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ESTIMATING SPATIAL AND TEMPORAL PATTERNS OF RECENT SEDIMENTATION UNDER CHANGING HYDRODYNAMIC CONDITIONS, IN THE LOPATNA-MATITA-MERHEI INTERDISTRIBUTARY DEPRESSION, DANUBE DELTA, ROMANIA

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Abstract. Deltaic environments are shaped by the sediment accumulation in lacustrine and marine depositional settings, reflecting the transition between the river basin and the marine basin. Representing a distinct component within the Danube Delta Biosphere Reserve, the *Lopatna-Matita-Merhei* interdistributary depression represents a good example for the environmental exposure to several stressors, both natural and anthropogenic. This study aimed to identify to what extent the natural and anthropogenic factors may be related to the recent sedimentation in this specific depositional environment. The investigated lakes within the interdistributary depression are located in the distal part of the fluvial delta, being less impacted by the upstream input of water and sediment brought by the Danube River. Upstream freshwater and alluvial load are differentially reflected in the delta's interdistributary depressions along the main and secondary hydrographic network of the Danube River. To corroborate and enhance previous investigations related to aquatic sediments in the deltaic area, this study was performed to assess the impact of alluvial supply (water and sediments) in the case of a considerable naturally and/or anthropogenically influenced aquatic ecosystem in the Danube Delta, Romania. Gaining insights from the lacustrine sedimentation patterns on different environmental stressors is important for the conservation value of the shallow-water delta lakes that are vulnerable to clogging/siltation, as well as for the assessment of delta resilience under future conditions.
Keywords: core, delta, lake sediments, patterns, sedimentation

1 INTRODUCTION

Globally, river deltas are areas of high importance, for economic, social and environmental reasons, providing food, supporting economies, sustaining biodiversity and being home to many people (Vörösmarty *et al.,* 2009). Equally important to mention, the river deltas are subject to climate changes expressed as pollution, urban expansion, flood and droughts, land subsidence, coastal erosion, decrease of sediment flow and overall loss of environmental quality and biodiversity (Syvitski *et al.,* 2009). For this reason, maintaining an adequate quality and quantity of the river water and sediment supply plays a determinant role across the entire delta edifice. Transported organic and inorganic matter varies across the delta landscape due to river water level, and hydrological connectivity. Sediments are essential for understanding and deciphering environmental issues as a consequence of its interconnections with physical, chemical and biological processes (*i.e.,* water quality impairment, eutrophication, chemical pollution, sedimentation and silting) in aquatic ecosystems (Forsberg, 1989). The climate changes (*i.e.*, long-term shifts in temperatures and weather patterns) alongside the anthropogenic events have already left their mark in the environmental landscape, triggering impacts in aquatic ecosystems (Plagányi É., 2019).

The Danube Delta covers an area of about 3510 km^2 (on the Romanian territory), it is the second largest in Europe (after the Volga River) and the twentieth in the world in terms of the landscape richness, coastal environment, as well as for flora and fauna species (Gâștescu & Știucă, 2008). It was internationally attested, as *i)* Biosphere Nature Reserve MAB UNESCO (within the "Man and the Biosphere" Program), *ii)* UNESCO World Heritage Sites and *iii)* Wetland of International Importance, due to its biological diversity, particularly for waterfowl (Ramsar Convention, 1987). Nowadays, the biodiversity loss and the degradation of the ecosystems within the Danube Delta region can occur at a much faster rate, due to the environmental factors such as climate change. In addition, a large number of anthropogenic stressors as the reduced influx of freshwater from the Danube River, the reduction in sediment supply occurring downstream (due to dams' obstructions), coastal erosion (Panin *et al.*, 1999), pollution (domestic, agricultural and industrial sewage) and over-exploitation of fish resources can affect the resilience capacity of the Danube Delta. In this context, this study was performed to assess the impact of alluvial supply (water and sediments) in the case of a considerable naturally and/or anthropogenically influenced aquatic ecosystem in the Danube Delta, Romania. Consequently, the main objective of the present study was to investigate the main lithological components (*i.e.*, total organic matter - TOM%, total carbonates - TCAR%, siliciclastic fraction - TSIL%) and their spatial accumulation and distribution in response to changing hydrodynamic conditions. Thereby, several sediment cores were extracted from various aquatic ecosystems belonging to the *Lopatna-Matita-Merhei* interdistributary depression. Gaining insights from the lacustrine sedimentation patterns by reason of different environmental stressors is important for the conservation value of the shallow-water delta lakes that are vulnerable to clogging/siltation, as well as for the assessment of delta resilience under future conditions.

2 MATERIALS AND METHODS

2.1 Study area

The studied lakes belonging to the *Lopatna-Matita-Merhei* interdistributary depression are located in the northern part of the fluvial Danube Delta plain, between *Chilia* and *Sulina* Danube's branches, in a low-energy hydrodynamic area, less influenced by the Danube River alluvial input (Fig.1). The relationship between input and output of the water across this interdistributary depression depends on the Danube River regime, specifically in the course of the summer-autumn period (Gâștescu & Știucă, 2008). The most significant supply and drainage channels are represented by *Eracle*, *Lopatna*, *Dovnica*, *Răducu*, *Bogdaproste*, *Sulimanca* and *Roșca* (Bondar & Panin, 2000). The investigated lakes within this study are categorized as very shallow lakes (maximum depth of 3 m), but with a wide water area (large aquatoriums), as follows: *Merhei L.* (1057.5 ha), *Merheiul Mic L., Ciorticuț L., Rădăcinoasele L., Babina L.* (432 ha), *Matița L.* (652.5 ha), *Miazăzi L., Polideanca L., Șerbata L., Rădăcinos L., Trei Ozere L.* (437 ha) and *Bogdaproste L.* (435 ha).

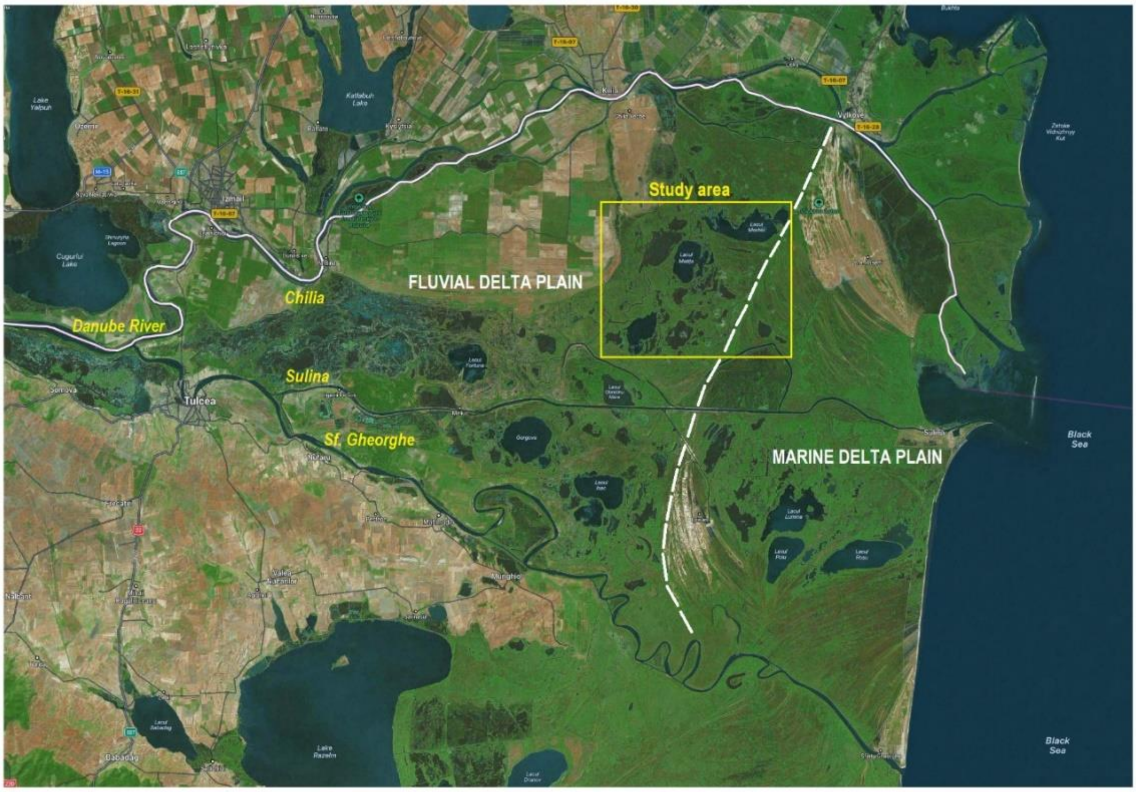

Figure 1. Map of the study area under investigation (https://satellites.pro/Romania_map)

2.2 Coring and Core Analysis

Sedimentary data for this study were acquired from a total number of 35 gravitational cores collected in different years (2010, 2011, 2013, 2014, 2016, 2020 and 2023), within *Lopatna-Matita-Merhei* unit (Fig. 2) as follows: *Matița L.* (7 cores), *Babina L.* (6 cores), *Ciorticuț L.* (1 core), *Rădăcinoasele L.* (1 core), *Miazăzi L.* (2 cores), *Polideanca L.* (1 core), *Merhei L.* (3 cores), *Merheiul Mic L.* (1 core), *Bogdaproste L.* (4 cores), *Șerbata L.* (1 core), *La Amiază L.* (1 core), *Trei Ozere L.* (4 cores) and *Rădăcinos (Covaliova) L.* (3 cores) (Fig. 1). The sediment cores were retrieved using an integrated water sampler Hydro-Bios gravity corer, with a transparent plastic tube. The cores, ranged in short length from ~24 cm to ~64 cm, due to very soft, unconsolidated fine-grain sediments which is typical for the investigated freshwater lake (lacustrine) deposits. Short cores were split in the on-board laboratory, and sectioned into 2 cm for physical characteristic descriptions (color, structure, texture, grain size, sorting, stratification, the main lithoclast/bioclast elements) and further laboratory analysis. Bottom sediment samples from the muddier layers of all short cores were placed into plastic recipients (100 g) and stored at lower temperatures (4˚C) for preanalytical phase and further laboratory analysis.

The preanalytical phase was related to percent moisture content of the core sediment sub-samples which were oven-dried at 105°C (Memmert Etuve) using the Loss On Drying (LOD) method (Smith & Mullins, 2000; ASTM-D2216/2010). Next, the core sub-samples were exposed to sequential heat (Snol 8.2/1100 Laboratory Furnace) at different temperatures by Loss On Ignition (LOI) method (Dean, 1974) and measuring the weight loss between heating stages. For example, the estimation of the total organic matter was acquired by burning the core sediment sub-samples at 550°C (Bengtsson & Enell, 1986; Beaudoin, 2003; Boyle, 2001; Boyle, 2004). Further on, the percent mass loss during calcination of sub-samples at 950°C-1000°C (Digerfeldt *et al*., 2000; www.geog.cam.ac.uk) was related to the total carbonate content (TCAR%). Finally, the leftover sediment mass is overall attributable to siliciclastic/minerogenic/detrital fraction (TSIL%) content. The results were identified as percentages of the total sediment sample's mass.

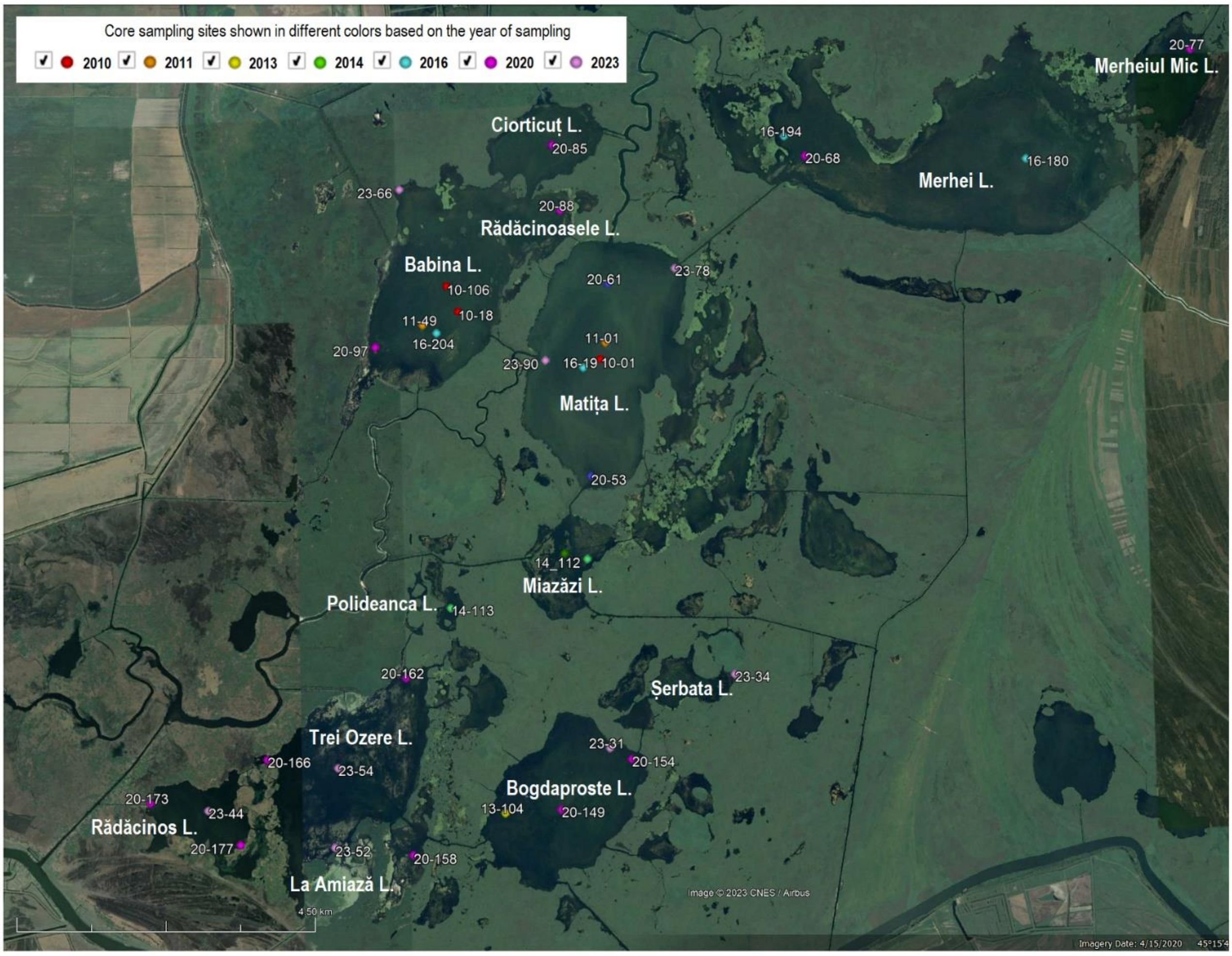

Figure 2. Map of the *Lopatna-Matita-Merhei* interdistributary depression, viewing the location of the investigated sediment cores with sampling sites shown in various colored marks (http://www.google earth.com map)

3 RESULTS AND DISCUSSIONS

Mostly, the aquatic sediments (porous, soft, or lithified) contain three main constituents *i.e.,* organic matter, carbonate, and siliciclasts that establishes their solid fraction (Ricken, 1993). This study aimed to identify the lithological characteristics (*i.e.,* TOM-%, TCAR-%, TSIL-%) of core sediments by using the LOI (Loss on Ignition) method. This method has a good potential to provide a rapid percentage estimation related to the total organic matter, total carbonates and siliciclastic constituents from each investigated core sediment samples. The cores were collected from the *Lopatna-Matita-Merhei* interdistributary depression that is located in the distal part of the fluvial delta, being less impacted by the upstream input of water and sediment brought by the Danube River. Upstream freshwater and alluvial load are differentially reflected in the delta's interdistributary depressions along the main and secondary hydrographic network of the Danube River. In this study, the percentage content (%) of the main lithological components (TOM%, TCAR%, TSIL%) significantly ranged among the investigated sampling sites in terms of their geographical coordinates and primarily lithological composition. The results are summarized in the accompanying table (Table 1), and presented as ternary diagrams (Fig. 3), as well as spatial distribution of the investigated cores (Fig. 4, 5).

Total organic matter (TOM %). In general, the organic matter content in sediments is considered an environmental indicator for the assessment of the quality of lake ecosystems from various perspectives. Thereby, it could be directly linked to the supply of food to the benthos communities (Fernández-Rodríguez *et al.,* 2019), plant nutrient availability (Tranvik *et al.,* 2009), crop production, impacting the physical-chemical circumstances of the sedimentary substrate, as well as the immobilization and mobilization capacity of different contaminants (Xu *et al.,* 2015). In addition, within the framework of a lacustrine basins, that are recognized as highly productive systems, the major contribution of the organic matter can be appreciated in terms of allochthonous and/or autochthonous origin, serving to assess the impact of anthropogenic activities on aquatic ecosystems (He *et al.,* 2020). The results obtained in this study were compared to a conventional systematization (Perrin, 1974; Tate, 1987; Van der Veer, 2006), that integrates two main types of sediments, according to the percentage of the organic matter content, as: *mineral sediments* (≤15-30% organic matter), and *organic sediments* (≥15-30% organic matter). In general, the investigated cores from the entire suite of the lakes were characterized by a high vertical increase of the total organic matter content with values more than 30% of the total weight of the dry residue, excepting three cores (DD10-01, *Matița* L., mean value = 15.85 TOM%; DD20-88, *Rădăcinoasele* L., mean value = 9.19 TOM% and DD20-158, *La Amiază* L., mean value = 20.19 TOM%) (Table 1, Fig. 3, 4, 5). The high values of the TOM (%) content can most likely be attributed to lacustrine transitional environment conditions that characterized the *Lopatna-Matita-Merhei* interdistributary depression. Being located at a distal part from the direct alluvial input of the Danube River, these lacustrine habitats are generally characterized by relatively stable conditions of the main physical- chemical parameters of water, and relatively passive water currents, adequate for abundant vegetal development (autochthonous biomass), in contrast to fluvial-lacustrine environments, which are characterized by expansive variations in these conditions.

Total carbonates (TCAR%). The carbonate content of the sediment is considered an environmental indicator with applications in different research areas (*i.e.,* paleoenvironmental and depositional biogeochemical conditions), being able to provide a beneficial recording of the environments of their formation and ulterior diagenesis (Clayton & Degens, 1959; Zhao *et al.*, 2016). In general, carbonates in sediments are attributable to biogenic (*i.e.,* hummus, plant residues, biogenic wastes) or abiogenic structures (*i.e.,* calcite, aragonite) (Kennedy & Woods, 2013). The results obtained from this study were related to a classification scheme (Emelyanov & Shimkus, 1986), comprising three main types of sediments: *non-carbonated sediments* ($CaCO_3 \leq 10\%$), *low calcareous sediments* ($10\% < CaCO_3 \leq 30\%$) and *calcareous sediments* ($30\% < CaCO_3 \leq 50\%$). The inter-comparison between the investigated cores revealed a remarkable downcore variation along the vertical profile of the total carbonates' contents in the core-sediments. Thereby, in the entire interdistributary depression, the carbonate content values (TCAR%) fell within the spectrum of the 3 types of the above-mentioned classification sediments. So, from the total number of 35 investigated sediment-cores, 18 cores covered the interval of *non-carbonated sediments* ($CaCO_3 \leq 10\%$), 16 cores belonged to *low calcareous sediments* ($10\% < CaCO_3 \leq 30\%$) and 1 core is included in the *calcareous sediments* category ($30\% < CaCO_3 \leq 50\%$) (Table 1, Fig. 3, 4, 5). In spite of that, it is difficult to draw a complete picture of the spatial patterns of total carbonates distribution in lakes.

Table 1. The percentage concentrations (%) of the main lithological constituents

No. Crt.	Lake	Core index	Core length (cm)	Number of samples	Lithological components of core sediments								
					TOM (%)	TCAR (%)	TSIL (%)						
					Min	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*
1	*Matița*	DD10-01	55 cm	n = 27	4.62	55.58	15.85	12.15	41.32	22.94	21.80	83.14	61.21
2		DD11-01	53 cm	n = 23	11.81	85.69	58.11	7.42	27.95	14.70	6.27	68.97	27.19
3		DD16-19	48.5 cm	n = 26	3.34	77.27	39.58	10.57	37.30	19.16	12.16	78.68	41.27
4		DD20-53	46 cm	n = 23	9.49	64.10	46.65	9.52	55.37	17.27	2.75	76.04	36.07
5		DD20-61	62 cm	n = 31	34.64	82.65	58.69	9.84	24.19	15.57	6.48	46.63	25.74
6		DD23-78	54 cm	n = 27	34.46	82.79	57.94	8.13	27.63	18.19	5.72	46.08	23.87
7		DD23-90	42 cm	n = 21	21.20	65.03	40.36	4.71	64.75	13.32	9.90	63.74	46.32
8	*Babina*	DD10-18	55.5 cm	n = 25	3.13	69.69	29.85	2.76	71.36	10.43	8.56	91.83	59.72
9		DD10-106	44.5 cm	n = 21	10.43	79.66	55.55	2.26	21.57	12.45	9.06	86.21	32.01
10		DD11-49	38 cm	n = 15	6.48	83.07	34.78	9.00	21.17	12.81	7.92	82.63	52.42
11		DD16-204	57 cm	n = 28	17.20	83.37	65.29	1.44	11.54	6.49	7.30	81.14	28.22
12		DD20-97	40 cm	n = 21	12.85	80.62	57.84	2.04	7.95	5.55	13.77	85.11	36.62
13		DD23-66	36 cm	n = 18	18.55	82.18	48.60	5.65	9.60	8.02	9.11	73.33	43.39
14	*Ciorticuț*	DD20-85	60 cm	n = 30	17.23	92.20	40.74	2.23	39.73	15.84	4.89	62.01	43.42
15	*Rădăcinoasele*	DD20-88	46 cm	n = 46	72.40	91.51	83.46	1.84	20.09	9.86	4.50	9.52	6.67
16	*Miazăzi*	DD14-104	45 cm	n = 22	62.18	90.65	84.84	1.83	13.49	4.95	5.17	27.55	10.21
17		DD14-112	44 cm	n = 21	9.19	88.06	58.98	1.90	11.87	5.13	9.07	80.63	35.89
18	*Polideanca*	DD14-113	24 cm	n = 12	49.74	84.11	72.92	1.50	4.77	2.83	14.39	45.49	24.24
19	*Merhei*	DD16-180	43 cm	n = 21	13.35	84.94	67.38	11.06	19.56	13.88	3.86	70.77	18.74
20		DD16-194	37 cm	n = 18	24.59	87.30	63.63	1.63	10.54	4.20	7.58	64.87	32.17
21		DD20-68	46 cm	n = 23	3.89	84.51	39.04	3.88	14.21	8.82	10.29	82.39	52.14
22	*Merheiul Mic*	DD20-77	46 cm	n = 23	1.64	95.12	69.67	2.59	19.75	10.26	2.29	89.62	20.07
23	*Bogdaproste*	DD13-104	48 cm	n = 24	3.10	82.97	49.80	3.19	34.49	9.56	7.03	87.69	40.64
24		DD20-149	43 cm	n = 21	4.44	86.71	49.40	1.56	17.16	8.31	6.96	81.25	42.29
25		DD20-154	64 cm	n = 32	3.97	85.17	53.61	2.32	14.46	7.36	8.80	93.17	39.03
26		DD23-31	38 cm	n = 19	9.86	87.98	46.62	1.50	11.99	5.16	7.53	79.40	48.22
27	*Şerbata*	DD23-34	38 cm	n = 19	12.02	96.14	54.23	0.79	12.11	5.07	2.99	76.76	40.70

28	*La Amiază*	DD20-158	46 cm	n = 40	2.15	52.63	20.19	3.55	46.68	21.85	24.31	92.12	57.96
29	*Trei Ozere*	DD20-162	52 cm	n = 26	64.03	88.21	76.28	1.76	13.17	6.67	10.02	26.55	17.05
30		DD20-166	43 cm	n = 22	13.65	85.17	43.07	2.78	7.50	3.67	11.68	83.23	53.26
31		DD23-52	30 cm	n = 15	59.60	91.99	84.93	1.42	9.09	3.11	6.58	35.80	11.96
32		DD23-54	46 cm	n = 23	28.72	84.11	60.44	4.03	15.25	7.78	6.34	66.12	31.78
33	*Rădăcinos*	DD20-173	47 cm	n = 24	25.61	88.91	67.44	2.16	6.90	3.79	7.77	71.04	28.77
34		DD20-177	49 cm	n = 25	39.89	88.37	72.20	2.28	33.21	5.81	5.40	57.03	21.99
35		DD23-44	46 cm	n = 23	51.51	88.47	73.97	1.27	13.80	5.40	9.21	43.25	20.62

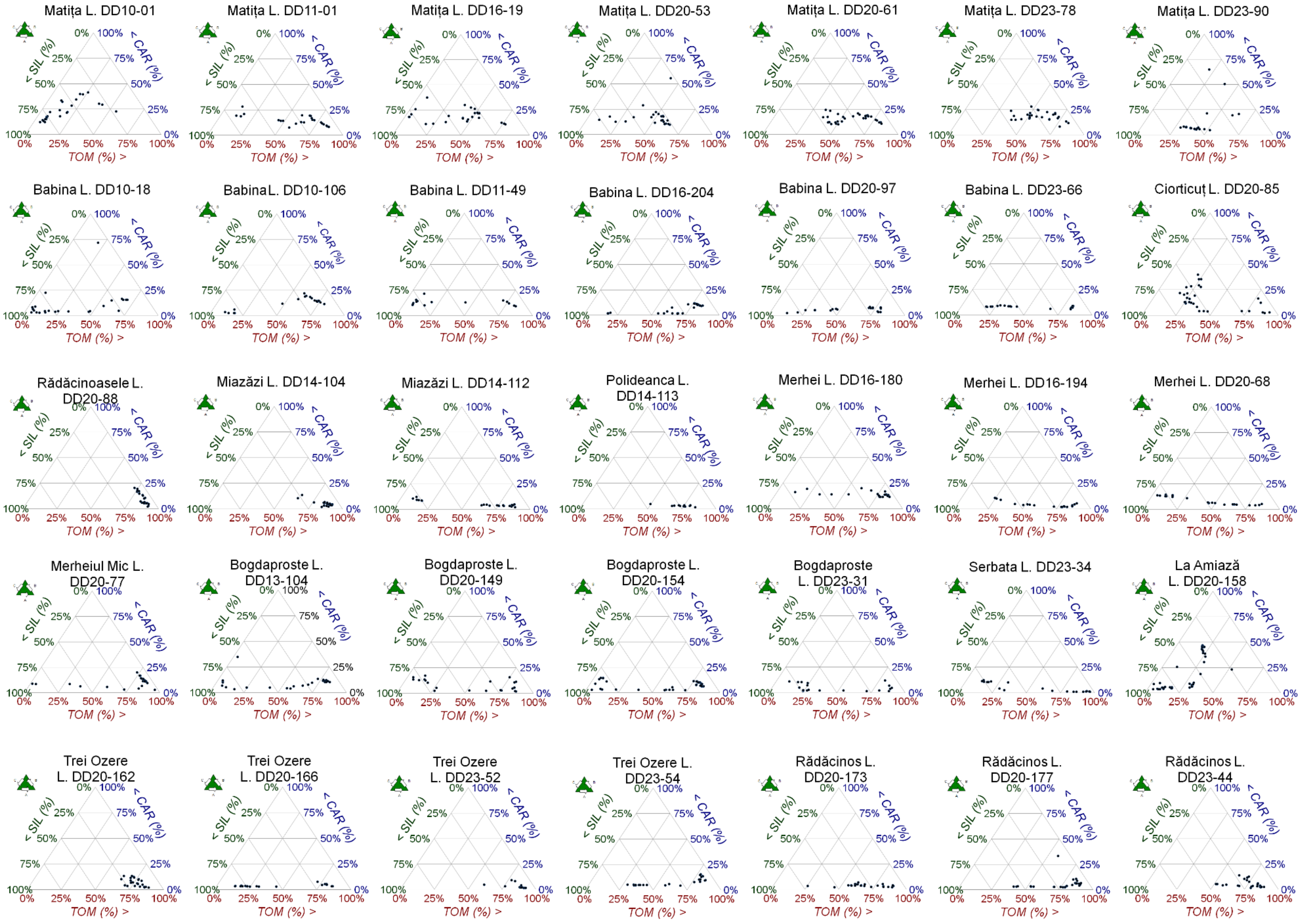

Figure 3. Ternary diagrams showing the percentage distribution (%) of the considered parameter

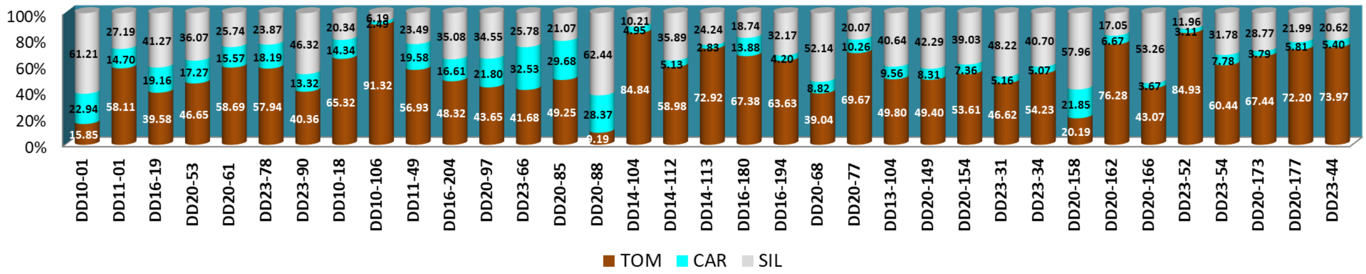

Figure 4. The lithological components (TOM, CAR, SIL) content (%)

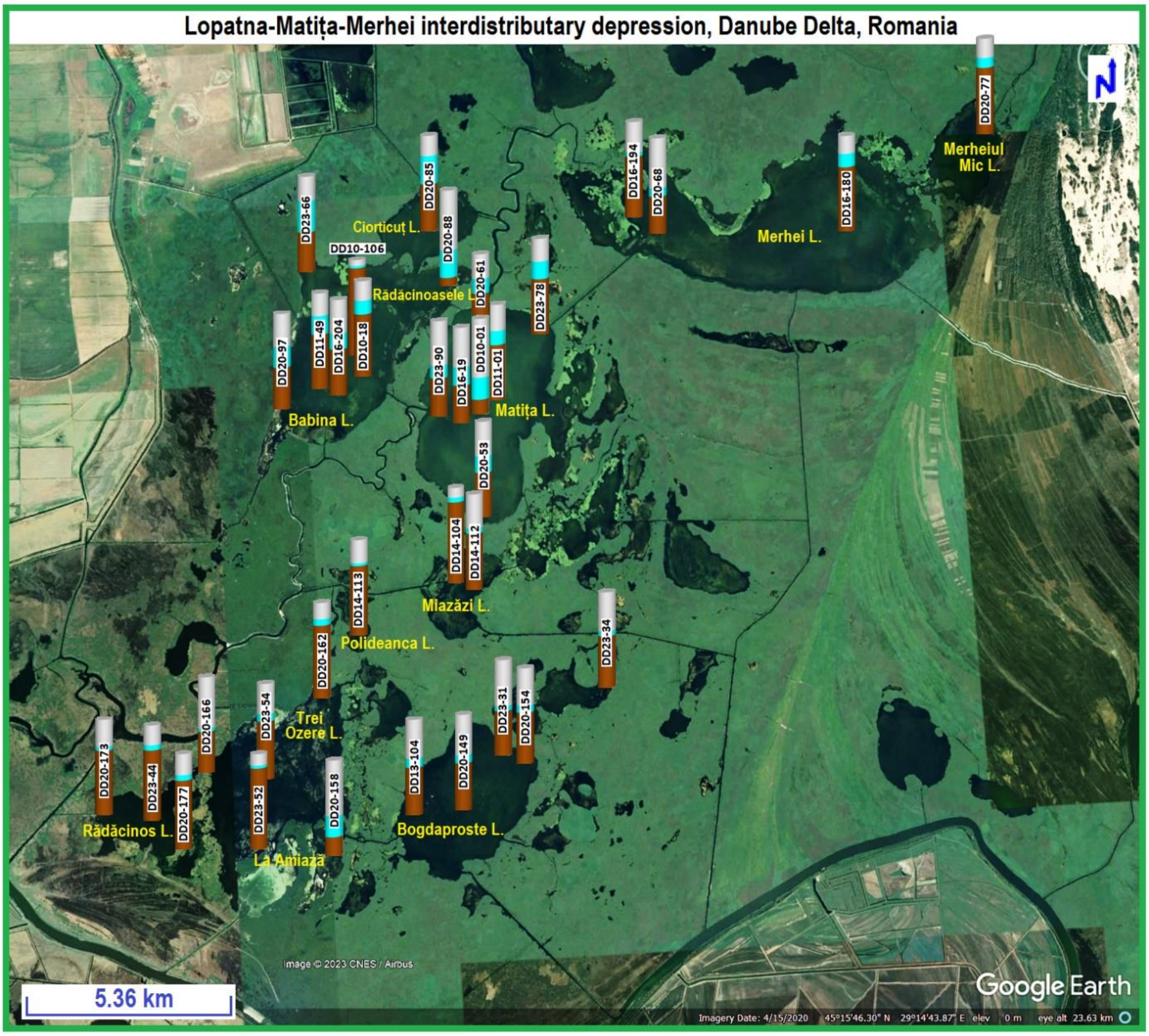

Figure 5. Distribution of the lithological constituents (TOM%, TCAR%, TSIL%) in core sediments (http://www.google earth.com map)

The relatively carbonate-rich sediments are mainly attributable to biogenic calcium carbonates derived from shells but some of this TCAR (%) compounds can be brought by the river or it forms in the water column (Rupp & Adams, 1981; Glunk *et al*., 2011).

Siliciclastic fraction (TSIL%). The inter-comparison between the investigated cores generally showed a low vertical decrease of the siliciclastic fraction content (TSIL%) with values less than 30% of the total weight of the dry residue. These lower values (< 30%) were encountered in 17 cores from the total number of 35 investigated sediment-cores (Table 1, Fig. 3, 4, 5). The rest of them (18 cores) registered higher values (>30%) of the siliciclastic content that can be the result of the seasonal and long-term changes of the terrigenous sediment deposition, and from the erosion of lake sediment substratum or shorelines.

In brief, the acquired results of core-sediment investigations expressed a large lithological variability according to the main dominant lithological component (TOM%, TCAR%, TSIL%) to total sedimentation (Fig. 3, 4).

In this way, generally, the recent unconsolidated sediments identified a mixed lithology represented by organic-rich sediments, subsequently followed by low siliciclastic-rich contents and a variable carbonate content that occurred across the investigated lakes. Contrastingly, in more dynamic water environments (*i.e.*, near the outlet of a canal, in the vicinity of the lake shorelines) high siliciclastic-rich sediments were distinguished, subsequently followed by low organic-rich sediments and a variable carbonate content. In the present case, it can be asserted that the recent sedimentation is mainly controlled by the hydrodynamic factor of the Danube River regime, so that, it is the result of terrigenous, organic and residual input. In the same manner, the autochthonous input (in-lake processes) also leaves its mark on recent sediments. Therefore, both situations are valid for the transitional environment that characterize the investigated *Lopatna-Matița-Merhei* interdistributary depression. These results show that generally, sedimentation in lakes as Matița, Merhei and Babina is controlled by the input of the Danube, through the connecting channels, while in smaller, more isolated lakes, the in-situ sedimentation prevails.

4 CONCLUSIONS

The presented study establishes a useful database framework for future research related to the allochthonous and/or autochthonous material presumable origin, to the total sedimentation and the evolution of lacustrine depositional systems presented in a contextual meaningful *Lopatna-Matița-Merhei* interdistributary depression from the Danube Delta, Romania. The lithological analysis applied on investigated core-sediments contributes to relevant data about the general organic and inorganic constituents in recent lacustrine sediments. Further analyses will be required to determine the extent and significance of the natural and anthropogenic changes, and how they affect the sedimentation process in a specific depositional environment over time.

Gaining insights from the lacustrine sedimentation patterns by reason of different environmental stressors is important for the conservation value of the shallow-water delta lakes that are anyway vulnerable to clogging/siltation, as well as for the assessment of delta resilience under future conditions.

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