within Iezer catchment the maximum elevation is 1364 m a.s.l. in the northern part of the perimeter on the main summit of Obcina Feredeului. Thus, the evelation gap is 433 m, which is typical for medium-altitude mountain regions when related to the study area.

The lithological substrate, moderately resilient to external agents, favored the development of the drainage network which reaches peak values of ca. 5km/km^2 in the central-eastern sector where several streams converge (Fig.10).

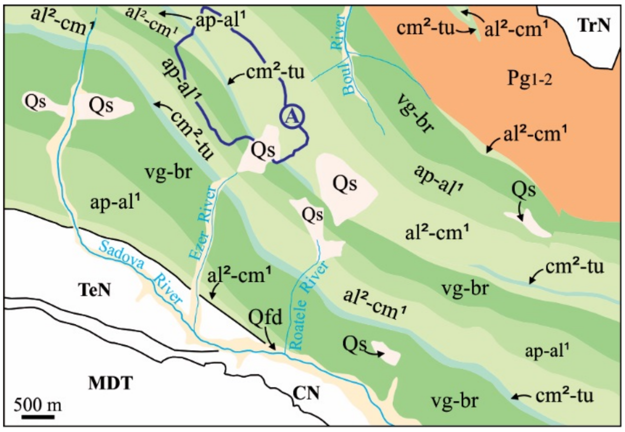

Figure 10. Lithological map of the Iezer Lake area (abbreviations according to legend of Figure 2). (A) Iezer Lake catchment.

The lithological details of the Iezer Lake catchment area: **Audia Formation**: ***The Sideritic Lower Member*** (vg-br) outcrops on a surface of 0.70 km^2. It consists of black clays (reaching up to 60% of the lithological column, with rhythmic interbeddings (in variable proportions) of sandstones, silicolitic rocks (spongolites, gaizes and lydians) and siderite limestones, developed lenticularly. ***The Black Silicolites Median Member*** (ap-al^1) outcrops on a surface of 0.35 km^2. It consists of a layered structure of clayey-calcareous rocks, interbedded with quartz-siltites which sometimes turn to fine sandstones. The lithological column of the member is ended by alternating silicolitic rocks, represented by spongolites, lydians and quartz-sandstones. ***The Glauconitic Quartz-sandstones Upper Member*** (al^2-cm^1) outcrops on the greatest surface of the basin (2.41 km^2). It consists of fine to medium-sized quartz-sandstones and glauconitic sandstones, interbedded with quartz-clayey siltites and black clays. The arenitic materials vary in the lithological column between 60 and 75%. **The Variegated Clays Formation** (cm^2-tu) outcrops on surfaces reduced in size (0.25 km^2), on the edge of the thrust sheets. It consists of a siltic-lutitic base, with varieties of reddish, greenish and variegated clays, seldom greyish / blackish, interbedded with calcareous sandstone and silicolitic rocks (Ionesi, 1971).

The depth of relief fragmentation ranges between 30 and 40 m/ha, typical for the upper third of hillslopes. However, the lower sectors of slopes, as well as the landslide deposits, have gradients ranging from 3 to 10º, whereas a large part of slopes unaffected by landsliding and landslide scarps have gradients above 15º. This indicates that the relief is highly fragmented within the catchment and affected by advanced current geomorphological processes, among which fluvial-torrential erosion is dominant. Another feature of Iezer catchment is the asymmetry of the drainage network, with a short steep-sloping right-side slope opposing the longer, more gently-sloping left-side slope. This asymmetry is a result of tectonics which, due to reverse faulting, resulted in the contact between the striped clay formation and the black shale formation. The axis of Iezer valley was superimposed along this fault which directed its evolution. The asymmetry of the catchment is very relevant geomorphologically and hydrologically in mitigating major floods due to the slower runoff on the left-side slope which moderates the effects of the rapid flow on the opposing slope (Lesenciuc, 2009).

As regards the sediment delivery, indirect assessments of the sediment yield in catchments of various sizes were carried out for most mountain areas of the Carpathian flysch. Several functions differentiated according to the resistance of rocks to erosion were introduced and employed for such studies (Ichim & Rădoane, 1986; Rădoane & Rădoane, 2005 Rădoane et al., 2005, Dumitriu, 2007). These functions use a set of variables which control the sediment yield and delivery (i.e. the Strahler order, catchment area, shape coefficient, total density of drainage network, relief ratio and mean monthly precipitation). Furthermore, direct and indirect measurements were performed on the sediment delivery in catchments pertaining to Trotus drainage basin (Dumitriu et al., 2016).

Iezer Lake from Obcina Feredeului is highly relevant for studies on the sediment delivery in small catchments, as it allows for the direct assessment of sediment delivery in such a catchment across a significant time-frame. While there are other natural lakes or reservoirs (such as Lacul Roșu, lake Cuejdel or lake Bălătău etc) based on whose sediments the sediment delivery rates can be assessed, they are considerably younger compared to Iezer Lake, and the time factor is arguably very significant for data accuracy.

By applying the methodology detailed previously we reached the conclusion that the initial volume of the lake basin (calculated up to the 937 m a.s.l. elevation line) was 300400 m^3, whereas the present-day volume (calculated up to the 937 m a.s.l. elevation line) including the water of the lake, amounts to 211200 m^3. The difference between the two values yields the amount of sediments stored in the lake basin:

Vi-Va=Vs 300400-211200=89200

where

Vi= the initial volume of Iezer lake basin

Va= the present-day volume of the lake basin (including the water of the lake)

Vs= the volume of deposited sediments

Therefore, the volume of sediments accumulated in the lake basin amount to 89200m^3. The annual sediment accumulation/silting rate is determined by dividing this value to the age of the lake. Considering the probable age of the lake equates ca. 1035 - 1176 yrs, the resulting rate is 76 - 86m^3/yr. Furthermore, by relating the annual sediment accumulation rate to the catchment area (3.71 km^2), we obtained an annual sediment delivery rate of 20.48 - 2318 m^3/km^2/yr.

5. CONCLUSIONS

Within the framework of the Romanian Carpathians, the technical studies regarding the harnessing of the hydroenergetical potential need a series of quantitative values concerning the current geomorphological processes connected to the hydrographical basins. The present study has attempted to use a new methodology for assessing the rate of effluence of alluvial deposits in the small basins of the Romanian Carpathians. Using the GPR diagrams obtained through scanning the deposits in the old natural dam Iezer Lake, we have been able to estimate, with relatively high precision, the annual deposit rate for a small basin (3.71 km^2). The advantage of this assessment is connected to the old age of Iezer Lake.

The lithology associated to the flysch area favours large-scale geomorphological processes. Within the catchment area of Iezer Lake, landslides have affected the slopes almost entirely, providing a heterogenous base for erosion and transport processes. The conditions of the landslide have been analyzed in great detail, and we have noticed that the structural and lithological factors of the area have also affected other slides in the same region. Taking into account other physical-geographical characteristics of the analyzed catchment basin (the particularities of rainfall, the density of the hydrographic network, the fragmentation depth, the amount and type of vegetation that has grown etc) we consider that the annual rate of deposit effluence, calculated for the age of the lake, has values between 20.48 and 23.18 m^3/km^2/yr, significantly smaller than the estimated numbers for other flysch areas in the Eastern Carpathians.

The methodology recommended by the present study can be considered accurate for assessing the deposits in the lacustrine cuvette over a longer timespan.

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