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ORIGINAL ARTICLE

Using GPR for assessing the volume of sediments from the largest natural dam lake of the Eastern Carpathians: Cuejdel Lake, Romania

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Abstract Cuejdel Lake in the Eastern Carpathians (Romania) formed in 1991 following the damming of the Cuejdiu brook from torrential rainfall causing a massive landslide of natural deposits. In 2011, using a Bathy-500DF Dual Frequency Hydrographic Echo Sounder, the first detailed bathymetric model of the lacustrine cuvette was produced, using more than 45,000 depth readings. This was the first ever use of a Ground Penetrating Radar (GPR—a Malå Ramac X3M GPR with a 100 MHz antenna) in Romania for evaluating the rate of clogging of a dam lake. The thickness of the alluvial deposits and the rate of clogging were determined on the basis of the measurements taken in wintertime, when the ice cover was 30–45 cm. The data concerning the clogging were correlated with the solid transport from the level of the catchment basin developed in the flysch area, and with the sedimentation conditions of the lake (the analysis of the annual non-glacial varve, in situ biodegradation). The morphologic evolution of the lacustrine cuvette, determined on the basis of three DEMs, revealed a significant quantitative dynamics of the alluvial deposits (sediment accumulation rate 1–16 cm/year; volume of sediments across bathymetric levels 33.6–440.4 m^3/an; total volume accumulated in 22 years 103,988.87 m^3, which represents 8.5 % of the initial volume (1,223,001.33 m^3); average annual clogging rate 4521.26 m^3/year or 0.36 %/year). In 2004, Cuejdel Lake was declared a protected natural area; accordingly, no hydrotechnical works can be carried out in order to stop the erosion and, implicitly, the clogging.

Keywords GPR · Sonar · Sedimentation · Natural dam lake · Carpathian Mountains

Introduction

Dam lakes are the outcome of geomorphological processes and come into existence when watercourses are blocked by mass amounts of natural deposits (soil, rocks, debris flow), lava flow. In some cases, the body of water accumulates behind these obstacles which can constitute a hydrological risk. The lakes formed by landslides and moraine lakes are most likely to lead to frequent changes in the landscape. They usually appear in mountainous areas with clayish substrata, narrow valleys and steep slopes, where accumulation of water is dependent on only a relatively small volume of obstructive materials. The life expectancy of the water accumulations is directly proportional to the geomorphological relationship between the consistency of the occlusion and the shape of the valleys (Costa and Schuster 1988; Meyer and Leidecker 1999; Neuffer and Bruhn 2005; Schneider et al. 2013).

Most of the dam lakes in Romania were formed as a consequence of landfall and gravitational landslide processes. The most favourable conditions for the emergence of dam lakes are found in the Eastern Carpathians, the Curvature Subcarpathians, and the Moldavian

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Subcarpathians, as well as in some isolated areas of the Moldavian Plateau. From a geological point of view, the highest susceptibility is displayed by the area of the Carpathian flysch, where the sequences of permeable and impermeable (particularly clays) layers, and the lithological alternation with deposits of different hardness and increased declivity, lead to the emergence of slope processes in the terrain. After morphodynamic stabilisation, the lakes take the role of sediment traps; as such, they can provide real quantitative information on the rate of erosion in the afferent catchment basin and on the clogging rate for the lacustrine cuvette (Kalff 2003; Bălteanu et al. 2010; Romanescu et al. 2013a; Romanescu and Nicu 2014).

The best known dam lake of the Eastern Carpathians is the Red Lake, formed in 1837 by a landslide that detached from under the Ucigaşu Peak (Hăşmaş Massif) and dammed the valley of the Bicaz River (Romanescu and Stoleriu 2010; Romanescu et al. 2013a, b). The dedicated literature mentions over 20 such dam lakes, most surviving only for limited periods of time (Mihu-Pintilie and Romanescu 2011). Most of the dam lakes in Romania are located in the Eastern Carpathians, where the lithological configuration favours landslides.

Cuejdel Lake is the newest and largest dam lake formed in the mountainous area of Romania. It formed 23 years ago, and according to specialised studies dedicated to it are rare and only of a descriptive character (Ichim et al. 1996; Rădoane 2003). On account of the exceptional natural conditions, Cuejdel Lake was declared a protected area in 2004. Since 2011, a programme of seasonal monitoring was implemented, which employs a series of non-invasive techniques for bathymetric charting (GPS, echo sounder, Total Station) and for determining the variation of the physical–chemical parameters of the water (Hach Multiparameter, mobile laboratory, etc.) (Mihu-Pintilie and Romanescu 2011; Mihu-Pintilie et al. 2012, 2014a, b, c; Romanescu 2009; Romanescu et al. 2012, 2013a, 2014; Romanescu and Stoleriu 2014a, b).

The investigations concerning the rate of clogging and the nature of the sediments commenced in 2013. In the international literature, there are numerous examples of GPR technology used for scanning various sedimentary environments. It can be mentioned the investigation of permafrost (Wu et al. 2012), alluvial deposits (Sass et al. 2007; Pueyo Anchuela et al. 2014), alpine environments (Sass and Wollny 2001), lacustrine sediments (Banks and Johnson 2011; Moorman and Michel 1997; Schwamborn et al. 2002), littoral banks and coastal morphostructures (Loveson et al. 2014), ponds (Shuman and Donnelly 2006). The use of the GPR technology for producing a hydrodynamic model of lacustrine sediments is a first for Romanian limnological research.

Dam lakes appear by accident in the landscape, and generally have a limited life span. The method employed allows to expediently establish the clogging index, to estimate the water loss, and to produce a hydrodynamic model of the sediments within the lacustrine cuvette. The present study aims to assess the morpho-hydrological relationship the cuvette of the Cuejdel Lake has established with the afferent catchment basin. The results obtained can be used as a reference for determining the clogging rates of the natural lakes and of the soil erosion within hydrographic basins with surface areas under 10 km^2, information which is currently absent from specialised Romanian works (Rădoane and Rădoane 2005; Vanmaercke et al. 2014).

Study area and site description

Cuejdel Lake is located in the south-eastern part of the Stânişoarei Mountains, a component of the Central Group of the Eastern Carpathians (north-eastern Romania). The lacustrine depression was formed in the upper basin on the Cuejdiu River (affluent of the Bistriţa River), 1.5 km upstream of the confluence, at an altitude of 661 m. From the administrative point of view, the lake is located on the territory of the Gârcina commune, at 21 km NW from the city of Piatra Neamţ (Neamţ County). Cuejdel Lake is located between 47°01′54″N latitude and 47°02′21″N latitude, and between 26°13′02″E longitude and 26°13′07″E longitude (Fig. 1).

Lake's genesis and evolution

Lake Cuejdel emerged after a landslide from the left versant of the Cuejdiu valley, from under the Muncelului Summit (1117 m). The first gravitational movements portending the occlusion of the valley occurred in 1978, when a small lake was formed (length of 200–250 m; max. depth 4–5 m). A few years later the lake was drained, as flash floods swept the diluvial dam (Ichim et al. 1996). In 1991, the landslide reactivated at a greater scale: the maximum elevation of the detachment cornice is 930 m (left lobe); the maximum difference in elevation is 349 m; the length of the landslip is 1062 m; the length of the blocked watercourse is 1215 m; the surface area is 67.74 10^4 m^2; the thickness of the diluvial mass is 5–25 m, etc. The causes of the gravitational destabilising were multiple: the intercalation of clayish layers in-between grezous-limestone packages; the existence of the initial landslip; heavy rains in May–August 1991 (cumulated value 741.4 mm); the earthquake of 1990 (5.4° Richter); the construction of a forest road at the base of the destabilised versants. The body of water that accumulated behind the dam at that time had the following characteristic properties: surface area

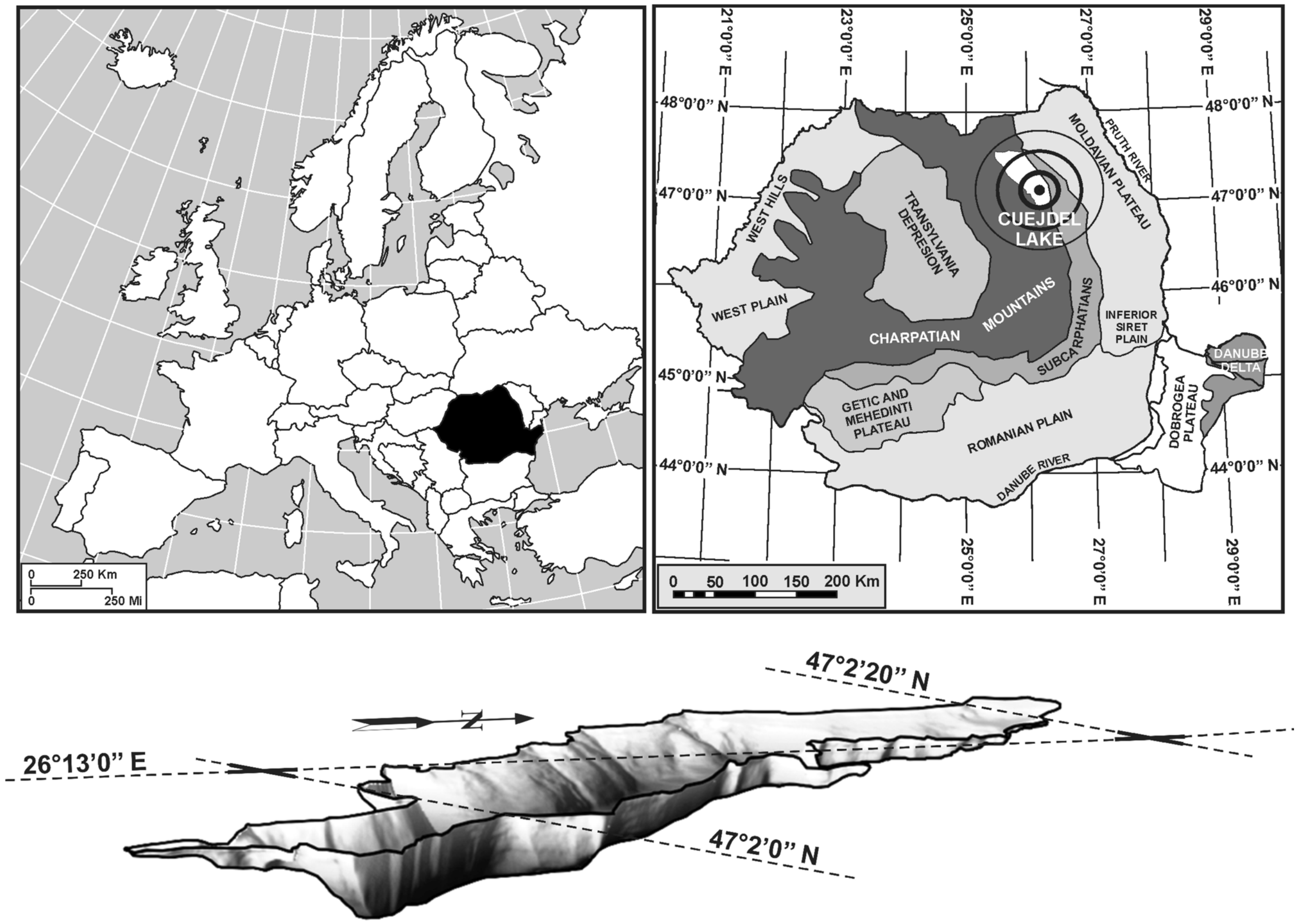


Fig. 1 The geographical location of Cuejdel Lake in the Eastern Carpathians of Romania. 3D model of the lake basin (2011)

16.22 10^4 m^2; volume 122.3 10^4 m^3; max. depth 18.8 m; length 1.17 km (Ichim et al. 1996; Mihu-Pintilie et al. 2012).

The first bathymetric measurements using a Bathy-500DF Dual Frequency Hydrographic echo sounder were taken in 2011. Twenty years after the formation of the lake, the surface area diminished by −2.37 10^4 m^2, the depth by −2.3 m, and the volume by −26.77 10^4 m^3. Cuejdel Lake has established itself as the largest dam lake in the mountainous area of Romania (Mihu-Pintilie et al. 2012) (Fig. 2).

Source of sediments and clogging

The lake's alluvial deposits originate from two sources: (1) in situ sedimentation caused by the dynamics and the pressure of the water exerted at the level of the submerged northern versants, and by bioaccumulation (in the sectors where the slope is greater than 20°–30°, mud lobes detach from the upper portion and slide down to the level of the lacustrine micro-terraces or to the bottom of the lake); (2) from the surface of the reception basin as a result of the transportation of sediments along the drainage network or through areolar flow. The formation of the alluvion is also due to the gradual decrease in the water level, particularly in the sector of the alluvial cone formed upstream of the lake, where clogging is produced by the Glodu and Cuejdel affluents. The fine and easily mobilised deposits are reintroduced into the lacustrine domain.

The main morphometric characteristics of the reception basin are listed in Table 1. In terms of hypsometry, the reception basin of Cuejdel Lake is characterised by elevations ranging from 1117 m (Muncelu Peak) to 661 m (the level of the lake), with the greatest participation from elevations below 850 m (>70 %) (Fig. 3a). The geological complex is composed of an arrhythmic arrangement of schistic, schistic-grezous or grezous flysch, with intercalations of red, green or grey-greenish clays, marly sandstones and marls (Fig. 3b). The soil layer is thin (0.5–1 m), of medium texture (clayish-sandy and clayish) and a quantity of humus ranging from moderate to very high

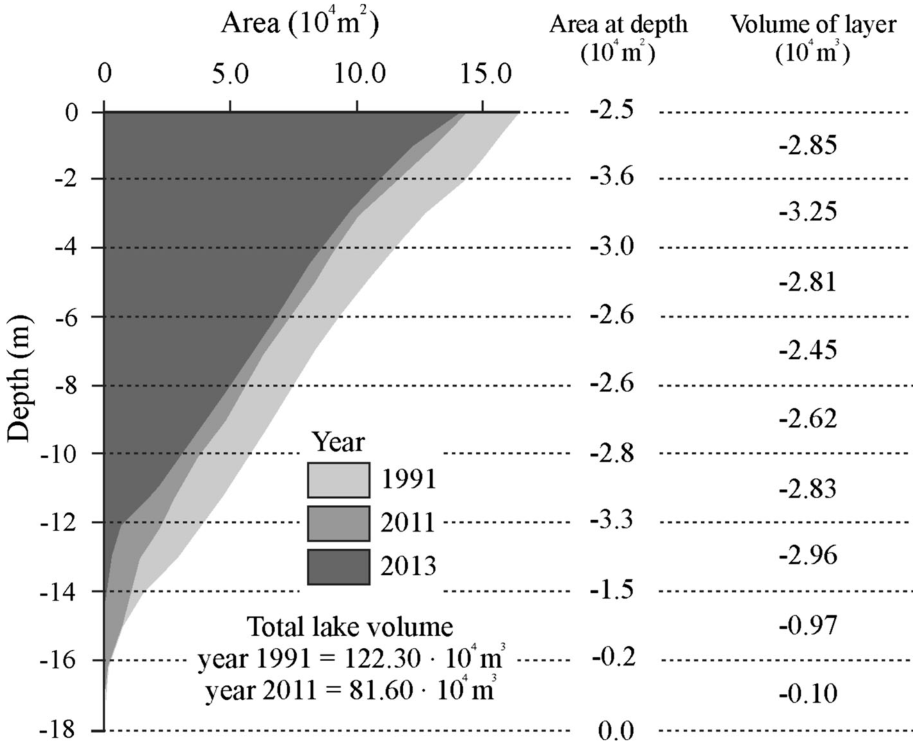


Fig. 2 The depth-area hypsographic curve and lake volume loss between 1991 and 2013, calculated using the formula: $V(X1X2) = [(AX1 + AX2)/2] \times (X2 - X1)$ for each depth interval and adding up the resulting volumes

Table 1 Characteristics of catchment lake basin

Variable	Value
Catchment area (10^4 m^2)	877
Catchment perimeter (km)	12.75
Length (km)	2.67
Max. length (km)	3.31
Width (km)	4.25
Max. altitude (m)	1117
Min. altitude (m)	661
Water course length (km)	4.96
Spring altitude (m)	750
Asymmetry coef.	0.26
Form factor	0.8
Circularity ratio	0.67
Elongation ratio	0.95
Coef. of watershed develop.	1.21
Report form	0.86
Afforestation degree (%)	96.2

(between 3.9 and 13.5 %). These correspond to the typical forest soils of the Cambisols class (>85 %), and to Argillic soils (12 %), and to a lesser degree to unevolved soils formed at the surface of the mantle-rock. In this morphologic context, the slopes range between 5° and 61°, with the greatest values (>45°) being generated by the lithological escarpments or by the transversal valleys that accelerate the erosion and enhance the solid charge of the brooks during torrential rains (Fig. 3c). In terms of land use, 96.2 % of the reception basin is covered by leaf litter, coniferous and mixed forests, and the remaining 3.8 % by sub-alpine meadows. One of the main reasons due to which the lake survives in the landscape is the forest, which slows down the erosion by intercepting the surface runoff (Fig. 3d).

The watercourses have a total length of 4.96 km and develop a potential drainage network of the 4th order (according to the Horton-Stahler classification). On the basis of the runoff coefficients, it was established the production probability with an insurance of 5 % ($Q_{5\%}$) of the maximum discharge. The values estimated shows that during the last 20 years, a flash flood with a maximum discharge between 0.5 and 2.0 m^3/s occurred on each of the affluents, considering that the stem (the Cuejdiu River) registers at 8 km downstream of the lake a modal discharge of just 0.54 m^3/s (Fig. 3e). The level of alluvial charge in high waters can also be discerned from the hydronymy of the watercourses that flow into the lake: the Cuejdel ('stony') Brook ($Q_{5\%}$ 1.81 m^3/s), the Glodu ('muddy') Brook ($Q_{5\%}$ 1.37 m^3/s) or the Făgetu ('beech forest') Brook ($Q_{5\%}$ 0.64 m^3/s).

Materials and methods

For determining the thickness of the sediments accumulated in the lake, a GPR was used, consisting of a Malå Ramac X3M GPR with a 100 MHz shielded antenna. The

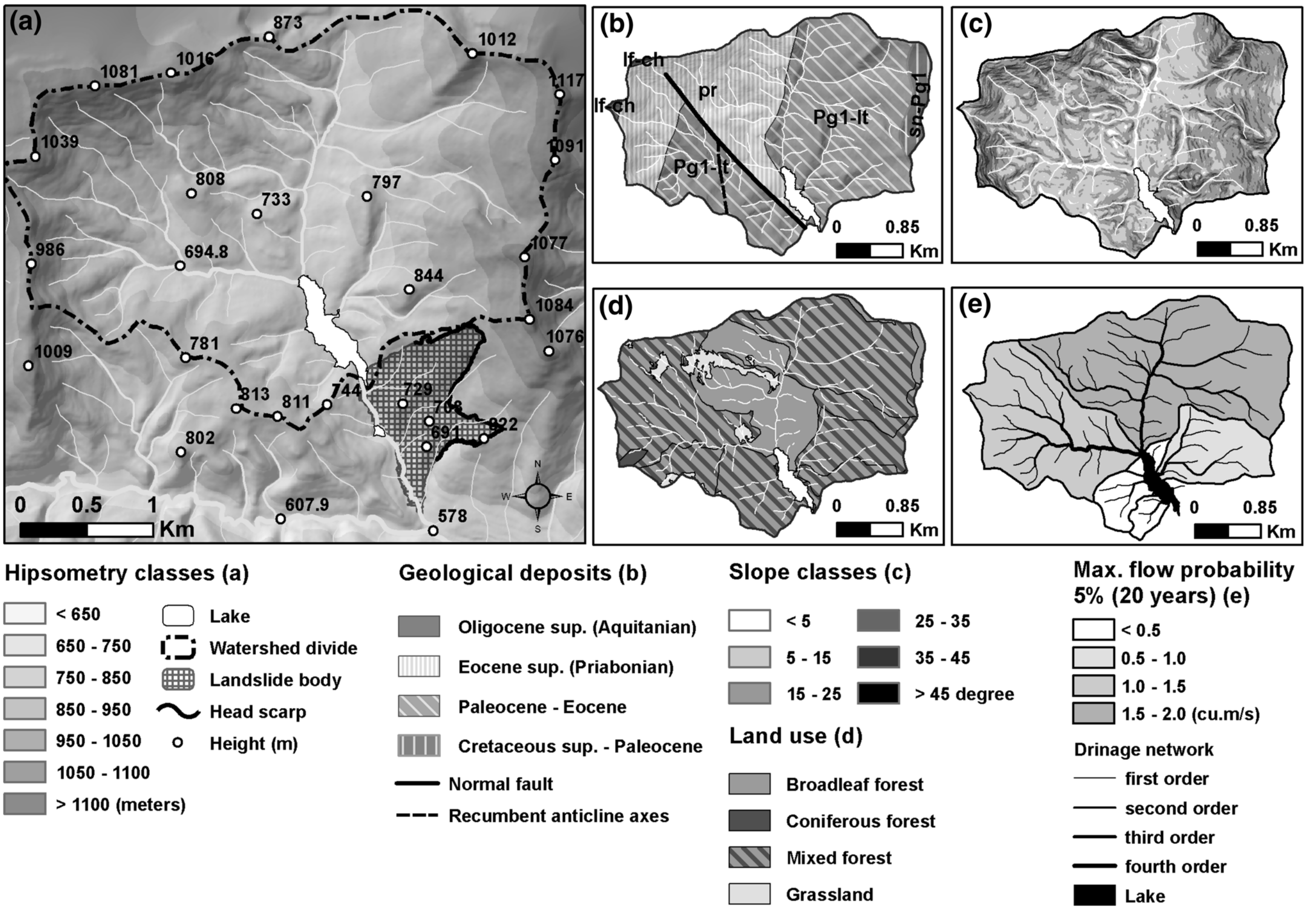


Fig. 3 The reception basin of Lake Cuejdel: **a** hypsometric map; **b** geologic structure; **c** slope map; **d** land use; **e** probability of exceeding the maximum discharge for 20 years (5 %)

spatial coordinates were recorded using a Leica System 1200 and Rover GPS. The measurements were taken in February of 2013, when the lake was mantled by an ice cover measuring 30–40 cm in thickness. Twelve transversal profiles (C.S.) were traced starting from the left shore towards the right one, with lengths ranging from 72 to 228 m, as well as a longitudinal profile (L.S.) of 914 m in length, traced upriver, which intersected all the transversal profiles. For maximum precision, the data was georeferenced in the Romanian national projection system (STEREO 1970), and cross-checked with the GPS readings. As such, the cartographic-projection errors of the GPR profiles were minimised (±2 cm) (Table 2; Fig. 4).

The best results were obtained with a perfectly frozen aquatic surface, since melted ice or snow produces noise. For revealing the alluvial deposits and the lithological structures within Cuejdel Lake, a series of values of the relative permittivity of materials specific to the aquatic environment (*T* °C, pH, LDO 101, CDC 401) were taken into account. Likewise, for verifying the data, four sedimentary core samples (C.1, C.2, C.3 and C.4) were extracted using gravitational coring sample during winter from the intersection of the C.S.1, C.S.5, C.S.8 and C.S.10 transversal profiles with the L.S.13 longitudinal profile. The analysis of the annual non-glacial varves indicated a

Table 2 Characteristics of GPR profiles

No.	Type	Direction	Length (m)	Water depth (m)
1.	C.S.	N–S	91.97	1–3.2
2.	C.S.	E–W	126.67	0.5–7.5
3.	C.S.	E–W	120.16	0.5–9.8
4.	C.S.	E–W	90.76	2.8–9.5
5.	C.S.	E–W	228.07	1–11.3
6.	C.S.	NE–SW	178.76	0.8–12.2
7.	C.S.	NE–W	210.65	1–12.0
8.	C.S.	NE–SW	218.63	0.8–13.8
9.	C.S.	NE–SW	73.28	1–15.1
10.	C.S.	NE–SW	72.03	0.8–14.9
11.	C.S.	E–W	79.13	1.5–12.6
12.	C.S.	E–W	62.85	0.0–3.5
13.	L.S.	SE–NW	914.17	0.2–15.1

C.S cross section, *L.S.* longitudinal section

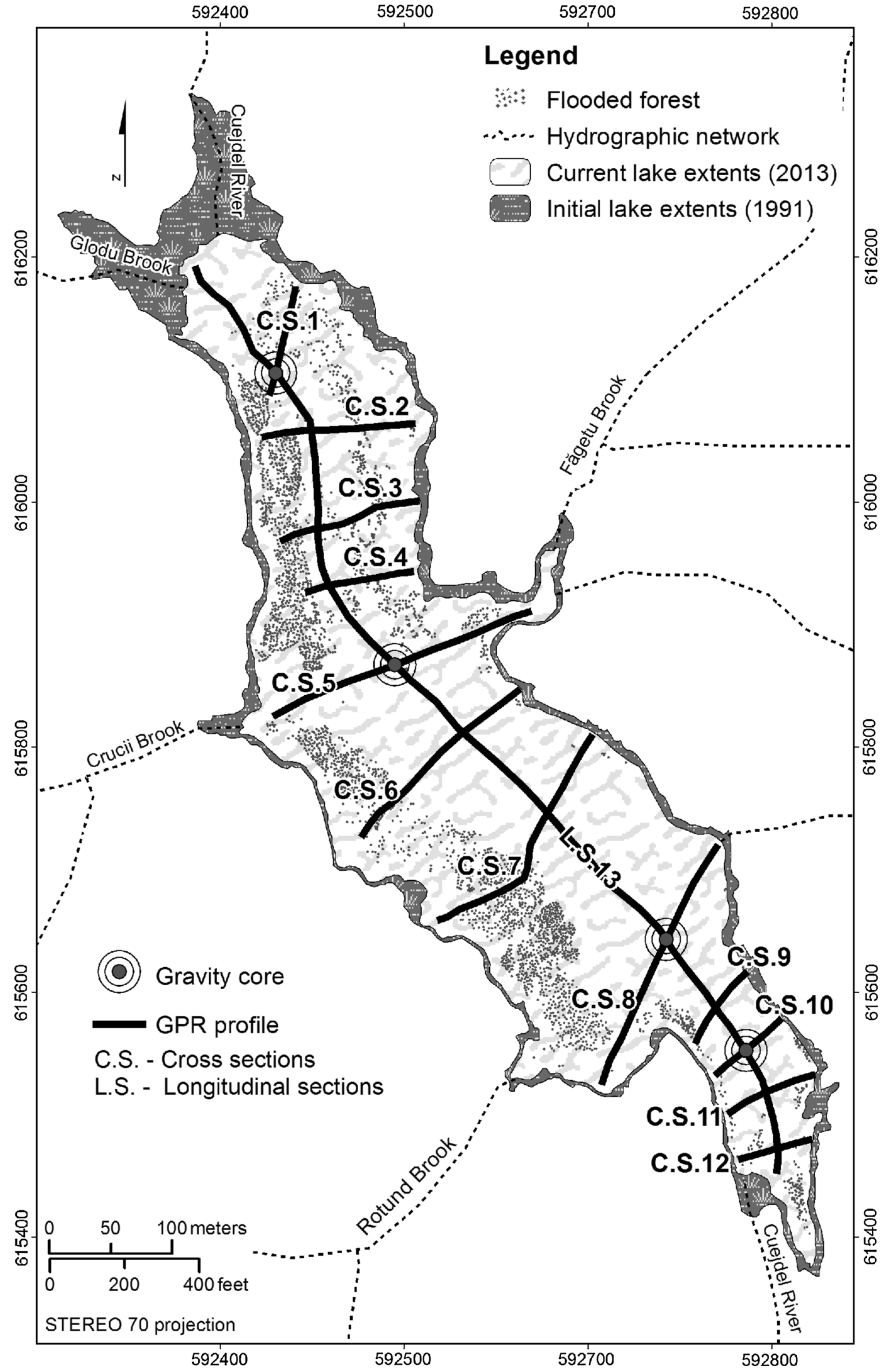


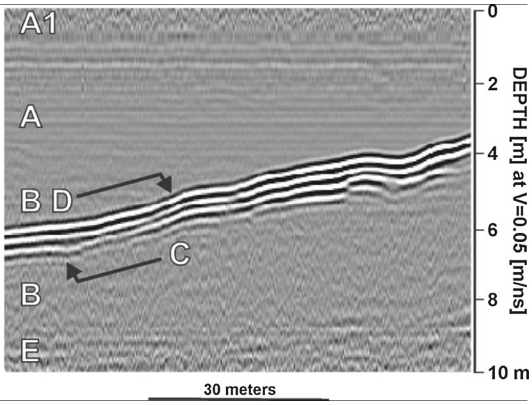
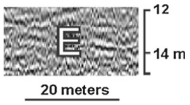
Fig. 4 The network of GPR profiles traced in 2013 across the frozen surface of Lake Cuejdel, and the locations of the core drills

good horizontal stratigraphy, with frequent changes in colour vertical along according to the lithological nature of the sediments. In this case, the value of the permittivity was determined on the basis of the granulometric ratio of the laminations (Ø grain size) and the total organic carbon (TOC) content (Tables 3, 4).

Table 3 Characteristics of gravity core sample points (C.1, 2, 3 and 4—gravity core)

No.	Type	Water depth (m)	Sample thickness (cm)	No. of lamination/sample
1.	C.1	3.50	39.00	16
2.	C.2	11.50	49.00	19
3.	C.3	14.90	47.00	21
4.	C.4	8.50	48.00	17

Table 4 The physical–chemical characteristics of the aquatic [T °C; pH; LDO 101 (mg/L); CDC 401 (mg/L)] and sedimentary [TOC (g/100 g); Ø (mm)] environments in Lake Cuejdel, determined for calibrating the GPR device

No.	Material	O'_s (mS/m)	$\mathcal{E}_{ave}$	TOC (g/100 g)	Ø (mm)	T °C	pH	LDO 101 (mg/L)	CDC 401 (mg/L)
	Air	0	1	–	–	1	–	–	–
A1	Fresh water, frozen	1–0.000001	3	–	–	0.0	8.1	6.5	185–190
A	Fresh water	0.1–10	78–88	–	–	0.0–4.5	7.92–8.08	6.4–0.04	185–380
B	Sand, dry	0.0001–1	3–6	1.05–5.40	<0.004–>0.063				
	Sand, wet	0.1–10	10–30						
C	Soil, dry sandy	0.1–100	4–6						
	Soil, wet sandy	10–100	15–30						
	Soil, dry clayish	0.1–1	4–6						
	Soil, wet clayish	10–100	10–20						
	Soil, dry loamy	0.1–100	4–6						
	Soil, wet loamy	100–1000	10–15						
	Soil, normal	5	16						
D	Clay, dry	1–100	2–20						
	Clay, wet	100–1000	15–40						
E	Limestone, dry	0.001–0.0000001	4–8						
	Limestone, wet	10–100	6–15						
	Sandstone, dry	0.001–0.0000001	4–7						
	Sandstone, wet	0.01–0.001	5–15						
	Schists, saturated	10–100	6–9						

Examples from the reading interface of the Malå Ramac X3M GPR [*O'_s (mS/m)* static conductivity, $\mathcal{E}_{ave}$ relative permittivity (average), *TOC (g/100 g)* total organic carbon in sediments, *Ø (mm)* grain size of laminations, *T °C* water temperature, *pH* in water, *LDO 101 (mg/L)* luminescent dissolved oxygen in water, *CDC 401* standard conductivity of water)

The processing of the data was carried out using the ReflexW software programme, and the images were filtered as follows: dewow the data (all traces, time window = 10 ns); gain the data (all traces, energy decay, scaling values = 1); static correction/move start time (manual, −0.25 ns); band pass filter (different values for each profile); background removal. On the basis of the results, the current thalweg of the lake was traced, along with the thickness of the sediments, the configuration of the initial valley, as well as a series of details concerning the internal geological structures.

Using specific GIS software suites (TNTmips, ArcGIS), the bathymetric information was interpolated, yielding two digital elevation models (DEMs): the first corresponding to the initial configuration (bedrock); the second representing the current shape of the lacustrine depression. The difference between the two models basically represents the thickness of the sediment deposits accumulated in Cuejdel Lake since its formation up until 2013. The results were compared with the initial DEM of the flooded river sector, produced on the basis of the topographic maps (1:10,000, ed. 1981; 1:25,000, ed. 1985).

Result and discussion

The thickness of the lacustrine deposits in Cuejdel Lake varies between 0.1 and 3.6 m, dominated by the 0.8–1.0 m range (Fig. 5a, b). Because it was not possible to trace the transversal profiles C.S.1–4 and C.S.11 from one shore to the other due to the presence of trees projecting above the surface of the ice cover, the minimal value registered on the right shore ranges between just 0.35 and 1.04 m. The maximum thickness of the sediments (>3.0 m) was determined in the case of the transversal profiles C.S.4 (3.2 m), C.S.9 (3.7 m), C.S.11 (3.51 m), and C.S.12 (3.4 m), as well as for the longitudinal profile L.S.13 (3.42 m). The alluvial deposits with intermediary thickness (1–2 m) were determined for all sections, usually found in the central sector of the transversal profiles (indicate a constant progradation along the old watercourse of the Cuejdel River) (Fig. 5c, d).

After interpolating the bathymetric information (on the GPR profiles and from the analysis of the core samples) and running them through the GIS tools (TNTmips, ArcGIS), we produced three DEMs of the lacustrine cuvette.

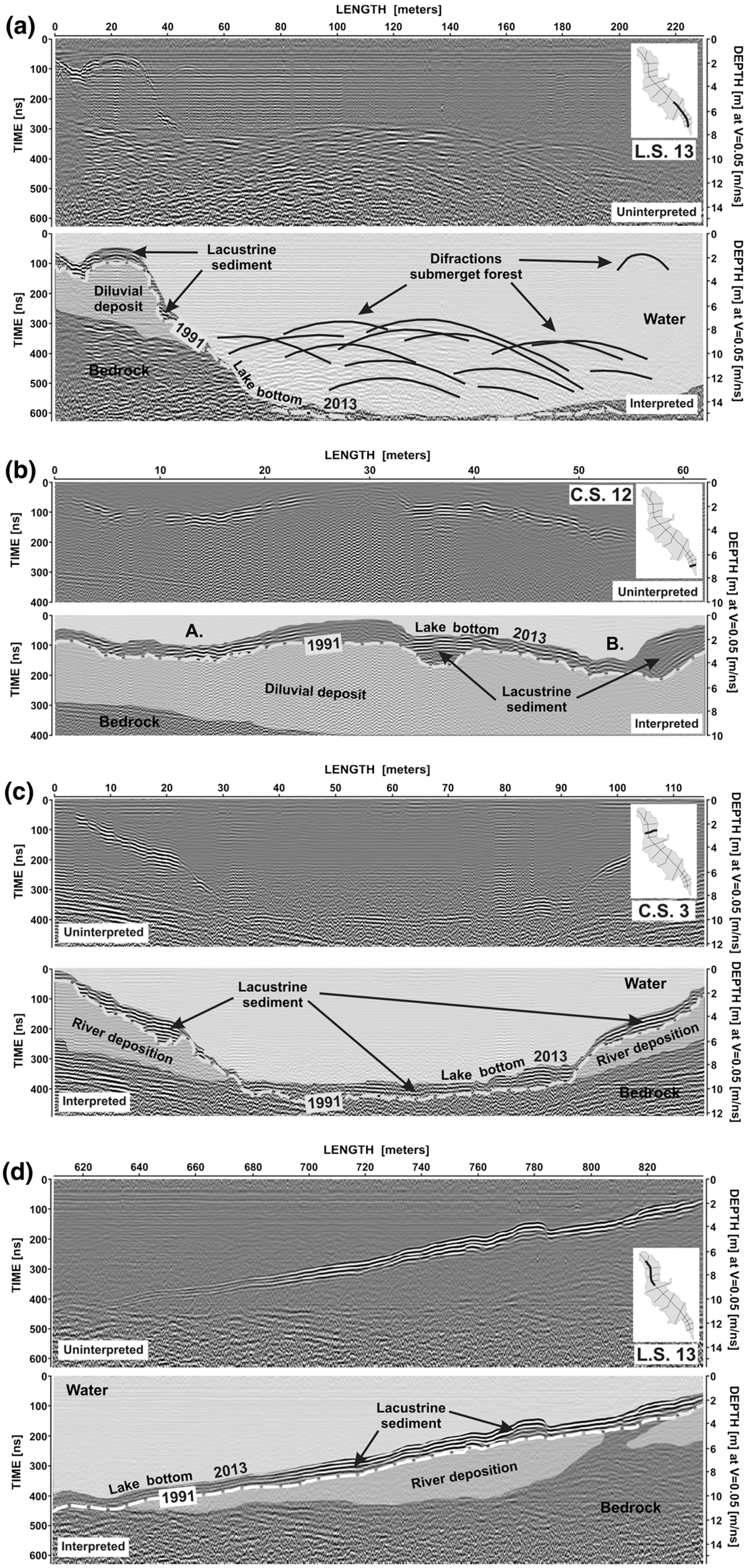


Fig. 5 **a** Interpretation of the GPR images. The L.S. 13 profile (SE–NW alignment, sector 0–230 m), in which the lacustrine sediments, the diluvial deposits (natural dam) and the diffractions induced by the presence of the submerged forest are highlighted; **b** interpretation of the GPR images. The C.S.12 profile (E–W alignment, length 0–65 m), in which the alluvial bank from the area of the lacustrine outlet (maximum thickness) is highlighted. *A* Initial outlet; *B* current outlet; **c** interpretation of the GPR images. The C.S. 3 profile (E–W alignment, length 0–105 m). The lacustrine sediments and alluvial deposits of the Cuejdel River that was submerged/flooded after the formation of the lake are highlighted; **d** interpretation of the GPR images. The L.S. 13 profile (SE–NW alignment, sector 610–840 m). The lacustrine sediments and alluvial deposits of the Cuejdel River that weas submerged/flooded after the formation of the lake are highlighted

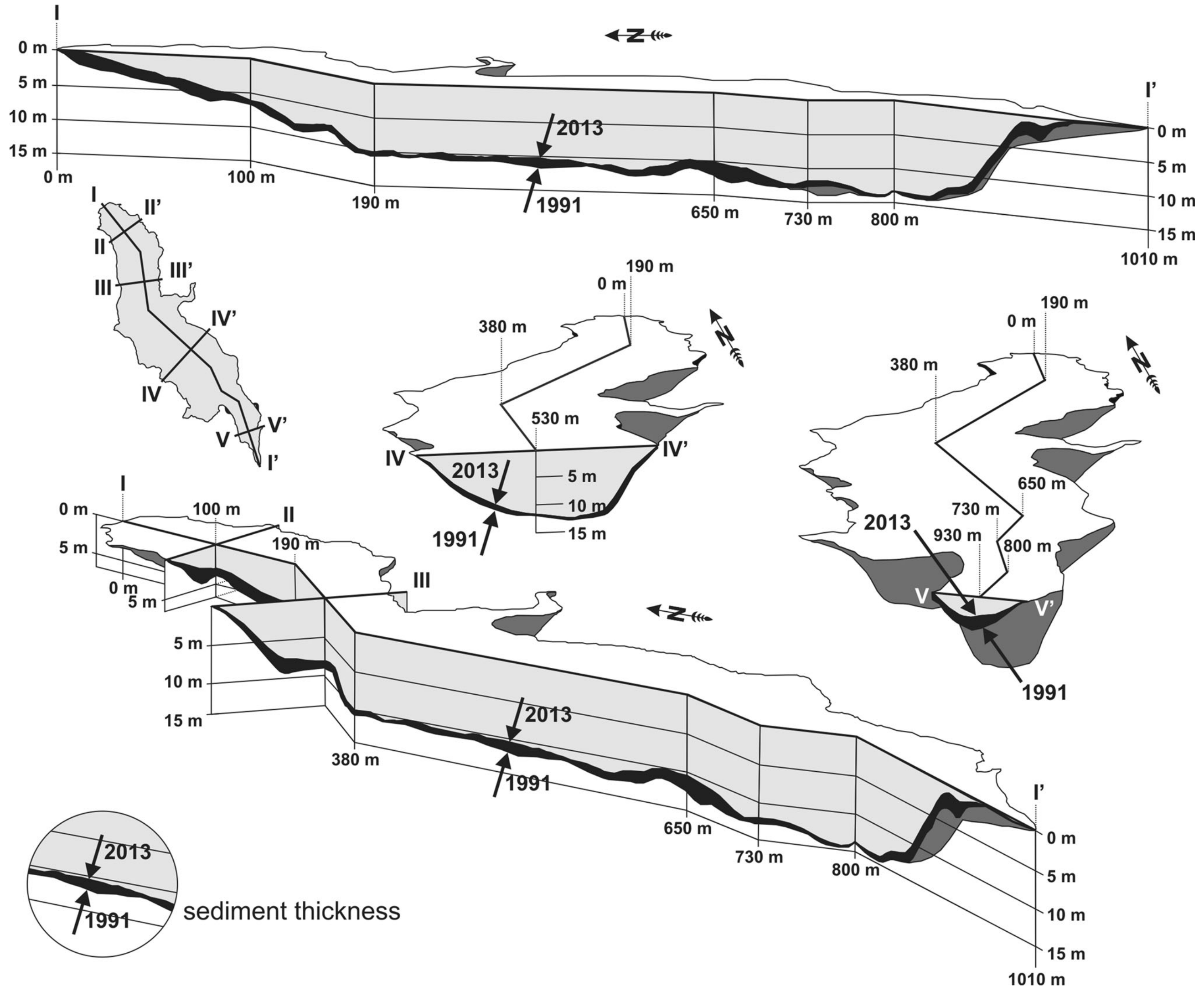


Fig. 6 3D sections across the cuvette of Lake Cuejdel, with the thickness of the sediments marked by removing DEM 2013 from DEM 1991

The first bathymetric model corresponds to the initial configuration (DEM 1991), respectively, the sector of the valley under water. The second model shows the current shape of the lacustrine depression (DEM 2013); in this case, the bathymetric map produced by the echo sounder in 2011 (DEM 2011) was also used for reference. The difference between the two models represent the thickness of the sediment deposits accumulated in Cuejdel Lake since its formation (1991) until 2013 (Fig. 6).

According to the hypsometric integral, which represents graphically the relation between the depth and the surface of the isobaths specific to different stages of the lacustrine basin's evolution, at the moment of the measurements (DEM 1991, 2011 and 2013), the lake displays a normal tendency towards morphological equilibrium. If at the moment the body of water accumulated over an uneven terrain (1991) the integral presented a hypsometric profile with thresholds corresponding to the abrasion terraces hewed by the first lake, 22 years later the lake's floor had a different configuration on account of permanent alluvial accumulations and accretions processes. In 2013, the curve of the hypsometric integral indicated a more balanced slope, since the measurements were taken during winter, when the ice cover instils a reduced morphodynamic state.

The hypsometric curve or the ratio between the surface of the isobaths/depth (%), respectively, the accumulated volume/depth (%), indicate for 1991 a linear surface/depth ratio [$f(0.5)$–$f(1.5)$], equivalent to a relatively steady shape, and a convex volume of water/depth ratio [$f(-0.5)$–$f(-1.5)$]. These values betray the presence of thresholds in the 10–16 m bathymetric level, most probably induced by the shores of the minor bed of the old watercourse. Presently, the most important changes occurred only at the level of the isobaths' surfaces as a consequence of constant water

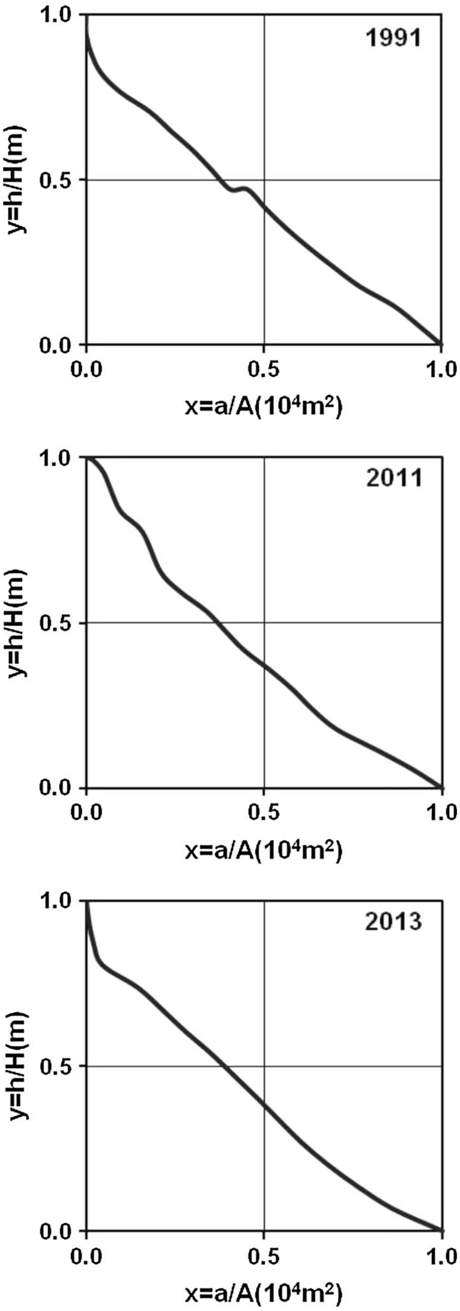


Fig. 7 The hypsometric integral of the Cuejdel lacustrine cuvette according to DEM 1991, DEM 2011 and DEM 2013 [oY axis: $y = h/H$, h the depth of the bathymetric points in a transversal profile (m), H maximum depth of the lake (m); oX axis: $x = a/A$, a relative surface of the isobaths (m), A surface area of the 0 m isobath]

loss, with the slightly convex shape of the hypsographic curve [$f(0.5)$–$f(-0.5)$] indicating a decrease of the lacustrine floor by compared to the total surface. In what concerns the ratio between the total volume of water and the current bathymetric levels, even if during the 22 years of the lake's evolution there have been some changes, they occured only in terms of values, but not proportions (Fig. 7).

The thicknesses of the lacustrine sediments from Lake Cuejdel have the following ranges: 0.1–1.0 m (8.522 10^4 m^2, 60.7 %); 1.0–2.0 m (4.676 10^4 m^2, 33.32 %); >2.01 m (8326.5 m^2, 5.93 %). In the most representative range (0.1–1.0 m), the thickness of sediments between 0.8 m and 1.0 m predominate (2.596 10^4 m^2), followed by the thickness from 0.6 to 0.8 m (2.915 10^4 m^2), and 1.0 to 1.2 m (2.04 10^4 m^2). In total, the 0.4–1.4 m range hold 9.984 10^4 m^2 (71.16 %), while deposits with extreme thickness are limited (0.1–0.4 m: 63.25 m^2; 3.2–3.6 m: 132.5 m^2). The sectors with alluvial thickness up to 1.0 m are principally found in the littoral area corresponding to the right versant, between the outlets of the Glodu and Rotund brooks. The low values of the sedimentary accumulation are due to the submerged versants with reduced slopes (5°–15°) and to the high density of trees in the water. The western shoreline, entirely covered by forest, as well as the low fragmentation of the versants, are conducent to weak erosional processes.

In the area of the mouth of the Piciorul Crucii brook, the alluvial deposits are being pushed towards the old confluence with the Cuejdel brook. A similar situation is also found on the left versant of the lake, between the outlets of the Cuejdel and Făgetu brooks. In general, the lake's versants have limited lengths, and this determines the wash of the alluvia on the background of level oscillations, and their transportation towards the deeper area. The average value of terragenous accumulation is 2.1–4.3 cm/year. Reduced thicknesses of the alluvial deposits are also found in the area of the Făgetu (0.1–0.5 m) and Rotund (0.4–1.0 m) brooks, which reveal an intense erosional activity. The valleys of the two tributaries have high declivities (15°–18°), which continue until the middle of the lake through submerged versants (with slopes >35°). For this reason, the sediments are transported by the lateral currents and deposited in the old bed of the Cuejdel brook. In the area of the Făgetu brook, where the lake's main current receives the lateral ones, the high turbidity forms small circular micro-depressions where the thickness of the alluvia is just 0.2 m, as also confirmed by the C.2 core sample. The average clogging rate in these sectors does not exceed 1 cm/year.

The areas with the thickest lacustrine sediments were identified in the upper sector of the lake, along the right bank generated by the north-western versant of the Rotund Spur, in the area with maximum depths, as well as on the submerged surface of the dam, respectively, to the left of the current outlet. The alluvia introduced into the lake by the Glodu and Cuejdel brooks form, at the tail of the lake, an alluvial fan with thicknesses ranging from 1.5 to 3.6 m. The alluvia are propagated along the initial valley, up to near the old confluence with the Făgetu brook. The elongated shape of the deposits along a N–S alignment indicate

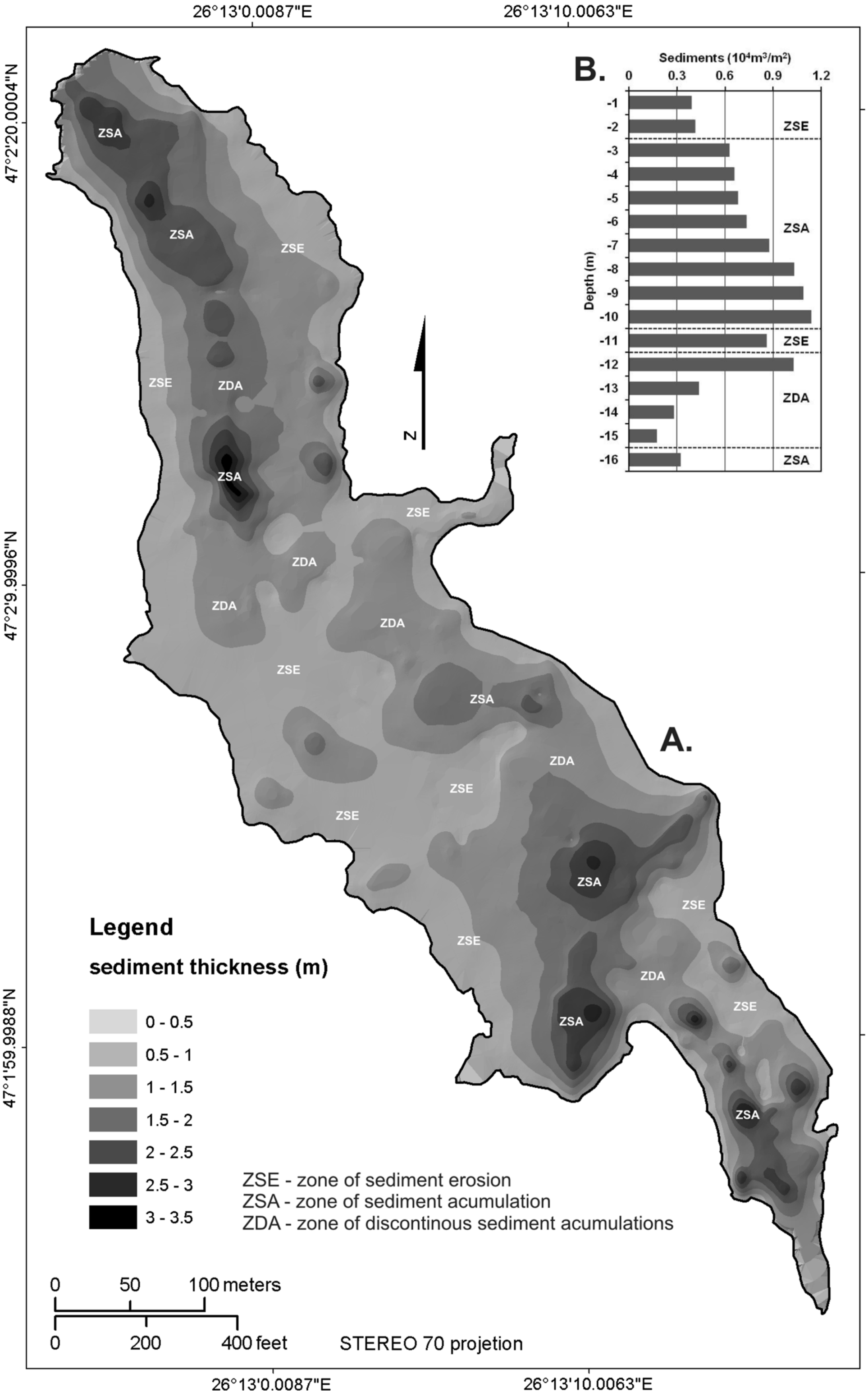


Fig. 8 *A* Map of thickness of the sediments (m) accumulated in Lake Cuejdel since its formation until 2013 (22 years); *B* distribution of sediments (104m3/m2) along bathymetric intervals (−1 m), indicating: *ZSE* zone of sediment erosion, *ZSA* zone of sediment accumulation, *ZDA* zone of discontinuous sediment accumulation (zone of transportation)

the absence of trees on the lacustrine floor. The average rate of sedimentation in this sector is 6.5–15.5 cm/year.

In the sector with maximal depths (12–15 m) and on the right versant of the valley generated by the Rotund brook, the thickness of the deposits is 1.8–3.2 m. The accumulation occurs on the background of the torrential activity on the right versant, amplified by the short banks along the entire eastern slope. The transversal shape of the alluvial bank, on the SE–NV alignment, is due to the general direction of the currents and to the versants with high declivity (35°–50°). The average rate of accumulation of sediments in this sector is 9–10 cm/year, reaching 15 cm/year in the sector with depths >14 m.

The sector in front of the dam has a complex morphology, engendered by the diluvial materials deposited haphazardly on the floor of the lacustrine depression. This is why the thickness of the alluvial deposits range considerably (0.4–36 m), and the annual rate of sedimentation reaches 16 cm/year. The high thickness of the alluvial deposits is due to the steep versants (>45°), from the surface of which mud lobes often detach and slide to the lacustrine floor. The solid charge transported along the main current is deposited at the base of the dam, forming a consistent alluvial bank.

The rate of accumulation of lacustrine sediments is 1–16 cm/year; extreme values are found only in limited areas. The most frequently encountered values belong to the 3.5–5 cm/year range, which indicate the highest share of some alluvial deposits accumulated in 23 years, 0.8–1.15 m thick. Along bathymetric levels, the volume of sediments ranges from 33.6 to 440.4 m^3/year. These values are influenced by the surface of the versants located between two isobaths with an equidistance of 1 m (area 2D). The average volume of sediments accumulated on the surfaces between 1 and 1.2 ha is 300–450 m^3/year (Fig. 8).

The volume of sediments existing in Lake Cuejdel was estimated by adding up all the partial volumes resulting from the subtraction of two bathymetric models. Thus, from 1991 until the winter of 2013, the lake accumulated 103,988.87 m^3, which represent 8.5 % of the initial volume (1,223,001.33 m^3). The average annual rate of collimation is around 4521.26 m^3/year (0.36 %/year).

Conclusions

Collection and interpretation of data obtained through the use of the GPR and the echo sounder is a first for hydrogeomorphological research in Romania. Previous studies relied solely on indirect methods for estimating the soil erosion at the level of the reception basin and the solid transport in natural reservoirs. The quantity of sediments estimated through the GPR method, in the case of Lake Cuejdel, is greater by +28,352.94 m^3 (+1232.68 m^3/year) than that determined through arithmetic means at the level of the reception basin (USLE) (Wischmeier and Smith 1962, 1978). Thus, the indirect method proves to be inefficient for detailed analyses, since it underestimates the sedimentary budget and, implicitly, the solid transport. For this reason, the erosion at the level of the reception basin and the rate of alluvial effluence into the lake, determined from direct measurements, is 4.3346 t/ha/year. The difference of ±1.307 t/ha/year between the direct methods presented in these pages and the indirect ones can be explained either by an underestimation of the sediment production values of a process, either by failure to include existing processes into the classical USLE formula.

The Cuejdel dam lake is the largest of this category of lacustrine accumulations from the Carpathian Mountains. Its status as protected area implies certain restrictions in what concerns the hydrotechnical development of the cuvette and, implicitly, of the catchment basin. The non-invasive methods applied for bathymetric charting and evaluating the rate of colmation have proven to be efficient for assessing these parameters without disturbing the natural habitats of the limnosystem. If the use of the echo sounder is a classical method for investigating lacustrine cuvettes, the GPR technique is a new tool for limno-geomorphologic charting. Nevertheless, the validation of the results was only made possible by the conjoint use of these two methods. We regard this model to be very efficient and precise for researching small anthropic lakes with receptions basins <10 km^2.

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