

Article

Investigation of Sediment Characteristics and Nutrient Content in Relation to Pilot Dredging at Kis-Balaton Water Protection System (Hungary)

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Abstract: The internal nutrient load of natural and artificial lakes is a worldwide problem. To minimize its potential risks, the dredging of the highly eutrophic shallow first reservoir of Kis-Balaton (Lake Hídvégi) is planned in the near future. Our study aimed to evaluate the potential effects of dredging and desiccation on water and sediment quality. Experimental dredging was carried out in the northernmost part of Lake Hídvégi (2023). The physical and chemical characteristics of the sediment and nutrient loss during desiccation were examined in a column experiment. The relationships between the properties of leachate and sediment were identified using principal component analysis (SPSS). Spatial variations in sediment particle size distribution, nutrient content, and other chemical parameters (e.g., organic matter) suggest that deeper core sampling than the depth of preliminary dredging is necessary for a more comprehensive assessment of potential impacts. We found that spatiotemporally varying the dominance of chemical and biological processes affects the amount of and changes in phosphorus fractions under lake-/sediment-specific conditions. The readily available calcium- and iron-bound phosphorus, texture, and organic matter content of the sediment play an important role in phosphorus fixation/release. Based on our results, dredging and desiccation are feasible within the intended operating parameters. The sediment's composition does not preclude potential agricultural disposal.

Keywords: phosphorus fractions; texture; porewater; shallow lakes; hardwater lakes

1. Introduction

Protecting the quality of surface waters and habitat restoration programs is high on the agenda of today's international environmental and conservation policy (e.g., European Union's (EU) Biodiversity Strategy; Organization for Economic Co-operation and Development's (OECD) Water Quality Standards; EU Water Framework Directive 2000/60—"River Basin Management Plan", updated in Hungary 1242/2022 (IV. 28.)).

The main objective of the Kis-Balaton Water Protection System (KBWPS) is to reduce nutrients, especially the phosphorus load of Lake Balaton [1], in addition to flood prevention and nature conservation functions (Ramsar Conventions, 1971; Natura 2000 Network). The two major reconstructions and expansions of the KBWPS (Phase I~1985; Phase II~1992/2015 [1]), as well as the current dynamic management system, require economic, operational, and conservation aspects in their operational planning.

One-third of the nutrient load from the Balaton catchment and almost half of the phosphorus load [1,2] are delivered by River Zala to the B arandi water area of Lake H idv egi (northwestern part of KBWPS). The amount of nutrients entering Lake Balaton has decreased in recent decades (due to reconstructions, development of wastewater treatment, and sewerage reduction in fertilizer use) as a result of the economic crisis, etc. [1,3–5]. At the same time, the filtering capacity of the KBWPS has fluctuated (e.g., 10–60% P retention [4–7]). The rate of different external nutrient loads relative to the KBWPS (including Balaton) has also varied (e.g., with the amount of nutrients periodically transported by erosion, inland water formation, or temporal flooding due to extreme rainfall events [3,4,8–11]). More than three decades of sediment and nutrient accumulation may impact the inflow area of Zala. The possibility of excessive internal loads due to the release, desorption, dissolution, etc., of nutrients stored in the sediment has increased [12–15].

The periodic internal loading of lakes is a worldwide problem for water quality protection for both natural and artificial waterbodies, e.g., reservoirs constructed for recreational purposes or for drinking water supply [4,11,15–19]. In Mediterranean lakes, phosphorus (occasionally the accessibility of nitrogen) is the main limiting nutrient in eutrophication processes [12,20–22], but it is strongly influenced by environmental impacts [23]. The rate of the internal P load may approach the amount of the external load [22,24,25]. Internal loading can occur under both reductive and oxidative conditions, e.g., [26], in almost any season [18,27–30] at both high and low external loads (as compensation [25,28]). It can also be induced by changes in meteorological conditions (e.g., with increasing temperatures [30–32]), by water-level fluctuations (due to low precipitation and inflow, high evaporation, heavy rainfall, etc.) [18,19,25,33], or by biological processes ("pumping-suction effects" [34]). Readily available P (e.g., Fe and Ca or labile organic-matter-associated P) may be a potential source of orthophosphate-P in water and can limit the realization of internal loads under given environmental conditions (pH, temperature, and dissolved CO₂), near abiotic or biotic processes, or microbial activity [12,13,35–37].

To prevent and minimize the eutrophication of reservoirs, a number of procedures have been developed and recently applied successfully, e.g., the chemical precipitation of phosphate, increasing the sorption capacity of sediments by adding Fe/Al [38], P extraction by reed harvesting [39], or nitrate addition, etc. [40,41]. Most of the chemical methods are not applicable in the KBWPS, mainly because of its nature conservation functions and status. Other recommended feasible chemical treatments, such as controlling pH and phosphate precipitation by the addition of Ca(OH)₂ or lime, e.g., [42], in artificial surface waters (e.g., recreational and fish ponds) are also not recommended. The sediment from the Balaton catchments already contains significant amounts of Ca/Mg carbonate [43]. Experiments of local relevance have been conducted worldwide with water level control [35,43,44] and

biomanipulation (species composition control [45,46]), but the special ecosystem of the KBWPS limits their application.

Recently, the constraints of dredging have been the cost, the environmental impact of exploitation, and the potential excessive load of leachates (e.g., trace elements and unfavorable amounts of nutrients) [44]. However, the P content of sediments can be an important secondary source of P, e.g., [35,47]. The renewal of Hungarian regulations has allowed the agricultural disposal of sediments after dredging (Government Decree 50/2001 (IV.3)), but practical experiences and the development of a methodology to assess the environmental impacts are urgently needed for its proper application.

Monitoring systems set up to prevent eutrophication usually primarily determine water quality parameters (in Hungary as well). The sediment is not monitored regularly. Only general information is available on water quality (no standard monitoring points); there is no information on the physical, chemical, and biological properties of the sediment in either the B ar andi water area of Lake H idv egi or Lake Balaton [14,48–50]. However, the knowledge of sediment characteristics and their spatiotemporal variability is essential for modeling the long-term effects of changes in load quantity and quality, as the P retention of sediment can be orders of magnitude greater than the overlying water phase. Furthermore, the sediment is the main source of internal P-load [12,14,28,51].

The objective of our study was to provide background data for a pilot dredging project planned for November 2023 in the B ar andi water area of the KBWPS. We evaluated the results of autumnal on-site dredging, desiccation in winter, and experiments that modeled the gravity drainage of sediment samples. In our work, we aimed to answer the following practical questions: (a) How heterogeneous are the nutrient content and the physical and chemical properties of the sediment? (b) Is the sediment suitable for agricultural disposal? (c) How much nutrient loss can be expected during the desiccation process? (d) Does the composition of leachate inhibit its direct return? (e) Which other sediment characteristics might affect the nutrient loss?

2. Materials and Methods

2.1. Site Description

Kis-Balaton is a semi-artificial reservoir system (KBWPS I and II) in West Hungary (Figure 1). Geologically, its watershed (the southern part of the Balaton catchment) is mainly characterized by Quaternary sediments (Pannonian clay, sand, and sandstone). Triassic dolomite and Pleistocene loess and sand (overlying the bedrock) are typical of the Keszthely Mountain region. In the catchment of the KBWPS, forest soils are predominant, while meadow and peat soils are typical in deeper areas. The sediments of the Kis-Balaton area are mostly covered by peat [52].

The KBWPS retains nutrients from the watershed area (~5180 km²) before the water reaches Lake Balaton primarily by sedimentation; adsorption by sediments; uptake by macrophytes, periphyton, or algae; and by enhanced denitrification. The KBWPS is a shallow (average depth of ~1 m; surface area: 69 km²), hardwater (EC 730.8 ± 117.9) reservoir with fluctuating trophic states in space and time (oligotrophic–hypertrophic) [2,4].

The water quality of the KBWPS system is regularly monitored at 20 monitoring points (e.g., z15, kb4, kb10). Basic statistics of the water quality data from these three monitoring points were available for the period of the study (Table A1). The water arrives indirectly at Lake Balaton after an average residence time of ~30 and ~90 days in KBWPS I (Lake H idv egi) and KBWPS II (Lake Fen eki) (actual residence time is unknown, only modeled [7]). The investigated B ar andi water area (9 km²) is located at the inflow of the river Zala, within Lake H idv egi (Figure 2). There is no regular monitoring point in this area, and only a few sediment samples have been investigated formerly (Figure 2) [52].

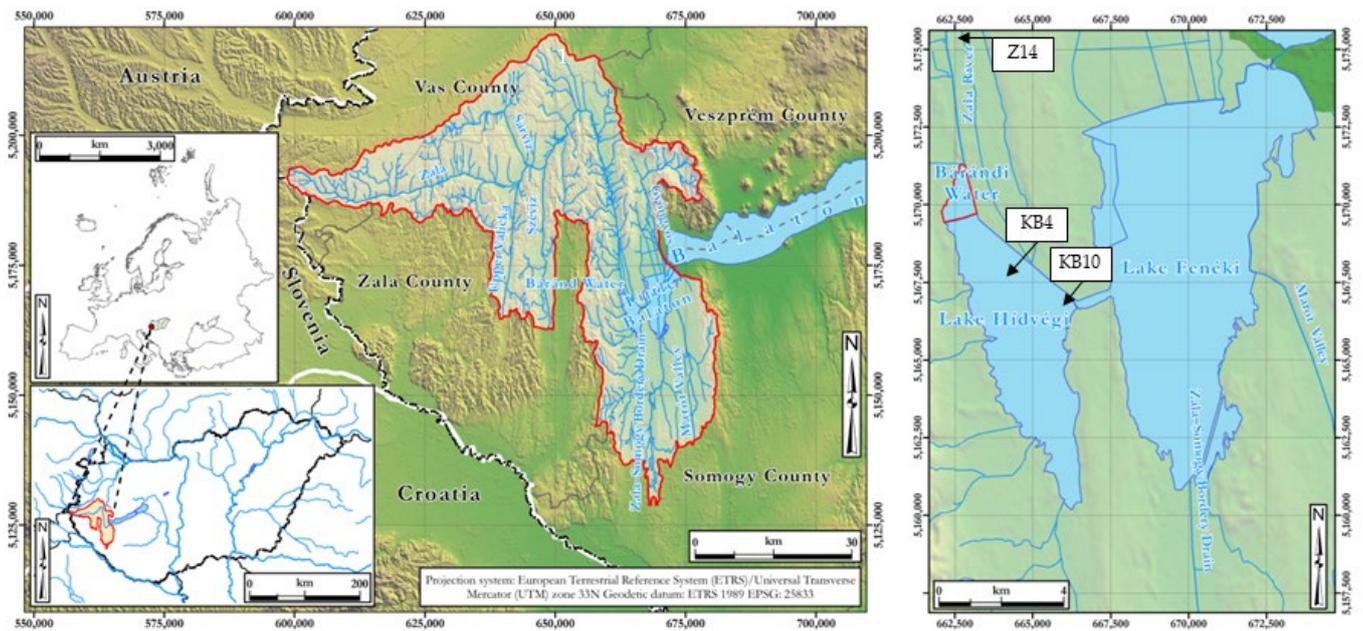


Figure 1. Location of KBWPS and its catchment area and the main reservoirs of Kis-Balaton (KBWPS I—Lake Hídvegi and KBWPS II—Lake Fenéki) with some monitoring points (z14, kb4, and kb10—data of these were used in our investigations).

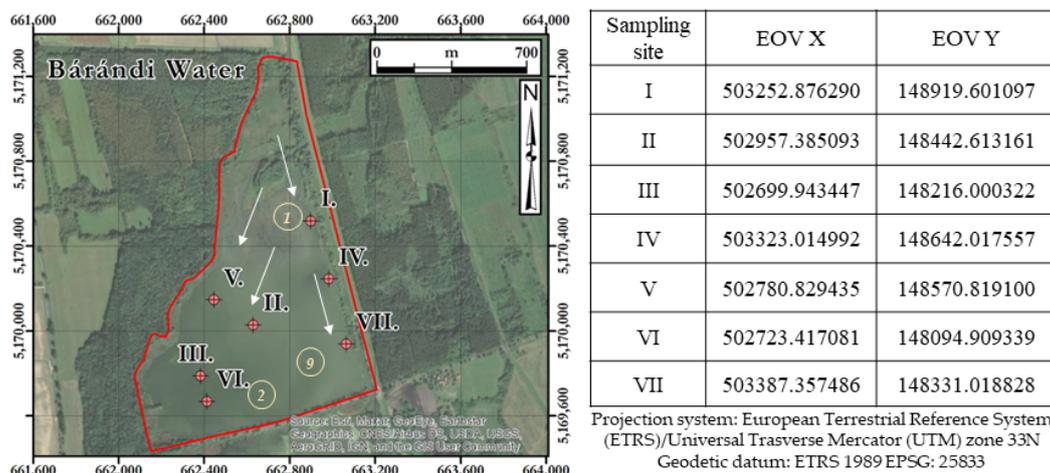


Figure 2. The current sediment sampling sites (I–VII) with coordinates and the previous ones (1, 2, and 9—[52]) at Lake Kis-Balaton, Bárándi water area. The presumed main flow directions [2,50] are represented by arrows.

2.2. Sampling and Experiments

Based on the results of a previously conducted detailed sediment depth assessment (Lowrance Live 12 sonar/Garmin GpsMap 86 [53]) in the Bárándi water area in 2018, three (I–III samples) and, later, three more (IV–VI) sampling points were selected within the reservoir area (Figure 2). Afterward, one additional sampling point was selected for dredging (VII). At these points, the sediment layer was deeper, and points were located close enough to the shoreline; thus, experimental dredging may be feasible.

The sediment samples were collected into 30–30 L plastic barrels in three replicates (per sampling site) at approximately the planned dredging depth (cca. 30 cm). Using the collected, disturbed, and homogenized sediment samples, column experiments were set up (in September 2022, June, and November 2023) in an open greenhouse of the Department of Agronomy, Institute of Plant Production, (Hungarian University of Agriculture and Life Sciences—MATE, Keszthely, Hungary). We used double-walled columns made of PVC

pipes. The inner tubes of the columns were filled with 20–20 L of sediment collected from the sampling points (in three replicates). The outer pipe was fitted with taps, which allowed it to collect run-off. The sediment-filled columns were placed on a scaffold (Figure 3A). Average homogenized sediment samples were taken from the sample barrels at the time of column filling. During approximately 100 days of the column experiment, the water draining from the columns was continuously sampled (approximately on the 1, 5, 10, 15, 40, 70, and 100 days and after 130 and 160 days only from I–III).



Figure 3. (A) Experimental sediment column and core sample (III); (B) arrangement of the pilot desiccation and dehydrating pad with polyacrylamide addition: (a) a settling pit (b) with inflow (c) and outflow (d) (north—at sampling site I); (C) photographs of column V at the end of the experiment, and (D) shows the desiccated sediment on site.

At the same time, seven 100 cm long (\varnothing 4 cm) core samples were taken (Figure 3B) with an AMS-type sampler at a maximum depth of 1 m. Core samples were frozen and cut into 0–5, 5–10, 10–20, and 20 cm layers (corresponding to approximately 0–15, 15–30, 30–60, and 60 cm layers due to the compaction effect of the sampling). Layer samples were taken for laboratory analysis. At the end of the experiment (January and October 2023, and February 2024), columns were separated into 20 cm pieces (from the bottom to the top, 0–20, 20–40, 40–60, 60–80, and 80–100 (100-) cm layers—Figure 3C), but the chemical analysis was performed only on disturbed samples from the 0–20, 40–60, 80–100 cm layers.

During the pilot dredging project, an average of 200–210 (sampling point VII) and 196 m³ (sampling point I) of sediment was dredged from 19 to 21 cm depths with two hydro-mechanization excavators. The removed sediment was desiccated (with approx. 1 m depth—Figure 3C) in two longitudinal (south and north) settling pits on the other side of the reservoir dikes and a dewatering pad (with added polyacrylamide) (Figure 3D). Periodic water sampling was carried out at the outlets of the objects.

2.3. Determination of the Physical and Chemical Parameters of Sediments and Leachates

The sediment samples were first investigated in the laboratories of Hungarian Research Network, Centre for Agricultural Research, Institute for Soil Sciences (HUN-REN ISS) and at the University of Sopron, Institute of Environment and Nature Conservation (US IENC); later, the laboratory of Hungarian University of Agriculture and Life Sciences, Institute of Plant Production, Department of Agronomy (MATE DA), performed the major part of the chemical analysis. Measurements of water retention (pF determination) and particle size distribution were also carried out by HUN-REN ISS (laboratory of soil physics). However, some of the tests were preliminary experiments; thus, not all parameters could be

determined from all samples (see details in Table 1), and there were no sampling replicates of core samples (only measurement replications).

The particle size distribution of disturbed samples (I–III) was determined with a laser diffractometer (Malvern Mastersizer 3000). Samples were chemically dispersed by adding a 25 cm³ Calgon solution. Physical dispersion was performed in a Hydro LV dispersion unit (pumping and stirring speed: 2750 rpm; obscuration: 5–20%) with ultrasound (4 min. at maximum intensity, 40 kHz [54]). The particle size distribution was calculated according to Mie theory from diffraction and intensity data using common optical indices (absorption index AI = 0.1; solid phase and water refractive index: RI: 1.52 and 1.33). The size limit of clay, silt, and sand fractions was 7 and 50 µm (as proposed by Makó et al. (2019) [55]).

Table 1. Measured characteristics of the leachate and sediment samples.

Leachate Samples			
Properties	Standard	Method/Equipment	Investigated Samples
Total phosphorus (TP; mg/L)	MSZ EN ISO 6878:2024 [56]	Skalár SA5000—S25 Elemental analyzer	Water leaching from artificial sediment columns I–VI
Total nitrogen (TN; mg/L)	MSZ EN 12260:2004 [57]	Elementar VarioTOC S-20-0402 TOC + TN analyzer	
Total potassium (TK; mg/L)	MSZ 448-10:1977 [58]	BWB XP Flame photometer	
Sediment samples			
Particle size distribution (PSD—clay, silt, and sand content; %)	ISO 11277:2009(E) [59]	Laser diffraction (Malvern Mastersizer 3000)	Disturbed samples I–VII *
Water retention (pF; vol%) /hygroscopic moisture content	ISO 11274:2019 [60]	Sand/kaolin box/pressure membrane apparatus/ at CaCl ₂ ×6H ₂ O environment	Disturbed samples I–III **
Bulk density (g/cm ³)	ISO 11274:2019 [60]	Calculated (dry weight (105 °C)/volume)	Disturbed samples I–III **
Chemistry (pH _(Dw) in distilled water)	MSZ-08-0206-2:1978 [61]	MultiLine P4, WTW Multi 350i	Disturbed samples IV–VII **
Ammonium-lactate-soluble P and K (AL-P; AL-K; mg/kg)	MSZ 20135:1999 [62]	UV/VIS Thermo Scientific Genesys spectrophotometer	Disturbed * and core samples I–VII
Total nitrogen (TN; mg/kg)	MSZ 20135:1999 [62]	Elementar vario Macro Cube Elemental analyzer	
Total organic nitrogen (TON; mg/kg)	MSZ 20135:1999 [62]		Disturbed * and core samples I–VII
Total organic carbon (TOC; %)	MSZ 20135:1999 [62]		Disturbed samples IV–VII * and core samples I–VII
Ca and Mg content (mg/kg)	MSZ-21470-50:1998 [63]	Aqua regia microwave digestion/ICP-OES	Disturbed samples IV–VII **
Carbonates (CaCO ₃ ; %)	MSZ-08-0206-2:1978 [61]	Scheibler method, calcimeter	Disturbed samples IV–VI **
CDB and HCl extractable-P (CDB-P and HCl-P; mg/kg)	[64]	UV/VIS Thermo Scientific Genesys spectrophotometer	Disturbed samples IV–VII *
Total phosphorus and potassium (TP, TK; mg/kg)	MSZ-21470-50:1998 [63]	Aqua regia microwave digestion/ICP-OES	Disturbed samples IV–VII **

* Sampling before and after; ** sampling independently from the column experiment.

The water retention of sediment samples (I–III) was determined at 0–1000 kPa (using a sand/kaolin box by gravimetry), and at 1500 kPa, it was determined with a pressure membrane apparatus in three replications. The hygroscopic water content was measured

in a permanent moisture content (31.5%) environment ensured by $\text{CaCl}_2 \times 6\text{H}_2\text{O}$ [65]. The bulk density was calculated as the ratio of absolute dry weight (105 °C) to the volume of undisturbed samples.

The total P and K contents were determined after digestion with aqua regia in a microwave Teflon bomb by means of ICP-OES (Perkin Elmer Avio 550 max), using Merck calibration standards and following the manufacturer's instructions. In each measurement session, the extract of a standard soil sample was used as a control. Readily available P and K were measured from ammonium-lactate extract (AL-P; AL-K), and TN was also determined—these are currently required before agricultural disposal in Hungary.

For the determination of phosphorus fractions bounded to primarily iron (crystalline and amorphous iron (oxy)hydroxides—CDB-P) and carbonates (mainly CaCO_3 —HCl-P), the same samples were extracted in two consecutive steps with CDB (40 mL of 0.3 M $\text{Na}_3\text{C}_6\text{H}_5\text{O}_7$ + 5 mL 1 M NaHCO_3 + 1 g $\text{Na}_2\text{S}_2\text{O}_4$ was added per gram of sediment—citrate–dithionite–bicarbonate solution); then, HCl solutions (50 mL of 0.5 M HCl/g sediment) were used, similarly to the extraction method of Anshutz and Debore (2016) [64] (without ensuring reductive conditions with N_2). All P fractions were measured according to the Murphey and Riley (1962) spectrophotometric method [66].

The total organic carbon and total nitrogen were determined by an Elemental vario Macro Cube Elemental analyzer. The Ca and Mg contents of the sediment were also measured by means of ICP-OES (Perkin Elmer Avio 550 max). The pH was determined by a MultiLine P4, WTW Multi 350i pH/EC meter using a combined electrode. The measurement of CaCO_3 content was carried out with Scheibler apparatus via the conversion of carbonates present in the sediment into CO_2 with the addition of 10% HCl (the carbonate content of the sample, calculated from the volume of the gas produced, with reference to the temperature and air pressure).

The chemical characteristics of the leachates were determined in the Water Protection Laboratory of the Western Transdanubia Water Directorate (WTWD). The TP of the leachates was measured by spectrometry with a P elemental analyzer, and TK was determined by flame photometry. The TN measurement was performed using an automated TOC and TN analyzer (by catalytic oxidation and chemiluminescence detection) (Table 1).

2.4. Statistical Analysis and Calculation

Univariate analysis (SPSS ver. 20.0) and the post hoc Tukey or Tamhane test were used depending on the results of Levene's test (SPSS/univariate analysis/homogeneity test) to assess the variability in clay, silt, and sand content between sediments from various sampling sites (I–VII) and the degree of sedimentation during the column experiment. Differences in nutrient content by the sampling sites and sample types (e.g., between disturbed samples or disturbed ver. core samples) of the sediment were investigated based on the basic statistics (Table A3). Univariate analysis and post hoc Tukey or Tamhane tests were used for more detailed analysis depending on whether Levene's test was significant or not (normal distribution of the investigated parameters was assumed).

The nutrient loss during desiccation was calculated based on the amount (L) and nutrient content (mg/L) of the leachate. The percentage of nutrient loss was determined using the average of the measured TP, TK, and TN values of the sediment samples.

Relationships between phosphorus loss (P_1) in the column experiment and sediment parameters were investigated by principal component analysis (SPSS/PCA/varimax rotation, and Kaiser normalization).

2.5. Comparison of Column Experiment Leachate, Experimental Drying, and Relevant Monitoring Points of Water Quality Data

The chemical properties of the leachate measured during the column experiments (2022–2023) were compared using basic statistics from the water quality data of three monitoring points (z14, kb4, and kb10 of KBWPS I—Figure 1) and the quality of water sampled at the outlets of the north and south settling pits (Figure 3B). The results were used to determine the maximum nutrient leaching during desiccation; to evaluate how well the column experiment modeled the processes that occurred in nature; to compare the quality of the leachate to natural water; and to gain preliminary insight into the potential maximum P load in the case of direct recirculation. Measured water quality parameters were compared with the limits for the Lake Balaton catchment in the national regulations concerning the recirculation of treated wastewater into natural water (28/2004. (XII.25) Environment and Water Ministry government regulation—there is no existing regulation on the recirculation of leachate from dredging).

3. Results

3.1. Physical Properties of the Sediment (Disturbed Samples of I–VII Sampling Sites)

Based on basic statistics (Table A2), the sediment was dominated by the silt fraction. Levene's test between sampling sites was significant ($p < 0.01$ —Table A4); thus, the Tukey test was used to compare the mean sand content of samples ($p < 0.05$). The results of the univariate analysis (Figure 4; basic statistics—Table A2) showed that the sand content of disturbed samples I and VII was somewhat higher (mean: 19.2 and 27.8%) than samples IV, V, and VI (mean: 10.0–13.2%). Sediment samples II and III and V and VI contained more clay-sized particles (25.9–30.6%), in contrast to samples I and VII (17.9 and 25.3%) (Table A2). No displacement of the fine fraction was observed in the column experiment (Figure 4A,B).

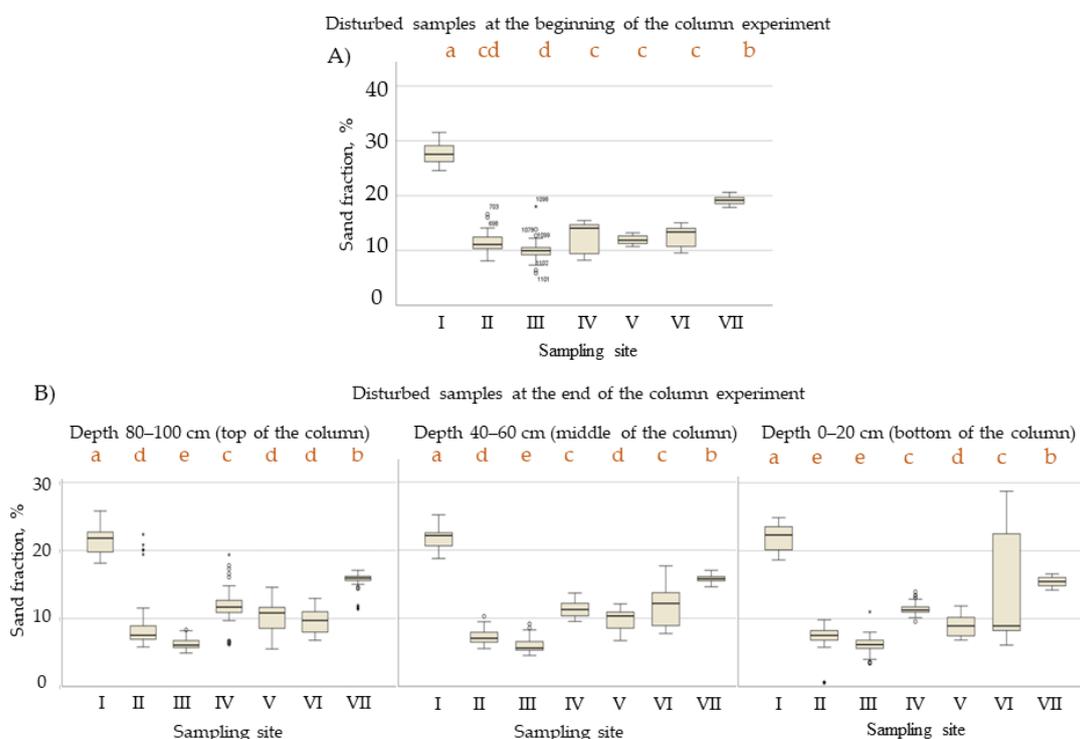


Figure 4. (A) Sand content of the disturbed sediment samples at the beginning and (B) at the end of the column experiment (SPSS/univariate analysis/post hoc/Tukey). Means denoted by the same letter (e.g., “a”) did not significantly differ at $p < 0.05$ (descending value of means signed in abc order).

However, the experienced decrease in the amount of sand fraction (approximately 28 to 23% at sample I) from the beginning to the end of the column experiment may have indicated a slight initial aggregation of the sediment. Samples had an average bulk density of 0.49 g cm^{-3} and dry matter content of 34.87% and 54.88% at the beginning and at the end of the experiment, respectively.

There were no enormous differences between the water retention of sediments I–III. Samples had an average of 82.08 vol% (± 1.75) with respect to saturated water content, and 15.74 vol% of moisture content at the permanent wilting point (PWP). The latter influences basically the desiccation time requirement. The significant standard deviation of PWP (± 4.03 vol%) was primarily due to differences in the particle size distribution of the sediment ($r_{\text{clay-PWP}} = 0.888$). The field capacity (FC) was medium: 39.38 vol% (± 1.21 vol%) (Figure A1).

On site, 350 m^3 of desiccated and compacted sediment (depth $\sim 1 \text{ m} \rightarrow 0.7 \text{ m}$) approached the field capacity (measured at pF 2.5 from disturbed samples) required for transportation (within approximately two months), despite precipitation in this period being 156 mm.

3.2. Chemical Properties of the Sediment

3.2.1. Core Samples

The total organic carbon (TOC) content of the sediment differed mainly vertically (for core samples, 3.7–22%), with the highest TOC content in the 30–60 and 60 cm layers for samples II and III (16–22%). For samples closer to the shoreline (V) and near the inflow (I), somewhat higher TOC content was measured (also) near the surface (7–10%). In the deeper region at sites II and III (S-W direction), the deeper layers also had higher TOC content. Toward the inflow, the degree of horizontal layering decreased (Table 2).

Table 2. The ammonium-lactate-soluble readily available phosphorus and potassium, the total nitrogen, and the total organic carbon content of the core samples.

Core Sample	Depth (cm)	AL-P	AL-K	TN	TOC	Core Sample	Depth (cm)	AL-P	AL-K	TN	TOC
		mg/kg						%			
I	0–15	211.8	218.4	3121.0	7.0	IV	0–15	430.6	342.8	3143.0	5.5
	15–30	116.2	138.6	9448.0	12.7		15–30	521.2	194.6	2878.0	5.4
	30–60	318.6	83.0	2647.0	4.7		30–60	311.2	176.6	2736.0	5.2
	60–	28.7	54.7	908.0	4.8		60–	594.4	186.5	3045.0	4.5
II	0–15	268.9	269.2	2886.0	6.1	V	0–15	312.4	167.3	5466.0	9.6
	15–30	299.7	235.7	8104.0	10.1		15–30	373.6	201.1	2875.0	5.4
	30–60	42.7	131.8	16,054.0	22.0		30–60	315.7	207.1	9369.0	11.9
	60–	172.8	62.1	2899.0	5.3		60–	326.4	139.0	11,857.0	14.9
III	0–15	340.7	156.9	2299.0	4.6	VI	0–15	241.8	167.6	3869.0	7.6
	15–30	490.1	109.4	2344.0	4.4		15–30	226.6	176.4	2925.0	6.9
	30–60	686.4	193.4	2591.0	3.7		30–60	255.3	182.3	2933.0	6.9
	60–	284.5	151.5	13,119.0	16.4		60–	215.3	167.2	8779.0	13.7
					VII	0–15	412.0	105.9	3463.7	5.0	
				15–30		415.8	91.7	3320.3	4.9		
				30–60		345.6	184.0	3480.3	5.0		
				60–		156.0	132.4	3590.3	5.1		

Notes: Coloring only indicates deviance between layers with more than a 10% difference relative to the average nutrient content (AL-P, AL-K, and TN and TOC: 307.8, 165.3, 5005.3 mg/kg and 7.8%); not a significant deviation as there was no repeated measurement.

Based on the results of the laboratory analyses, the nutrient content of the sediment varied spatially (vertically within the Bárándi water area and horizontally between layers of the core samples). The ammonium-lactate-soluble phosphorus (AL-P) content of sediments

was lower in areas closer to the inflow (sample I) and higher in the middle lake (III) and along the shorelines (IV, V, and VII), except for sample VI. The AL-P content of the surface layer (0–15 cm) was generally lower than that of the layer immediately below the surface, except for core sample VII (surface maximum). In some cases, the AL-P content of the subsoil was higher than that of the surface layers (III and IV). The AL-P maximum was closer to the sediment surface at samples IV–VII (collected in July and November IV–VII) than at samples that were sampled after a warm and droughty August (I–III).

Samples I, II, and IV contained more ammonium-lactate-soluble potassium (AL-K) at the surface or in the second layer. AL-K contents indicated that samples III, V, and VI were less stratified. The total nitrogen content (TN) of core samples shows lower horizontal variations near the surface (0–15 cm) of the samples (except in the case of sample V) than in the sublayers. The higher TN and TOC contents of sediment profiles were found mainly at sites in the middle lake (II, III, and V). TN followed the vertical change in TOC. The TOC content is higher in deeper layers (except IV and VII).

3.2.2. Comparison of Some Chemical Characteristics of Disturbed and Core Samples

Based on the results of Levene's test, the homogeneity of variances might be assumed in the case of the disturbed samples investigated (Table A4).

Significant differences were found between the measured nutrient content of the disturbed sediment samples at various sampling sites, primarily in the AL-P content, but it can be also seen in the case of AL-K and TOC contents (only the IV–VII samples were compared) and sometimes in TN contents (post hoc and Tukey's test results in Figure 5).

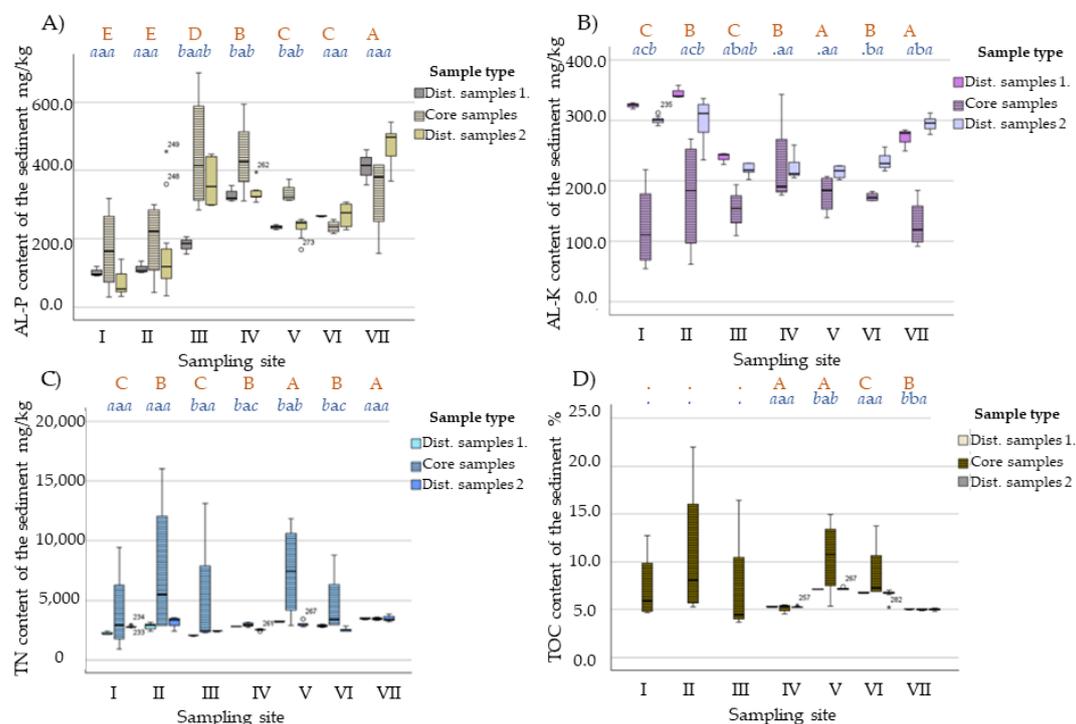


Figure 5. (A) The AL-P, (B) AL-K, (C) TN, and (D) TOC content of sediments at various sampling sites. A–E: letters represent different mean values of the investigated property by sampling sites at the beginning of the column experiment ($p < 0.05$ —SPSS/univariate/post hoc/Tukey—with decreasing values in alphabetic order); a–c: letters show the differences between the sediment properties of core and disturbed samples (with decreasing median values in alphabetic order) based on the results of the Tamhane test (see details in Table A4). The dots indicate where no measurement was taken from the samples. Sample-type meaning: Dist. sample 1.: disturbed samples at the beginning of the column experiment; Dist. sample 2.: disturbed samples at the end of the experiment.

Levene's test was not significant ($p < 0.001$) when comparing core and disturbed samples (by sample types) or when core samples were collected from various sites (by sampling sites) (Table A4). The variance of the investigated sediment characteristics was much greater in the case of core samples than in disturbed samples (Figure 5). According to the results of the Tamhane tests, the deviation between the nutrient and TOC contents of core and disturbed samples was in some cases significant ($p < 0.05$), even with greater differences between various layers of core samples (Table A4 and Figure 5). Furthermore, the AL-K of disturbed samples was in many cases deviated from the AL-K of core samples (I–III and VI and VII). These results also showed that the AL-P of core samples is mainly higher, but the TN and TK of core samples are mainly lower than disturbed samples.

3.2.3. Column Experiment

The total phosphorus (TP) of sediments IV–VII was nearly identical ($894.9 \text{ mg/kg} \pm 54.4$ —Table 3). The AL-P content of disturbed samples III, IV, and VII was higher than samples I and II and IV and V (Figure 5A). Similarly distinct groups could be established at the end of the column experiment (I–II, V–VI, III–IV, and VII), with the increase in AL-P content from inflow (similarly to the results of the investigation on core samples, see Figure 5A).

Table 3. Chemical parameters of sediment samples investigated before the column experiment (for the whole column, 0–130 cm) and after it (samples at 0–20, 40–60, and 80–100 cm depth from the bottom of the column/outlet of leachate).

Site	Depth	TP	TK	TN	AL-P mg/kg	AL-K	Ca	Mg	AL-P/TP * -	CDB-P mg/kg	HCl-P	pH -	TOC	CaCO ₃ %
IV	0–130	854.0	10,644.0	2794.0	328.5	221.6	82,148	10708	26 (33)	222.7	188.7	7.7	5.3	20.3
	0–20			2501.3	316.6	224.1				101.3	213.4		5.2	
	40–60			2570.0	331.7	226.8				120.6	194.4		5.3	
	80–100			2514.0	353.4	213.9				121.7	211.3		5.3	
V	0–130	879.4	7824.3	3213.0	234.0	214.5	133,064	9323	18 (22)	182.3	139.0	7.9	7.1	33.5
	0–20			3082.0	225.2	216.5				113.7	70.2		7.2	
	40–60			2902.0	232.1	209.5				124.3	84.0		7.1	
	80–100			2958.7	241.4	217.4				170.5	106.8		7.2	
VI	0–130	875.8	7047.1	2858.0	266.0	234.0	128,661	9353	21 (19)	158.4	84.5	8.0	6.8	32.0
	0–20			2569.3	289.4	224.4				195.4	114.2		6.4	
	40–60			2471.3	252.6	250.1				174.7	72.3		6.7	
	80–100			2566.0	258.5	227.6				216.1	123.8		6.7	
VII	0–130	970.5	7766.6	3463.7	270.79	270.8	66,471	10,599	30 (30)	215.9	194.5	8.2	5.0	
	0–20	977.0	7366.0	3590.3	289.77	301.5				240.3	73.9		5.1	
	40–60	961.0	7822.0	3480.3	297.93	294.7				275.2	184.1		5.0	
	80–100	974.0	8112.0	3320.3	296.73	288.2				238.0	107.7		4.9	

Note: TP, TK, and TN are total phosphorus, potassium, and nitrogen; AL-P, CDB-P, and HCl-P are the ammonium-lactate-, citrate–dithionite–bicarbonate-, and hydrochloric-acid-soluble phosphorus; Ca and Mg are the calcium and magnesium contents; pH is the chemistry; TOC and CaCO₃ are the total organic carbon and calcium carbonate content of the sediment samples; * AL-P/TP is the rate of ammonium-lactate phosphorus and total phosphorus; in parentheses are the quotients of readily available and total phosphorus ((CDB-P + HCl-P)/TP).

Regarding the readily available potassium content (AL-K and TK), sample IV was outstanding, but the total potassium (TK) of sample I was the highest, followed by sample VII. Various TK contents were measured for sediment samples from different sampling sites). The mean TN was 3082.2 mg/kg (± 76.1), and TOC was 6.05% (± 0.1). TN varied mainly with the TOC of the samples, except for sample site VII.

Our results in Table 3 show that the Ca content of the sediment is lower at the flow direction of I–IV–VII (at samples IV and VII) than on the western side of the reservoir (at samples V and VI). The Mg content varies in the opposite direction. The sediment chemistry was alkaline ($\text{pH } 7.96 \pm 0.19$).

The amount of readily available P (citrate–dithionite–bicarbonate-soluble phosphorus—CDB-P; and hydrochloric-acid-soluble phosphorus—HCl-P) was less than half of TP (Table 3). The remaining part of TP could be mainly recalcitrant/residual P (organic and mineral P) [56]. The CDB-P and HCl-P contents in the sediments decreased with distance from the inflow. The amount of readily available mineral form P was higher than Al-P.

According to our results, the HCl-P content of the sediments at sites far from the inflow was also lower, and even the CaCO_3 content of these samples was significantly higher than that of samples IV and VII. The calculated CDB-P/HCl-P ratio was approximately 60:40; the CDB-P content relative to HCl-P varied from 1:1.11 to 1:1.89 at the experimental setup and between 0.9:1 and 1.18:1 at the end of the experiment.

In some cases in the column experiment, both HCl-P and CDB-P were changed. The rate of AL-P/TP and readily available mineral P/TP was different, but overall, away from the main flow direction (V, VI), they are lower. No vertical nutrient movement was observed in the sediment of about 1 m thickness (based on the TP, TK, and TN results of samples VII). The AL-P in the upper layers of the column (80–100) generally seemed to be higher than deeper locations in the 0–20 or 40–60 cm layers. Not all sediment layers were analyzed in the laboratory, so our results do not provide a complete nutrient profile. The difference in the AL-K, TN, and TOC values of the different layers is not significant.

3.3. Evaluation of the Nutrient Loss in the Columns and Settling Pits

The experienced amount of the drained leachate was 4.8 L on average; thus, evaporation loss in the column experiment was approximately 27% (based on the average amount of drained water and the changes in dry matter content during the column experiment).

The leaching of nutrients showed different “patterns” in the sampling sites and over time (Figure 6). The observed large variance is the consequence of using 3–3 replicate samples from the same location. Relatively minor nutrient loss relative to the total nutrient content was experienced (Table 4).

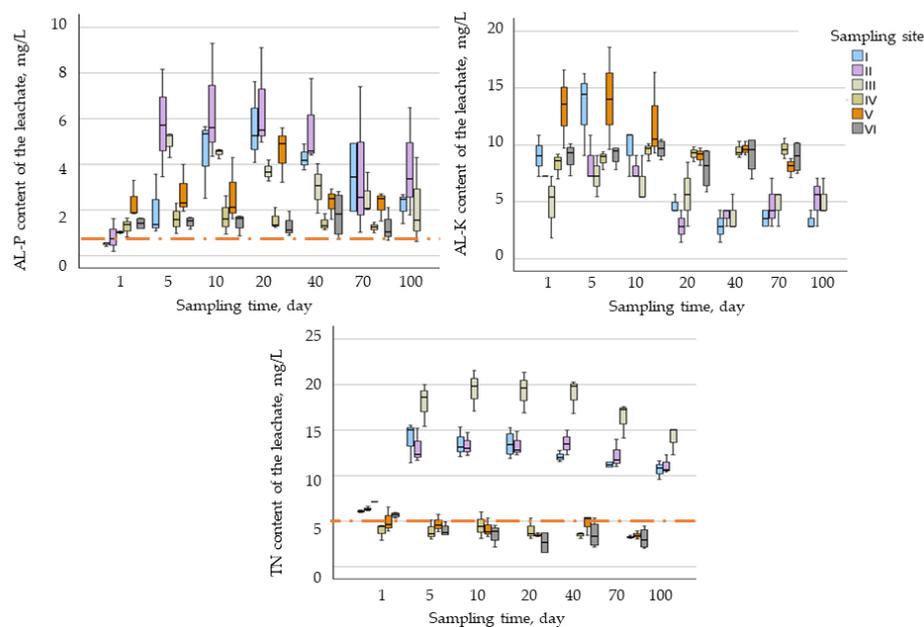


Figure 6. The nutrient content of leachates taken at different times (within 100 days) The dashed red line shows the water quality regional limits for the direct recirculation of treated wastewater in the Balaton catchment area in Hungary (Decree No. 28/2004 (XII. 25.) for “Direct receivers of Lake Balaton and its catchment area”).

Table 4. Nutrient loss in the column experiment.

	Drained Water L	P Loss	K Loss %	N Loss
Mean	4796	1.17	0.39	1.14
Minimum	3610	0.44	0.25	0.27
Maximum	5845	3.13	0.61	3.12

Based on the mean nutrient content of leachate and volume of the sediment extracted (~350 m³) during experimental dredging, the potential additional load could have been 4.1 kg P, 2.6 kg K, and 13.9 g N in the case of direct recirculation.

Comparing the water quality parameters measured at monitoring points close to the Bárándi water area (Figure 1: z14, kb4, and kb10—during the experiment period; Table A1) and the leachate quality measured in the column experiment and properties measured during the three types of desiccations, it can be concluded that the concentration of leachate of the columns differed from the maximum nutrient content of water from the monitoring points of the KBWPS I mainly in their TP content. The column experiment modeled the equilibrium condition during on-site leaching well in the sense that no nutrient leaching exceeded the experimental value compared to the on-site leaching measured in the column experiment (Table 5). The amount of nutrients (the average TP, TK, and TN) in the leachate of columns was higher than that of natural water. The mean loss of the TP and TN of polyacrylamide-treated sediments was more significant (Table 5).

Table 5. Nutrient content (mg/L) of the leachates of the settling pits at sites I (north) and VII (south) and the column's experimental desiccation, the quality of natural water at monitoring points (z15, kb4, and kb10), and the regulatory limit according to the 28/2004 (XII.25.) Decree of the Ministry of Water and Environmental Protection.

Sampling Site	TP min.	TP max.	TP mean	TN min.	TN max.	TN mean	TK min.	TK max.	TK mean
Leachate of dehydrating pad (Site I) + PAA *	0.07	0.49	0.28	3.20	6.70	4.95			
Leachate of the northern settling pit (Site I)	0.07	0.65	0.20	0.85	9.30	5.00			
Leachates of the southern settling pit (Site VII)	0.07	0.56	0.25	3.40	10.70	5.70			
Column experiments (I–VI.)	0.10	9.30	2.50	1.50	21.50	8.30	1.40	18.60	7.50
Monitoring points (z15, kb4, and kb10)	0.04	0.55	0.15	0.66	5.20	2.45	2.90	6.60	4.60
Regulatory values			0.70			5.00			

Note: * PAA—polyacrylamide; regulatory values are the water quality regional limits for the direct recirculation of treated wastewater in the Balaton catchment area in Hungary (Decree No. 28/2004 (XII. 25.); for “Direct receivers of Lake Balaton and its catchment area”).

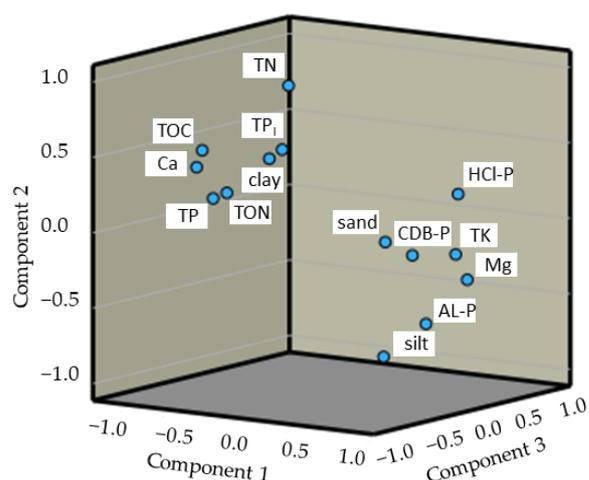
In comparison to the water quality regional limits for the direct recirculation of treated wastewater in the Balaton catchment area in Hungary (Decree No. 28/2004 (XII. 25.); for “Direct receivers of Lake Balaton and its catchment area”), the nutrient content of the leachate could be close to the limit, e.g., the average TN content of the leachate of the on-site desiccation, and might even exceed it for both TP and TN (primarily in the column experiment—Table 5). No regulatory requirement for a threshold K value has prevailed (indirectly, the electrical conductivity of leachate may limit its recirculation).

3.4. Relationships Between P Fractions, Loss, and Sediment Properties

Principal components (PCs) with an eigenvalue exceeding one, selected by Kaiser normalization, are shown in Figure 7.

Table 6. PCA of sediment properties and P loss (TP₁) (SPSS 20.0/PCA/varimax rotation and Kaiser normalization). The intensity of colors shows the magnitude of component scores.

	Principal Components			Communality
	Quality of Sediment	CDB-P	HCl-P	
TP ₁ mg/L	0.427	0.115	0.478	0.425
clay%	0.487	0.864	−0.013	0.983
silt%	−0.714	−0.416	−0.469	0.903
sand%	−0.241	−0.910	0.283	0.965
TP mg/kg	0.674	0.567	−0.382	0.922
TK mg/kg	−0.836	0.349	0.165	0.848
TN mg/kg	0.697	0.405	0.523	0.923
Al-P mg/kg	−0.902	0.273	−0.257	0.955
TOC %	0.986	−0.082	−0.025	0.980
CDB-P mg/kg	−0.626	0.634	−0.003	0.793
HCl-P mg/kg	−0.544	−0.061	0.646	0.716
Ca mg/kg	0.965	−0.165	−0.125	0.973
Mg mg/kg	−0.963	0.207	0.125	0.985
TON mg/kg	0.743	−0.415	−0.068	0.729
Variance	53.6	22.1	10.7	
Σ Variance	53.6	75.8	86.4	

**Figure 7.** Three-dimensional plot of the principal component analysis (more detailed in Table 6).

The component scores (CSs) determined after varimax rotation were significant. The three (uncorrelated) PCs explained 86.4 percent of the total variance. The measure of sampling adequacy in the Kaiser–Meyer–Olkin test (MSA and KMO) reached a value of 0.5, thus being acceptable. Bartlett’s test was significant (chi-square: 637.7; Sig.: <0.001; df: 45), and principal component analysis (PCA) could be performed (Table 6).

Phosphorus loss (TP₁) from the leachate had a relatively minor component score in PCs (and lower communality). Some parameters (e.g., clay content, TOC, P fraction, TP) are presented with the same and opposite signed CSs (as TP₁) in PCs; thus, their role in nutrient cycles is more complex and may be nonlinear. The variance of other variables was well characterized by component scores (communality > 0.7). TC, TON, and P fractions had communality below 0.9.

According to a supplementary Spearman correlation analysis, the sand-size fractions and AL-P were positively correlated with TP₁ ($r_{TP_1\text{-sand}}: 0.633$; $r_{TP_1\text{-AL-P}}: 0.817$ at $p < 0.01$), but TP₁ was inversely proportional to the finer fractions ($r_{TP_1\text{-Silt}}: -0.517$; $r_{TP_1\text{-clay}}: -0.583$).

Principal component I (PC I), the “quality of sediment”, contains sediment properties that affect both the organic and mineral nutrient cycles with significant CSs. This principal

component summarizes the characteristics that determine the organic nutrient cycling and/or affect their mineral composition (usually with opposite signs). Separating the major component into two components was not statistically possible with the small number of elements, and a forced increase in the number of factors reduced the measure of sampling adequacy. In PC I, the rate of P loss (TP_1) was proportional to the TP content. However, the amount and change in the available P fractions could also contribute to the reduction in loss (they were oppositely signed).

AL-P content affected the change and development of nutrient transformation processes with the same sign as the other mineral P fractions (since, by definition, AL-P is supposed to indicate the amount of readily available, mainly mineral P forms). TOC, TON, Ca, and TP also had positive CSs similar to TP_1 , in contrast to parameters that affected the P cycle more strongly in the sediment, such as TK, silt (and sand) fraction, AL-P, and Mg (with negative signs). The role of Ca and Mg in the P cycle, and also presumably in the change in other chemical parameters, was opposite (see also PC III).

The internal relationships between sediment properties and CDB-P or HCl-P content are shown in separate components (PC II and PC III). This indicated that their variation is significantly determined by the P cycle (in PC I) and can also be affected to a large extent by partly independent factors (orthogonal rotation results in independent PCs). The CSs of PC II and III may also provide “background information” on what determines the presence and amount of this potential “buffer capacity” and the amount of CDB-P and HCl-P forms in the sediment. PC II, “the formation of CDB-P”, explains 22.1% of the total variance. The CS indicates that the CDB-P content was very closely related to the clay content of the sediment (which was also reflected in the negative CS of the sand fraction amount). CDB-P had an opposite sign with TP_1 in PC II and PC I, which probably refers to the more significant and complex role of CDB-P in P retention, but the main governing processes affecting the formation and dissolution of Fe-P fractions (e.g., reductive dissolution) are not entirely represented in our results. The CS of TN, together with the opposite-sign CS of TON, probably indicated that the change in CDB-P is not proportional to the organic N fraction (as the TOC content has not appeared in this PC with a CS > 0.4), but it may have seemed to depend more on the mineral N forms.

PC III, “the formation of HCl-P”, accounted for 10% of the variance of the population. The role of the particle size distribution in the evolution of this P fraction was less apparent than in PC II. Processes determining the formation and changes in HCl-P were related to silt fraction, TN content, and the amount of P_1 . The relationship between HCl-P and TN is difficult to explain, as neither TOC nor TON was represented.

4. Discussion

4.1. Physical Properties of the Sediment

On the northeastern side of the reservoir (I, IV, and VII samples), the higher sand content is explained by the flow-induced fractionation and partly by the coarser texture of the original subsoil (Figure 2 sand-covered peaty soils (sampling site 1), peaty marsh soils (2), and soils changing toward meadow soils (9)). The sediment texture appeared to become finer (sand, loam, and clay–loam) [52] as one moved from the north to the south. The results of the physical investigation suggest that the mineral composition of sediments differs depending on the geology of the catchment and the flow and sedimentation conditions (as experienced by, e.g., [50,67]). According to the findings of previous investigations in “dead zones”, silty clay, and clayey sediments may be typical at more favorable settling conditions, which leads to “zones parallel to the longitudinal axis” at Lake Balaton [12,48]. In the case of Bárándi water (Kis-Balaton), it was more likely to appear as sedimentation areas along the flow direction in “patches”, in accordance with the alternating slower/faster or turbulent

flow conditions within the lake bed and shoreline. It could be assumed that within the Bárándi -water area, a faster (along the I–IV–VII line) and a more complex, slower flow directions (in the bays - I, III, V, and VI) can be distinguished. This could lead to several moderately different sub-areas. Similarly, Szilágyi et al. (1990) and Istvánovics et al. (1997) had already proposed the consideration of at least two flow directions (Figure 2) [2,50].

From a practical point of view, the clay content of some samples (parallel with the higher permanent wilting point) might increase the time requirement of desiccation. In particular, however, maybe the amount and distribution of precipitation might limit dredging and desiccation in the winter (moreover, e.g., timing of disposal prior to sowing, incorporation, etc.), and the natural equilibrium nutrient levels of the lake must be restored before the onset of spring biological activity. Based on the particle-size data, the preliminary separation of the sand fraction (as it is lower than 30%) of the sediment is not necessary prior to agricultural disposal.

4.2. Basic Chemical Properties of the Sediments

The significantly higher TOC content of the deeper layers may be mainly related to the presence of peat, peaty, or humic subsoil [52]. Istvánovics and Somlyódi (1998) observed a “transitional zone” toward the “occluded subsoil”, which occupies 60–70% of the investigated sediment (>19 cm core) in their research [14].

According to the survey of Kosári-Tarnik (2019), the average thickness of the sediment layer was approximately 45 cm, so the subsoil was reached in almost all cases during our sampling [53]. However, the higher TOC content near the surface may also indicate the formation of a sediment layer by active biological processes (autochthonous organic matter). This was only supported by the slightly different C/N ratios of the sediments (17–24), which were lower in areas further from the shore.

The considerable $\text{CaCO}_3\%$ content of the sediment is primarily of alluvial origin (Table 6). A significant increase in carbonate content with a slight shift in pH was observed in the 1980s [14]. Similar changes in the water quality of Lake Balaton were reported by, e.g., Rostási et al. (2022) [67] and Vörös et al. (2024) [43]. The authors documented an increase in Ca and Mg content, Mg/Ca ratio, and salinity over the period 1891–2022, mainly caused by the quality of the inflow water. The annual variation in the Ca content of the water/solid phase is further influenced by the cyclical biogenic lime production (e.g., [14,68]) and is also promoted by the presence of clay minerals [69–71]. This may explain the variability of CaCO_3 in our results, which was more pronounced further away from the inflow as experienced by Istvánovics et al. (1997) [50] and maybe far from the shoreline (where reed stands—Istvánovics and Somlyódi, 1998) at Phase I [14].

Increases in carbonate content may represent a significant buffering capacity in the continuously thickening sediment layers. After 1990, the accumulation of Ca increased, but their ratio in the sediment seems to be steady. However, various degrees of nutrient fixation may be characteristic of the sub-areas within the reservoir as carbonates are not uniformly distributed (Table 3) and because, according to the literature, the ratio of Ca/Mg or crystalline/amorphous forms and their different adsorption capacity vary with changing environmental conditions [67,70].

The chemistry of the sediment was close to the carbonate precipitation limit (a higher pH than 8.5–9 led to a rapid decrease in the ratio of $\text{CaHCO}_3)_2/\text{CaCO}_3$). The importance of the small increase in pH with salinity is underlined by the fact that a one-unit change in water pH (from neutral to alkaline; $\text{pH} > 7.2$) might cause several times higher P loss in this sediment. According to the experiences of Istvánovics (1993) and based on the currently used monitoring data (pointing closer to the Bárándi water area— $\text{pH} 7.1\text{--}9$), this pH change

occurs within a year due to chemical and/or biological processes [49], so the system is considered to be increasingly sensitive to changes in chemistry.

4.3. Amount of Nutrients in the Sediments

With respect to the classification applied to agricultural soils (compared to a common brown forest soil—corresponding mainly to Luvisols in WRB—with an average nutrient supply typical of the area [72,73]), the sediment had poor to good available phosphorus (AL-P), medium to good available potassium (AL-K), and poor to medium total nitrogen (TN) at the top 30 cm layer. In deeper layers, higher nutrient concentration can also be found in some sites (up to 16,054 mg/kg TN, 686 mg/kg P, and 22% TOC).

The TP content of the reservoir has not changed markedly over the last 30 years (Table 7), and P saturation was 40–60% already in the 1990s [49]. Thus, the P saturation of the sediment of the Bárándi water area is close to its threshold, 1000 mg/kg, which may already be a significant source of internal loading [52]. Istvánovics (1994) noted that the adsorption isotherm of the sediments of the Bárándi water body (at sampling points 1 and 2—Figure 2) is already flattening at, e.g., pH 7.9 at approximately 1000 mg/kg of P content, even when different amounts of P were added (0.5–2.5 mg/L) [49]. Istvánovics et al. (1989) measured an increase in TP contents (in the range of 1080–2030 mg/kg) with the direction of the flow, indicating a similar situation in other areas [32]. Our results did not reveal similar changes in TP content from the inflow (probably due to the smaller area studied).

Table 7. Chemical properties of the sediment (Bárándi water body) according to previous laboratory analysis and our current measurement during pilot dredging and the relevant data of an accredited laboratory.

		TP	TN	TK	AL-P	TOC	Ca	pH _{DW} (pH _{KCl} **)	Loss of Ignition	CaCO ₃
	Sampling Site *	mg/kg						-		%
[53]	1, 2, 9	~1000						6.6–7.9	1.5–69	0.4–10.6
[50]	1, 2	1720–1780						8.12–8.19	12.6–19.2	20.4 ***
Our measurements in 2023	I–VII	854–977	2471.0–3890.3	7074–10,644	47–393	4.9–7.2		7.7–8.2		20.3–33.5 ****
Data from an ac- credited laboratory	I and VII	990–1090	1000–1100			2.7–3.1	236–286	7.57 **		

* Sampling sites are shown in Figure 1; ** pH measured in KCl; *** mean; **** just for samples IV–VII.

A higher percentage of AL-P in TP was observed at sampling points IV and VII (cca. 30%—Table 3) than in areas not directly following the main flow direction (II, III, V, VI).

The greater variance in the AL-P content of the core samples than that of undisturbed samples (hence, fewer significant differences) could be explained by the significant vertical deviations in the available nutrient content of the sediment (Figure 4).

The observed lower AL-P near the inflow is somewhat contradictory to the results of Istvánovics (1993), who reported decreasing readily available mineral P content (NaOHrP/Fe-P + HCl-P) further away from the inflow [49]. However, the author found similarly lower P retention in higher-sand-content and lower-organic-matter-content sediments closer to the inflow, and the higher adsorption capacity of Fe minerals was observed far from it.

Seasonal variations in P “profiles” can also be observed in our experimental results. The P maximum was typically below the surface in late autumn and winter (e.g., due to burial), while in summer, a maximum was observed closer to the surface (resulting from physical, chemical, and biological processes [16,18,31,38,43,51,67,74]). However, the identification of these processes at the Bárándi water would require further investigation. This could also be important because there are interactions between the composition of

the pore water and the water phase (TP, soluble reactive phosphorus—SRP and Fe-P [38]; TP [18]; and SRP and Fe [19]). The question remains open as to whether, if some buried layers of the sediment have higher P and or TOC contents, the consequences might be a possible internal nutrient load due to temporary seasonal or summer dredging.

There is only limited literature available on the K content of this sediment. The higher AL-K values in the 0–20 cm layers of points I–IV may reflect the surface location of the transported recent sediment. The AL-K content of core samples is known to be more significant in areas with higher mineral colloid content (as at III–VI). The AL-K was less variable at samples IV and VII. Its spatial variation may be somewhat caused by the mixing of sediments of various origins and changes in the ratio of organic–mineral elements. However, if the latter could only be explained by the high degree of mixing [16], it would also be reflected in the amount (or lack thereof) of other nutrients. Furthermore, it is difficult to explain why the AL-K content of the disturbed samples I, II, and VI was significantly different from that of the original layered samples (although the AL-P content of the columns was generally similar). It can be assumed that the higher sand content (SiO₂), the disturbance (via solubility), and possibly the observed low disaggregation of the sand fraction during the experiment also influenced the amount of AL-K.

Overall, the composition of the sediment did not restrict its agricultural disposal according to its chemical and physical properties (for example, lower than 30% of sand content, not too extreme hydrological properties, and poor to good nutrient content with a TOC higher than brown forest soils); in addition, it complied with the regulatory limits for the disposal of sewage sludge in agricultural practice (Government Decree 50/2001 (IV.3)) for heavy metals, major pollutants, etc.—not presented in this study. However, the spatial variability of nutrient content may determine the optimal location and depth of excavation, as well as the possible environmental impacts of dredging.

4.4. Phosphorus Fractions in the Sediment

The measured CDB-P and HCl-P content was similar in magnitude to the results of an investigation by Istvánovics et al. (1989) for sediment Phase I (Table 7) [32], but CDB-P was higher than that observed by Istvánovics (1994) [49]. Most Fe-P might be of subsoil origin [50], but the experienced differences between our results and previous findings are presumably due to changes in the composition of the alluvial sediment from the watershed (as it decreases with distance from the inflow, and the relationships between TK and Fe-P and Al-P in PCA). However, it is not known from our results whether the change in the CDB-P fraction is related only to the Fe-P fraction or also to the amount of NH₄Cl-P (the soluble reactive P, which was not extracted in separate steps before CDB-P measurement). The latter was not so high in the sediment of the Bárándi water area [49], but all these fractions could compensate for each other in response to seasonal changes in environmental conditions [18,38,49,74]. Both represent the potentially mobile inorganic P fraction (based on the results of ³²P exchange by Petterson and Istvánovics (1988) [75]. Ding et al. (2017) also described the prominent role of Fe-P in microbiologically enhanced redox-induced P loss [22].

According to Istvánovics (1994), the amount of NaOH reactive Fe-P fraction and HCl-P accounts for approximately 60–80% of TP [49]. However, our results indicate that only cca. 25–50% of TP may be extracted with CDB and HCl. If this deviation is not a consequence of methodological differences [76,77], it may indicate that the residual phosphorus formed locally at an increasing rate is essentially biological in origin [49].

The spatiotemporal variability of Ca-P and Fe-P was also reported in other investigations, e.g., [14,18,42,49]. CDB-P content was mostly higher than HCl-P in the sediment of the Bárándi-water. The generally lower AL-P than the total amount of readily available

mineral P fraction (HCl-P and CDB-P) may be explained by the fact that ammonium lactate extracts less P than HCl and CDB. Another reason could be that the latter releases a larger part of the labile organic P present in the sediment [50,75,78]. Moreover, the lower AL-P content (as easily available mineral P that is inversely proportional to resistant and organic P) might reflect the higher ratio of more resistant organic P and residual mineral fractions in the sediment of V and VI sampling points.

Our results show that both the HCl-P and CDB-P fractions play a significant role in sediment phosphorus retention. Only other studies provide data on the Fe content of the sediment for our analysis (32.4–30.9, i.e., an average of 31.65 mg/g [49]). The average Fe:P ratio (free absorption sites in the oxidized sediment [79], calculated with an average of 0.895 mg/g TP (measured)) was 37:1, indicating an important role of Fe minerals in P retention (reductive dissolution of P is more pronounced when lower than the 15:1 ratio [79]).

Further studies are needed for the sub-areas (on a larger number of samples, including detailed sequential extraction procedures and the separation of organic and inorganic P forms (e.g., SEDEX method of Vink et al., 1997 [80]; Anshutz and Debore, 2016 [64]) or the development of detection methods (e.g., Liu et al., 2020 [81]) to understand the variation and change in the P fractions, as they have different environmental “sensitivities”).

4.5. Evaluation of the Nutrient Loss

The slight nutrient loss experienced in the column experiment resulted from the fact that P is primarily a slightly soluble nutrient. The TK value of the leachate was similar to that originally measured in natural water. The naturally high TK concentration in the Bárándi water body might be a consequence of urbanization and the salinity increase associated with the natural life cycle of the lakes (similarly to Lake Balaton [41]). The observed TN was low. The experienced P loss was lower than the 0.5–10% measured by Istvánovics (1994) (at points 1 and 2, 0.5–2.1%; and 10% at point 9) using the centrifugal extraction method [49]. According to their experience (which is consistent with ours), the P loss was higher in organic-matter-rich areas (e.g., II, III, V) and in sediments containing more sand fractions (I). The higher P loss measured by Istvánovics (1994) can probably be explained by methodological differences (application of centrifugal suction forces higher than cca. 33 kPa at field capacity) [49]. Centrifugation time, force, and equipment geometry all affect the results of centrifugation (mainly the amounts of soluble salts, but sometimes also total organic P or molybdate-reactive P [76,77]). Furthermore, the nutrient losses determined in laboratory experiments do not represent natural processes adequately, as they neglect some key aqueous/solid phase interaction processes (e.g., no sedimentation) or even upward P release from organic matter decomposition, enzymatic processes, transport, and gradient fluxes [12,35,82].

The various patterns of leaching observed (Figure 5) could also be due to seasonal effects [25,51,83]. Assuming no other losses in the water balance (no plant uptake, infiltration, etc.), evaporation in the column experiment was ~27% on average. Under natural conditions, evaporation and water level changes can influence the precipitation of carbonates and silicates [16,36,67] and redox conditions. Thus, redox-induced dissolution and biological processes occur as well [12,22,28,35,84,85]. A change in temperature alone can trigger P release [12,30,35]. These may be the main reasons for the observed higher P and N losses, which were not completely systematic but were mainly measured at the beginning of our column experiment (I–III—samples collected in early September). With continuous significant evaporation, the nutrient concentration of the leachate fluctuated to a lesser extent (at samples IV–VI, in summer—Figure 5). Since the C/P ratio of the sediment in our experiment was approximately 60, the mineralization of organic phosphorus was not carbon (C/P < 150—as stated by Füleky for soils [86]) but rather temperature-limited. It

can also be assumed that the microbial activity of the sediment might contribute to the results of the column experiments (at least at temperatures higher than 10 °C).

In the experimental on-site desiccation and column experiment, the leachate was drained only at a certain “point” (no equilibrium P concentration with the surrounding solid phase was formed), and its concentration might be represented primarily by the equilibrium sediment/pore water concentration and its changes. In the latter, the nutrient concentration of the leachate generally decreased after the first month, reflecting gradual rebalancing. Moreover, the measured TP concentration of the leachate (0.1–9.3 mg/L) was similar in magnitude to empirical values of the pore water (which might be two or three times higher, even without considerable mixing (0.2–15 mg/L) [12,34,81,87–89]. This interfacial deviation in TP content could ensure a strong diffusion driving force [34,35], and it led to an increase in nutrient concentration in the water phase due to disturbance.

A further investigation is needed to determine the extent to which the TP content of the sediment in the Bárándi water area and, within this, the TP loss of pore water may be influenced by seasonal effects. It would also be important to understand the impact of the excess P loads by leachate on the water quality of the receiving reservoir. The experience of Sasaki et al. (2001) suggests that the arrival of excess nutrients can be buffered by adsorption up to a nutrient content of 0.03 mmol/L (~2.8 mg TP/l), above which a significant increase in the water-phase TP content is expected [89]. The adsorption/desorption concentration limits determined by Istvánovics (1994) for the Phase I reservoir showed a much lower limit (~0.9 mg TP/l) [49]. According to our results, these limits were exceeded in several cases by the TP loss of the model system. Thus, the leachate may not be directly recirculated without further research. Furthermore, our findings may well characterize the winter desiccation losses of the Bárándi-water sediment, but they cannot be generalized to transitional or summer drying periods when the opportunity for internal loading is greater.

4.6. Relationships Between P Loss and Sediment Properties

According to the results of PCA, the total phosphate loss TP_1 by leaching was influenced by sediment properties that strengthen and weaken one another and influence each other's role in nutrient release.

The lower communality of TP_1 might be caused by its variance, which is highly influenced by several environmental factors [18,22,31,35,86,90] or other sediment properties (e.g., pH, redox potential, etc. [12,26,31,35,49,89,91]). The ratio of certain chemical elements could also affect TP_1 (e.g., inversely proportional to the Fe/P ratio [79]). The impacts of sediment parameters on TP_1 are somewhat contradictory, as found by other researchers in previous studies (e.g., positive and negative effects of organic matter, even pH [31,75,92–95]). Similar reasons might be accounted for by the lower communality (<0.9) of TC, TON, and P fractions. Their variance may be affected by different factors, e.g., TK depends on mineral composition and dissolution conditions, or TN is formed by biological processes, and the variation of P fractions may also be influenced by various other sediment or environmental parameters prevailing during the experiment (as mentioned previously).

The results of the additional correlation analysis showed that TP_1 was inversely proportional to the clay and silt content, which might directly and indirectly (clays as mineral colloids or as constituents of organo–mineral complexes) enhance adsorption [75,79,94–97]. P loss increased with sand content [32]. The higher the proportion of finer elemental particles, the higher the P sequestration rate, especially by Fe-(oxi)hydroxides (e.g., [97]). This was verified by the fact that TP_1 was significant at sampling point I. (Figure 6). This is probably the reason for the relatively higher P saturation (in terms of adsorption capacity) of the sediment at the Bárándi-water inflow (>40% on average and above 80% at point 1 [49]). The importance of these experiences is emphasized by the sediment's particle size,

and it plays a significant role in the regeneration of eutrophicated lakes following excessive nutrient loading [16]; it is also strongly correlated with the TP content of porewater (inversely proportional to the finer fraction [98]).

Despite the opposite role of AL-P and TP₁ in “sediment quality” (PCI), their correlation was not inversely proportional (Table 2). The role of readily available P forms in P loss/retention may even be seen as oppositely related depending on the circumstances, and their causal relationship is more complex. The Spearman correlation between AL-P and TP₁ means that the “factors” that determine the AL-P content may also have a significant indirect effect on the composition of the leachate.

The amount of TP is related to the release potential (in PCI), but the available forms can also act as a sink and source of P loss. In addition, TP and TOC had the same negative sign in PC I, which might highlight the importance of organic matter in P cycles. It is also possible that it was not the AL-P TP₁ relationship that was reflected in our results but the correlation between TP₁ and the more resistant P fractions near the other direct components of the complex relationships between organic C and P cycles [75,84,95,99–102]. Since the difference between TP and AL-P is roughly proportional to the amount of organic and residual P fractions, it is not possible to determine from the results whether the close inverse proportionality relationship between TP₁ and AL-P is due to the organic P content and AL-P or whether it is due to the leaching reducing effect of the residual P fraction or their interaction.

The formation of iron-oxi/hydroxides (PC II) is a very important process in P retention (aggregate formation and nutrient fixation [12,35,74,75,79,97]). Fe-P may be the main source of P available to the phytoplankton [22,90,97]. Peticrew and Arocena (2001) found that the accuracy of the multivariate regression estimates of P loss was improved by the knowledge of Fe-P content (correlation between PO₄-P and Fe-P ($r = +0.59$)) [97]. Our results show that clay/sand contents are important sediment properties that relate to the amount of CDB-P. The relationship between Fe-P and texture may not only be direct (through adsorption) or indirect (by organo–mineral complexes or by their decomposition) [94–102]. Humic substances, carbonates, and Fe-oxi/hydroxides, which are key components of chemical and physical adsorption and co-precipitation, may also be predominantly enriched in clay and silt fractions [101] as in soils [103]. Further research on these complex processes is needed. Similarly to the relationship between AL-P and TP₁, there may be a condition-dependent interrelation between CDB-P and TP₁ (P sorption increases with the amount of Fe-P fraction in oxic environments, but this decreases near anoxic or reductive environments [12,26,49,75,89,91]).

The structure-forming effects of Fe minerals were not directly observed in our results (CS is opposite to CSs of TOC and TON), but the literature suggests that their role in soil aggregate stability is less significant at higher organic matter contents [103]. Our results have demonstrated that the TP variation is essentially directly proportional to the change in PCII Fe-P (as reported in the literature [104]) and texture, which may indicate the sedimentation-promoting effect of iron-oxi/hydroxides [85] and the importance of mineral P forms in the P content of suspended solids [12,28,35].

TON in PC II was not correlated with the amount of CDB-P, but the CS of TN suggests that mineral N may be the cause of this. Among the mineral forms of nitrogen, the amount of nitrate may be the one relative to which Fe-P content is sensitive, since it can also determine redox conditions (e.g., nitrate feedback to enhance degradation processes in wastewater treatment or nitrate addition to lakes to maintain an oxidized condition [40,41]). However, only further studies (sediment and water quality monitoring) can provide information on how these processes manifest themselves in the case of the Bárándi water area. Also, the ratio of C, N, and P can also significantly determine the turnover and availability of nutrients [20,22,75,79,82,103,105].

CDB-P and HCl-P had opposite signs in components II and III, indicating interconversion processes and a somewhat competitive relationship between them [14,75,105]. Transitions between the P fractions are condition-dependent and governed by complex mechanisms [32,49,70,79,82,91,104]. Li et al. (2020) [87] found that different mechanisms maintain the equilibrium P levels at various transitions of macrophyte and algal dominance in lakes. They found that the external P source is important at the beginning of algal growth, changes in the Fe-P fraction are the governing mechanisms upon algal dominance, changes in organic P hydrolysis and the Ca-P fraction are important in transitions, and even P deficiency can occur during macrophyte dominance [106]. More detailed research is required to carry out a better identification of these transformation processes between P fractions, for a better understanding of the role of organic P fractions in P release or internal P loading, and to gain more knowledge about the lake-specific role of biological P cycle elements. More detailed research is required to obtain better knowledge of these transformation processes between P fractions, to better understand the role of organic P fractions in P release or internal P loading, and to gain more knowledge about the lake-specific role of biological P cycle elements. The potential contribution of groundwater to internal loading also needs to be understood [29,85].

Similar positive CS values for TN in all three PCs suggested the role of the TN:TP ratio in P release, which may increase inversely proportional to the TN:TP ratio (e.g., [20,105]).

According to our results, Ca^{2+} content (as in the basic statistics) may act as a reducing factor in P release (in spite of the fact that HCl-P content did not follow a linear relationship with it) and may also be a significant source of P loss. The role of texture in the formation of HCl-P was less apparent, probably because the Ca-bearing minerals (adsorbed, coprecipitated crystalline, and amorphous forms) can be present in soils and sediments in a wider range of textures than Fe-(oxi)hydroxides [98]. The positive CS of TP_1 and sand content, but negative CS of silt content, may be proportional to the higher nutrient fixing capacity of the finer-sized carbonate elements.

The PCA results indicate an environment-dependent “competition” between Mg^{2+} and Ca^{2+} ions according to equilibrium conditions (opposite signs) (as observed by other scientists [67,70,71,101]). Ion competition could play a significant role because the mineral composition of sediment from a watershed can change over time (maybe as at Lake Balaton [11]). One-third of Ca^{2+} can generally sorb incoming phosphorus at chemical equilibrium [75], and excess Ca^{2+} prevails as CaCO_3 (mainly abiotic precipitation [2,32]), Ca/MgHCO_3 , or adsorbed forms on colloids, etc. Phosphates (e.g., apatites) and carbonates can compete for Ca^{2+} at the optimal temperature, chemistry, ionic composition, Ca/P ratio, etc., for coprecipitation [32,35,70,71]. These processes were probably the reason why the potential P fixation was not always proportional to the Ca^{2+} content of the sediment (higher CaCO_3 contents (~1.5 times) may correspond to the lower AL-P content of samples V and VI in the Bárándi water area than in samples IV or VII).

In our experimental results, a similar strong impact of Ca^{2+} content and TOC (especially in PCI, but always with the same sign of CSs) on P cycles was found. The amounts of carbonates can also be significantly influenced by biologically induced carbonate precipitation (pH increase during algal blooms provides the driving force [66]), which can be seasonally dominant [49]. The deep impact of the Ca cycle on P cycles can be highlighted by the fact that the pH of the Bárándi water area is around the carbonate precipitation limit. In the $\text{CO}_3^{2-}/\text{HCO}_3^-$ system, pH and its seasonal variation play a crucial role in nutrient loss [31,35,49,91,93]. Istvánovics (1994) found that the precipitation of apatite also depends on the $\text{CO}_3^{2-}/\text{HCO}_3^-$ ratio of water [50], which was identified as a key parameter determining chlorophyll concentrations at some sampling points [35].

5. Conclusions

The sediment of the Bárándi water area (Lake Kis-Balaton) was assessed as poor to medium in TN, low to medium in AL-P, and medium to good in AL-K content for agricultural use. Silt-sized particles dominated the sediment. The pre-separation of sand content (<30%) was not necessary before desiccation and agricultural disposal. The physical and chemical properties of the sediment did not preclude its agricultural use. However, the nutrient and organic matter content showed considerable spatial heterogeneity, resulting from the multiple flow directions and various hydrological conditions (concerning the sedimentation, turbulent flow areas, etc.), shallow water levels, and the properties of the bottom sediment or subsoil (e.g., peaty or sandy layers, meadow soils). The formation of sub-areas with different clay, silt, and sand contents and nutrient, organic matter, and carbonate contents, etc., may provide different initial conditions for physico-chemical and even more so biological processes. All these deviations may lead to various environmental impacts of dredging and/or a possible direct recirculation of the leachate. The results of our research suggest that sampling at a greater depth than the excavated layer is recommended before dredging after a preliminary assessment of the sediment's thickness.

The carbonate content increased significantly (to cca. 30%) before the 2000s, similarly to Lake Balaton, in parallel with the increase in sediment layer depths. More than half of the phosphorus was stored in organic and residual form, while a significant amount of P was retained in HCl-P and CDB-P. Previous experiences showed that closer to the inflow, changes in sediment quality were mainly governed by physicochemical processes, while in areas further away from the inflow, the role of the biological nutrient cycle may have temporarily dominated [12,49]. Our results show that the prevalence of these processes (e.g., the formation of various P fractions) can be largely determined by sediment characteristics and their spatial variability. The interaction of sediment properties and other environmental conditions leads to areas with different characteristics not only along the flow direction but also, e.g., in deeper, shallower, mid-lake, and shore areas within the reservoir. Because of the increasing CaCO₃ content (possibly salinity), the pH close to the CaCO₃ precipitation limit, the significant amount of CDB-P, and the low water level, the Bárándi water area was found to be highly pH- and redox-sensitive. Further research is needed to understand how the removal of carbonate-rich sediment may alter the nutrient cycling of the reservoir relative to the noncarbonate but organic-rich subsoil layers.

During the late autumnal excavation, combined with winter desiccation, nutrient loss due to drainage was less than 5% (for TP, TN, and TK), somewhat lower than what was previously observed by others [50]. However, the TP content of the leachate (in the column experiment and pilot desiccation) could be higher compared to natural water (at selected monitoring points) and sometimes reached regulatory limits for potential receivers (28/2004 (XII.25.) National Decree). The amount of nutrients in the leachate was similar to the composition of the porewater quality based on general information in the scientific literature. The balanced (solid/leachate) nutrient content of "pore-water with gravity drainage" depends on sediment characteristics (or environmental parameters that determine it indirectly), may be affected by disturbance, and may show seasonal variations. For on-site desiccation, a possible increase in the threshold for TN or TP was observed. At present, the possibility of recirculating leachate cannot be considered. This should only be envisaged if the efficiency of nutrient removal could be enhanced by recirculation through the appropriate manipulation of biological processes based on sufficiently detailed knowledge of the internal processes of the reservoir.

According to the results of the PCA, the "quality of the sediment", its basic properties, nutrient status, P forms, and P loss were significantly determined by the texture and readily available mineral P fractions (CDB-P and HCl-P) and indirectly by the organic P,

organic matter, and carbonate content of the sediment through more complex processes. The formation of available P forms in various sediment types in the Bárándi water sub-areas (through adsorption, coprecipitation, etc.) also varies with the sediment properties. Since, at Lake Kis-Balaton, “P desorption is the basic process that determines SRP (soluble reactive phosphorus) concentration in the Reservoir” [14], further research is needed to understand and recognize these relationships. As the P release is mainly a physico-chemical process (adsorption/desorption) but temporarily and seriously governed by biological factors [10,15,19,74,91,104–106], more research is thus needed concerning the biological P uptake and release in the Bárándi water sediments and the role of N and organic matter in P cycles (e.g., mineralization and limitations).

The quantification of P loss is lake-specific. Thus, studies could always be carried out for a specific reservoir, sub-area, or bay [23,31,51,88,106] with given conditions and processes when considering the disposal of leachate, direct and/or indirect recirculation, and use options. The spatial heterogeneity of sediment quality, its temporal variation, and the complex relationships between nutrient loss and sediment properties suggest that, in addition to water quality assessment, sediment monitoring prior to, during, and after dredging is necessary. For this purpose, detailed sediment monitoring and mapping are necessary, similarly to what has been carried out for Lake Balaton [48,107–109]. Experiences of further research could help us understand the nutrient dynamics, internal loading, and eutrophication processes in a given reservoir and explore the ways we can control them. The results of this research could provide the basis for an action plan and technology documentation to be developed for the dredging and disposal of sediment from different water bodies (especially shallow, hardwater reservoirs) relative to agricultural purposes. Mapping the sediment and the development of a well-designed sediment monitoring system would not only help us understand water quality changes and better dynamically control the KBWPS but would also provide opportunities for the application of possible alternatives of dredging (smarter water level control, design of reservoir areas supporting nutrient removal, and the use of biomanipulation techniques) to prevent internal load or eutrophication events.

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Abbreviations

The following abbreviations are used in this manuscript:

TP	Total phosphorus content (mg/kg or mg/L);
TK	Total potassium content (mg/kg or mg/L);
TN	Total nitrogen (mg/kg or mg/L);
AL-P	Ammonium-lactate-soluble phosphorus (mg/kg);

AL-K	Ammonium-lactate-soluble potassium;
TOC	Total organic carbon content (%);
DOC	Dissolved organic carbon content (%);
TSS	Total suspended solid (mg/L);
CDB-P	Citrate–dithionite–bicarbonate-soluble phosphorus (mg/kg);
HCl-P	Hydrochloric-acid-soluble phosphorus content (mg/kg);
PWP	Permanent wilting point (vol%);
NaOH-P	Sodium-hydroxide-soluble phosphorus content (mg/kg);
FC	Field capacity (vol%);
NH ₄ Cl-P	Ammonium-chloride-soluble phosphorus (mg/kg);
TP ₁	Phosphate loss by leaching (mg/L);
TK ₁	Potassium loss by leaching (mg/L);
TN ₁	Nitrogen loss by leaching (mg/L);
SRP	Soluble reactive phosphorus (mg/L);
EC	Electrical conductivity (μS/cm).

Appendix A

Table A1. Water characteristics of Kis-Balaton at the nearest monitoring points (kb4, kb10, and z15—Figure 2) to the investigated reservoir (Bárándi water) during the period of the column experiment (29 September 2022–15 November 2023).

Properties	Mean	Std. Dev.
pH	8.2	0.3
EC	730.8	117.9
HCO ₃	394.1	87.5
CO ₃	6.0	11.4
TSS	39.1	40.1
TP	0.2	0.1
PO ₄ -P	0.1	0.0
Na	28.5	8.9
K	4.6	0.8
TOC	10.0	3.4
DOC	9.4	2.5
TN	2.4	0.9

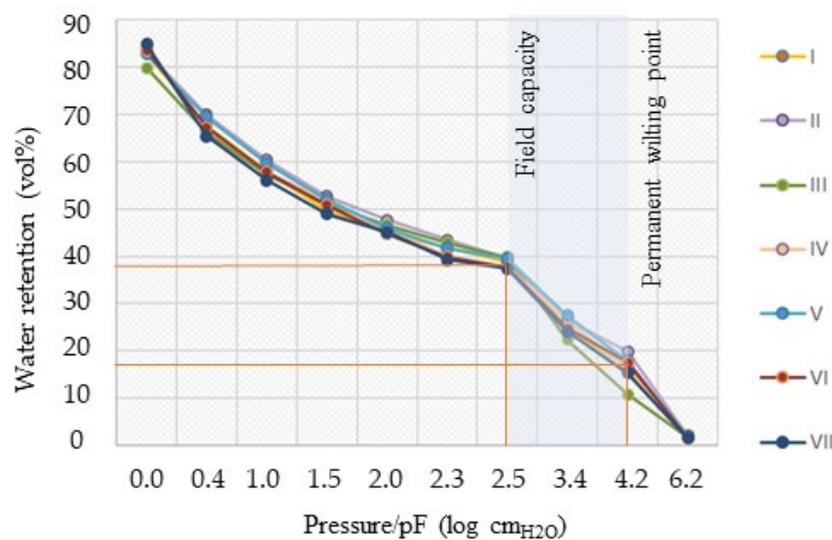


Figure A1. Water retention of the sediment samples from sampling sites I–VII.

Table A2. Particle size distribution of the sediment samples.

Sample	Depth	Clay (<7 μm)		Silt (7–50 μm)		Sand (>50 μm)		
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	
I	0–180	17.9	0.5	54.3	1.1	27.8	1.6	
	II	0–180	28.7	0.9	59.9	0.3	11.4	0.7
	III	0–180	30.6	0.2	59.4	0.3	10.0	0.4
	IV	0–180	26.3	3.6	61.1	0.5	12.7	3.2
	V	0–180	28.9	0.1	59.1	0.7	11.9	0.6
	VI	0–180	25.9	2.7	61.0	0.8	13.2	1.9
	VII	0–180	25.3	0.1	55.6	0.2	19.2	0.3
I	0–20	20.5	0.8	56.8	1.1	22.7	1.8	
	40–60	20.7	0.7	57.5	0.9	21.8	1.4	
	80–100	20.9	1.0	57.6	1.1	21.5	2.1	
II	0–20	33.5	1.0	59.0	0.3	7.6	0.8	
	40–60	33.7	1.5	59.4	0.6	7.0	0.9	
	80–100	33.2	1.9	59.0	1.1	7.9	2.3	
III	0–20	35.4	0.6	58.1	0.6	6.6	1.2	
	40–60	35.5	0.5	58.4	0.8	6.2	1.3	
	80–100	35.1	0.3	58.2	0.4	6.8	0.2	
IV	0–20	29.5	0.4	59.0	0.3	11.5	0.2	
	40–60	29.8	0.4	59.2	0.5	10.9	0.8	
	80–100	29.3	0.2	58.7	0.7	11.9	0.8	
V	0–20	34.7	0.7	56.3	0.7	9.0	1.2	
	40–60	34.2	1.0	55.9	0.9	9.8	1.8	
	80–100	34.5	1.4	55.4	1.5	10.1	2.3	
VI	0–20	33.2	0.7	53.3	3.2	13.6	3.8	
	40–60	33.3	0.6	54.9	2.1	11.8	2.7	
	80–100	33.7	0.9	55.7	1.5	10.6	2.3	
VII	0–20	29.5	0.1	55.1	0.5	15.4	0.6	
	40–60	29.4	0.1	54.9	0.5	15.8	0.5	
	80–100	29.5	0.4	54.9	0.4	15.5	0.6	

Column experiment 1. (at the beginning)

Table A3. Chemical properties of the sediment at the beginning (1.) and at the end (2.) of the column experiment.

Sample	TP		TK		Ca		Mg mg/kg		AL_P		AL_K		TN		TOC %		CDB-P mg/kg		HCl-P				
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.			
Column experiment 1. (beginning)	I	0–130								102.3	14.9	324.7	5.1	2252.3	121.9								
	II	0–130								113.1	18.0	345.5	10.7	2803.7	376.3								
	III	0–130								182.1	25.4	238.4	9.8	2029.5	53.8								
	IV	0–130	854.0	9.0	10,644.0	339.0	82,148.0	792.0	10708.0	17.0	328.5	24.2		2794.0	35.1	5.3	0.1	222.7	41.6	188.7	84.4		
	V	0–130	879.0	9.0	7824.0	1623.0	133,064.0	2147.0	9323.0	140.0	234.0	7.8		3213.0	55.1	7.1	0.0	182.3	19.2	139.5	36.7		
	VI	0–130	876.0	8.0	7047.0	149.0	128,661.0	1218.0	9370.0	49.0	266.0	1.6		2858.0	139.2	6.8	0.1	158.4	13.3	84.5	13.8		
	VII	0–130	971.0	9.0	7767.0	376.0	66,471.0	619.0	10,616.0	92.0	411.2	52.2	270.8	18.6	3463.7	75.0	5.0	0.0	215.9	44.8	194.5	68.9	
Column experiment 2. (at the end)	I	0–20								95.1	34.2	302.2	3.9	2793.3	111.5								
		40–60								71.9	59.6	295.2	6.6	2793.3	51.3								
		80–100								47.1	7.8	303.2	8.3	2746.7	35.1								
	II	0–20								181.6	184.3	296.3	41.7	3132.5	498.3								
		40–60								155.2	143.2	297.1	40.0	3177.5	460.0								
		80–100								135.0	45.6	305.5	38.4	3177.5	467.1								
	III	0–20								372.9	105.2	217.7	4.6	2410.0	70.7								
		40–60								393.0	66.9	215.6	19.0	2430.0	0.0								
		80–100								328.5	44.2	222.0	10.4	2410.0	28.3								
	IV	0–20								316.6	9.4	224.1	11.3	2501.3	96.0	5.2	0.0	101.3		213.4	0.0		
		40–60								331.7	9.1	226.8	28.1	2570.0	40.0	5.3	0.1	120.6		194.3	0.0		
		80–100								353.4	37.2	213.9	14.1	2514.0	61.6	5.3	0.0	121.7		211.3	0.0		
	V	0–20								225.2	49.7	216.5	12.8	3082.0	290.8	7.2	0.1	113.7		70.2	0.0		
		40–60								232.1	25.8	209.5	6.3	2902.0	50.5	7.1	0.0	124.3		84.0	0.0		
		80–100								241.4	12.0	217.4	12.2	2958.7	137.4	7.2	0.1	170.5		106.8	0.0		
	VI	0–20								289.4	16.2	224.4	5.0	2569.3	134.4	6.4	0.8	195.4		114.2	0.0		
		40–60								252.6	37.9	250.1	7.4	2471.3	96.7	6.7	0.1	174.7		72.3	0.0		
		80–100								258.5	37.9	227.6	11.7	2566.0	218.2	6.7	0.1	216.1		123.8	0.0		
	VII	0–20		977.0		7366.0		66,593.0		10,676.0	0.0	522.8	16.9	301.5	13.7	3590.3	303.0	5.1	0.1	240.3	43.1	73.9	86.4
		40–60		961.0		7822.0		6,5800.0		10,510.0	0.0	440.5	57.3	294.7	8.2	3480.3	121.8	5.0	0.1	275.2	40.3	184.1	99.2
		80–100		974.0		8112.0		67,020.0		10,661.0	0.0	448.4	70.0	288.2	12.5	3320.3	93.5	4.9	0.1	238.0	9.0	107.7	16.9

Table A4. Post hoc tests of (A) sediment samples' sand content (column experiment). (B) AL-P content of the core samples taken from different sampling sites. (C) AL-P content of the undisturbed samples at the beginning of the column experiment and (D) AL-P, AL-K, TN, and TOC content of the disturbed and undisturbed samples.

Statistical Analysis	Sampling Site		Properties	Significance		Core	Tamhane's Test Sample Types *	
				Levene's Test	Univariate Anova		Dist. 1.	Dist. 2.
Column experiment 1. ** (at the beginning)	A	I–VII	sand	0.001	0.001			
Column experiment 2. ** (at the end)			sand	0.001	0.001			
Core samples	B	I–VII	AL-P	0.083	0.001			
Column experiment 1.** (at the beginning)	C	I–VII	AL-P, AL-K, TN, TOC	0.001	0.001			
Comparison of the chemical properties of the disturbed (column experiment) and undisturbed (core) samples	D	I	ALP	0.006	0.095	a	a	a
		II		0.309	0.651	a	a	a
		III		0.026	0.270	a	ab	b
		IV		0.056	0.029	a	b	b
		V		0.306	0.001	a	b	b
		VI		0.003	0.129	a	a	a
		VII		0.229	0.037	a	a	a
		I	AL-K	0.001	0.001	b	a	a
		II		0.001	0.001	b	a	a
		III		0.233	0.001	b	ab	a
		IV		0.007	0.896	a		a
		V		0.002	0.008	b		a
		VI		0.126	0.001	b		a
		VII		0.042	0.001	b	a	a
		I	TN	0.002	0.398	b	a	a
		II		0.001	0.035	b	a	a
		III		0.004	0.320	b	a	a
		IV		0.010	0.001	b	a	a
		V		0.001	0.006	b	a	a
		VI		0.051	0.571	a	a	a
		VII		0.168	1.00	a	a	a
		IV	TOC	0.008	0.557	a	a	a
		V		0.001	0.037	a	a	a
		VI		0.001	0.092	a	a	a
		VII		0.295	0.993	a	a	a

Note: * Sample-type meaning: Core: core samples; Dist.1.: disturbed samples at the beginning of the column experiment; Dist.2.: disturbed samples at the end of the experiment; ** results of Tukey tests are shown in detail in the text (Figures 4 and 5). Post hoc tests (Tukey or Tamhane) were used depending on the results of Levene's test—SPSS/univariate/homogeneity test. The small letters (a–b) indicate samples with significantly different means of the investigated chemical properties based on the results of the post hoc test (in descending order of abc).

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