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The Assessment of External and Internal Nutrient Loading as a Basis for Lake Management

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Abstract: Successful management of lake ecosystems used for recreation requires firstly an identification of nutrient sources. It is necessary to identify the factors causing the deterioration of water quality and to plan measures for their mitigation. Analyses of the external and internal nutrient loading were carried out for the hypereutrophic Raczyńskie Lake. The study included flows from lake tributaries, stormwater runoff from impermeable areas and direct catchment impact as external sources of nitrogen and phosphorus, as well as bottom sediments as an internal source of phosphorus. In the case of external sources, the largest load (about 80% of N and 67% of P) is supplied from croplands via the shoreline. Both external and internal loading was characterized by distinct seasonal variability. The loads from watercourses supplying the lake played the most significant role in spring, whereas the release of phosphorus from bottom sediments (accounting for 81.4% of the total P load) was responsible for cyanobacterial blooms in summer. In order to improve Raczyńskie Lake water quality it is crucial to implement both in-catchment and in-lake measures by means of diversion of stormwater runoff, reduction of nutrient content in some of tributaries at their inflow to the lake (gabions filled with dolomite surrounded by macrophytes) and restoration treatments aiming at the inactivation of phosphorus in the water column and reduction of its release from sediments.

Keywords: nitrogen; phosphorus; external and internal loading; bottom sediments; lake management

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1. Introduction

Shallow lakes throughout the world are very vulnerable to eutrophication due to their natural characteristics [1,2]. Primarily, the role of bottom sediments is of paramount importance as a result of a high degree of wind mixing and sediment resuspension [3]. Moreover, shallow lakes are much more exposed to natural variability in nutrient concentrations due to seasonal inflows from tributaries [4]. Nutrient loading from modified catchments and urban inputs (stormwater runoff) are the main elements of anthropogenic pressure on which they are exposed [5]. As a consequence of nutrient loading, shallow lake ecosystems can quite abruptly switch between different stable states representing alternative equilibria [6], i.e., from a clear-water macrophyte dominated state to a new turbid phytoplankton dominated state. These excessive algal and cyanobacterial blooms are most serious symptoms of overfertilization with nitrogen (N) and phosphorus (P), affecting the provision of ecosystem services for the local community [7]. Eutrophication of shallow lakes, together with climate change, affects also habitat heterogeneity and ecosystem biodiversity; thus the need to preserve and restore the lakes is a key challenge for ecosystem integrity [8].

The path to lake degradation and methods of controlling this depends on local conditions, including the physical ones such as climate, tributaries inputs, and the transformation and retention of nutrients by the ecosystem [5]. A specific response of the lake is a resultant of these factors, affecting the intensity of eutrophication symptoms as well as the water quality in the outflow, extending the influence of adverse environmental changes to lakes situated downstream. It is particularly relevant in waterbodies in cascade systems, where water quality deterioration may propagate downstream [9]. Therefore, a lake management plan for the control and mitigation of nutrients is indispensable not only for the first lake in a cascade, but for the functioning of all interconnected lakes [10].

An integrated management approach, which combines nutrient control from both external and internal sources, is required to achieve water quality improvement; hence, a nutrient budget should be the starting point of each shallow lake management plan [11]. Point and non-point nutrient sources need to be included in this budget. Most European lakes are under law enforcement when it comes to point nutrient sources since the effluents from wastewater treatment plants must be directed to flowing waters; however, many of them are still polluted by point sources represented by stormwater runoff from urban areas. The nature of the runoff is determined by the type of catchment area and season of the year [12,13]. Stormwater inflows to lakes can contain fuel combustion products, ingredients derived from industrial emissions, mineral and organic parts of the soils. Contamination by nitrogen and phosphorus is also serious, especially in water outflowing from residential areas [14,15]. It can significantly affect the quality of the water and the composition of organisms in the receiver waterbody [16]. The microbiological contamination of stormwater runoff affects also the recreational values of urban reservoirs [17]. Most of the stormwater is treated in sedimentation tanks with oil separators before being discharged to the receiving waterbody; while suspended solids and oil products are reduced there, dissolved nutrients can still feed the lake water. This kind of detrimental effect is quite common in urban lakes [17,18].

Non-point sources (NPS) are related to catchment land use, and nutrients are transported via tributaries or via shoreline by surface and subsurface runoff [19,20]. Lakes situated in agricultural catchment areas, regardless of the means of transport, are mostly threatened by the inflow of nutrients. Studies of over 400 lakes in Denmark have shown that along with the increase in the share of farmlands in the entire watershed, the water quality undergoes deterioration to a higher extent. Furthermore, both transport with the waters of tributaries as well as across the shoreline is important, so any mitigation strategies must be directed to the entire catchment [21].

In the temperate climate zone, nitrogen leaching from intensively managed cropping systems is of great importance, especially in the aspect of seasonal variability [22] as it is highly related to early spring runoff during snowmelt [23,24]. It is estimated that nitrogen from fertilizers accounts for an average of 80% of nitrogen export to the Baltic Sea, and annual average nitrogen export from Poland was over 30 kg per capita in 2000–2005 [25]. At least a part of this load needs to be retained within the watershed, including small catchments of lake tributaries, surrounded by croplands. These watercourses serve also as a mode of P transportation into the lake, and its content is determined by various factors, such as the P content in soil (higher in the case of using animal slurry and in specialty crop watersheds), P sorption capacity (lower in watersheds with sandy soil and higher in case of soils with high organic matter content) and finally artificial drainage (arrangement of tiles and ditches). These conditions particularly affect the subsurface transport of P from the catchment area to the lake while surface runoff and erosion are strongly related to precipitation or the presence of plants on croplands [26]. Both nitrogen and phosphorus need to be monitored in the matter of loads supplying the lakes, as the need for a shift from an exclusive focus on P limitation to a dual N and P co-limitation strategy is increasingly recognised worldwide [27].

Nevertheless, the role of P remains crucial in shallow lakes due to greater impact of bottom sediments on its cycling in the system. In such lakes, bottom sediments in particular can be the main source of phosphorus, instead of acting as a trap for phosphorus [28,29]. The intensity and duration of the process of phosphorus release from bottom sediments to the overlying waters has a significant impact on the concentration of this element in lake water and, consequently, on water quality [30]. The process of phosphorus release from bottom sediments plays a significant role in lake eutrophication [29].

The aim of this study was to determine the external N and P loading of shallow Raczyńskie Lake and the internal P loading from its bottom sediments, necessary to establish a strategy to improve lake water quality. In order to achieve these goals, detailed studies of the waters flowing in and out of the lake through natural watercourses, rainwater discharged from neighboring built-up areas and bottom sediments were carried out. In case of P loads, a nutrient balance was constructed based on external and internal sources.

The authors hypothesized that (i) external loading with tributaries and from the direct catchment area supplies Raczyńskie Lake with highest loads during spring, (ii) P release from bottom sediments plays most important role in summer, (iii) the mitigation of both nutrient sources must be included in the lake management plan in order to improve water quality and ecosystem services for local community.

2. Materials and Methods

2.1. Study Area

Raczyńskie Lake is a shallow, hypereutrophic lake located in Western Poland (52°08′36″ N 17°09′56″ E). It has a total area of 84.4 ha, maximum depth of 5.8 m and mean depth of 2.7 m [31]. The maximum depth is situated in the central part of the lake and the second deepest place (4.5 m) is located in the southern part (Figure 1). There are two islands in the lake basin, and the larger called Edward Island is used as recreation facility during summer.

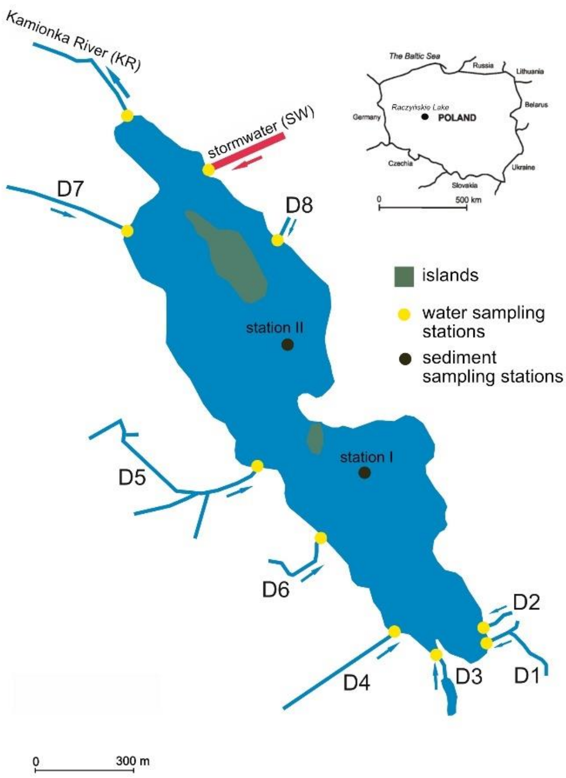

Figure 1. Location of sampling stations at the tributaries of Raczyńskie Lake (D1–D8), stormwater inflow (SW), outflowing Kamionka River (KR) and at Raczyńskie Lake (I and II).

The Lake is the source of the Kamionka River (21.6 km of total length), which is the axis of the chain of 8 lakes. The lake is supplied by 8 natural watercourses (D1–D8), some of them periodical, and stormwater sewer (SW) from the village of Zaniemyśl. The outflow of Kamionka River (KR) is located in the north-western part of the lake (Figure 1).

Significant tourist pressure and recreational use determines the role of the lake in the region. About 70% of the lake's shoreline is occupied by recreational facilities, residential properties and gardens. There are 3 beaches, water equipment rentals, as well as a ferry and a floating bridge from Zaniemyśl to Edward Island. About 8000 people use the bathing sites and resorts in summer. The sewage from most of recreational facilities is collected in septic tanks and transported to the sewage treatment plant situated outside the lake catchment, which also receives sewage from Zaniemyśl delivered via the sewage system [32].

Raczyńskie Lake belongs to the category of highly polluted, hypereutrophic lakes. Deterioration of water quality was observed between the 1970s and 1990s, manifested in cyanobacterial blooms, high nutrient concentrations and anaerobic conditions near the bottom, as well as low transparency and extinction of submerged macrophytes [31,32]. In the 21st century, water quality deteriorated further. In summer and autumn, along with an increase in the internal phosphorus loading from bottom sediments, cyanobacteria had the largest share in phytoplankton, the number of which exceeded 32,000 specimens mL^{-1} [31].

Unsuccessful lake restoration by means of water aeration was introduced in the 1990s, replaced by sustainable lake restoration with phosphorus inactivation and biomanipulation since 2018 [31].

2.2. Methods

In order to assess the external nutrient loading, inflows of Raczyńskie Lake, outflowing Kamionka River, and stormwater runoff were studied 6 times between March and October 2015 (March, May, June, July, August, October). At the same time, undisturbed bottom sediment cores used for ex situ tests were sampled 4 times (March, May, July, October) at two stations, to evaluate internal phosphorus loading. Additionally, the surface layer of bottom sediments (10 cm) was sampled at the same stations 6 times.

2.2.1. Watercourses and Stormwater Runoff

The study included water of 8 natural tributaries of Raczyńskie Lake (D1–D8), water of the outflowing Kamionka River (KR), and stormwater runoff (SW) discharged via the collector from Zaniemyśl (Figure 1). Natural watercourses are partly periodical, supplying the lake mainly in spring, thus sampling was limited for some of them only to this season (Table 1). Only inflows marked D5, D6 and D8 were flowing regularly to the lake. In the D2 and D3 watercourses, the water was stagnant throughout the research period, so they were not included in the calculations of the nutrient loads.

Table 1. Characteristics of watercourses and sampling scheme.

Sampling Station	Tributary Characteristic	Catchment Characteristic	Sampling (n = Number of Samples)
D1	tributary from the southeast, extension of the underground drainage line	meadows and croplands	only in spring and summer (n = 4)
D4	tributary from southwest	forest and croplands	only in early spring (n = 1)
D5	tributary from west, collecting waters from many small streams	forest and croplands	permanent water flow, n = 6
D6	tributary from west	forest and build-up areas	permanent water flow, n = 6
D7	tributary from northwest	meadows, forest and build-up areas	only in spring, n = 2
D8	tributary from east from Zaniemyśl village	green areas	permanent water flow, n = 6
SW	outflow from collector of stormwater from the impermeable areas of Zaniemyśl village	built-up area	sampling after heavy rainfall, n = 6
KR	outflow from the lake, decreasing water flow since March, no outflow since July	lake catchment covered by forest, croplands and built-up areas	only in spring and early summer, n = 3

Stormwater is supplied by a separate sewer system (length 2495 m, drained area 2000 m^2). Rainwater flows down to the collectors with a diameter of 250–500 mm. Before discharge to the lake, stormwater is treated in a sedimentation tank with a lamella oil separator (unpublished data from the Zaniemyśl Commune Office).

Water samples were collected directly from the tributaries before their inlet to the lake. Each time, the physicochemical parameters of water (temperature, pH, conductivity (EC) and dissolved oxygen (DO)) were measured directly in the field with a WTW Multi

350i multi-parameter meter(Germany). Water flow rate was measured using a Valeport electromagnetic flow meter (model 801) (Devon, UK).

In collected water samples the concentrations of nitrogen and phosphorus were analysed. Spectrophotometric analyses were made on Shimadzu UV Mini 1240 (Kyoto, Japan): N-NH_4—with Nessler's reagent; N-NO_2—with sulphanilic acid and 1-naphthylamine; N-NO_3—with sodium salicylate; SRP and TP—with molybdate method with ascorbic acid as a reducing agent. In order to assess organic N, the Kjeldahl method was applied with distillation of samples in Velp UDK 132, and TN was a sum of mineral N forms and organic N. All analyses were made according to Polish standards [33]. Analyses of TSS content were conducted using the weight method after filtration of samples on GF/C glass fiber filters.

2.2.2. Bottom Sediments

The upper layer of bottom sediment (10 cm thick) was sampled using Kajak core sampler at two stations located at the deepest places of the lake, i.e., in the central part of the lake (station II) and in the southern part (station I) (Figure 1). Total phosphorus and its fractions were analyzed according to the fractionation protocol proposed by Psenner et al. [34]. In a volume of 1 cm^3 of wet sediment, the following elements were analysed: loosely adsorbed (labile) phosphorus (NH_4Cl-P)—extraction with 1 M NH_4Cl; redox-sensitive phosphorus bound with iron (BD-P)—extraction with a mixture (1:1) of 0.11 M $NaHCO_3$ and 0.11 M $Na_2S_2O_4$; phosphorus bound to hydrated oxides of aluminium (NaOH-P) and organic matter (NaOH-NRP)—extraction with 1.0 M NaOH; carbonate- and apatite-bound P (HCl-P)—extraction with 0.5 M HCl and the residue (Res-P), which was the difference between total P concentration and the sum of the first five fractions.

Sediment samples were analysed for organic matter content (%) by drying to constant weight and incineration at 550 °C. Water content (%) was calculated from a difference between the wet and dry weight of the sample. SRP and TP concentrations were also analysed in interstitial water, after centrifugation for 1 h at 3000 rpm in closed containers to prevent any oxidation of the samples. The concentration of both forms of phosphorus were measured spectrophotometrically with ascorbic acid as a reducer (TP after mineralization). The analyses were done according to Polish Standard Analytical Methods [33].

The additional variables in bottom sediments were analysed only in June 2015 at both stations, namely: nitrogen, sulphates, iron, calcium and magnesium. Total nitrogen was determined using a TOC-L Shimadzu analyser with a TNM-L unit via catalytic thermal decomposition and the chemiluminescence method (Shimadzu, Kyoto, Japan). Determination of SO_4^{2-} was performed using the gravimetric method. Total water hardness and Ca^{2+} concentration were determined by the versenate method, while Mg^{2+} concentration was calculated from the difference between total hardness and the concentration of Ca^{2+} ions [35]. Determination of total Fe was made using atomic absorption spectrometry with flame atomization (F-AAS) (Shimadzu AA7000 Kyoto, Japan).

Intact cores of bottom sediments were collected using a modified core sampler 4 times during the study period i.e., in March, May, July and October from the same sampling stations. Three cores were taken from each station. The cores were used in ex situ tests to determine the quantitative analyses of internal phosphorus loading from bottom sediments. Intact sediment cores collected into transparent plastic tubes (PMMA—polymethylmethacrylate), after transport to the laboratory, were incubated in darkness under constant thermal conditions similar to the temperature within the lake during sampling. During the test, total phosphorus concentrations were analyzed in the water collected from each tube at 3–4 day intervals. Before water sampling for TP analyses, the temperature of overlying water, DO, pH and EC were measured in the tubes with a WTW Multi 350i-meter. Each test lasted two weeks, which allowed analysis of the changes in phosphorus concentration occurring in the water and determination of the mean release or accumulation of phosphorus per m^2 of sediment per day. Based on the results, the daily release or accumulation of phosphorus was calculated for each sampling station. TP analyses were carried out spectrophotometrically with ascorbic acid as a reducer.

2.2.3. Computational Works

The total catchment area of Raczyńskie Lake and the catchments of its individual tributaries were defined based on topographic maps at a scale of 1:10,000. The external loading of Raczyńskie Lake included N and P loads carried with: [i] the waters of the 8 tributaries (D1–D8), [ii] with stormwater (SW) and [iii] with the inflow from the direct catchment area through the entire shoreline.

[i] Daily loads of N, P and TSS flowing into Raczyńskie Lake and flowing out with Kamionka River were calculated as their measured concentration (*C*) (kg m^{-3}) multiplied by the water flow during sampling (*Q*), calculated for the day ($m^3 d^{-1}$). The average daily loads of these parameters were calculated by averaging the received loads from all measurements, and the annual loads (*AL*) by multiplication by 365 days.

$$AL = \frac{\sum_{i=1}^{n} C \times Q}{n} \times 365 \quad (1)$$

[ii] In case of stormwater runoff, the annual load was calculated based on the average concentration of TP and TN and the average content of TSS in the stormwater runoff and the annual amount of stormwater runoff discharged to the lake, calculated using the formula:

$$Q = h \times \psi av \times \beta \times A \times 10 \quad (2)$$

where:

h—precipitation [mm] (520 mm was assumed as the average multi-annual value)
ψav—rainwater runoff coefficient (assumed 0.9 for impermeable areas and 0.2 for other)
β—reduction coefficient (assumed 0.9)
A—catchment area
10—unit conversion factor.

[iii] N and P loads coming from direct catchment were determined according to the area of this catchment and standard unit loads, as proposed by Giercuszkiewicz–Bajtlik [36] in relation to the catchment management (croplands, forest, meadows, build-up areas). The area covered by a particular form of management in the direct watershed was evaluated on the basis of total catchment management.

3. Results

3.1. Quality of Water Flowing into and out of Raczyńskie Lake

The temperature of waters flowing into Raczyńskie Lake varied in different seasons. The lowest values were found in spring (4.2 °C-D2) and the highest in summer (18.1 °C-D5). On the other hand, pH oscillated over a fairly wide range from 6.28 (station D5) to 8.25 (station D1). EC varied from 481 μScm^{-1} at station D3 to 871 μScm^{-1} at station D5. Throughout the study period the inflows D5 and D7 were characterized by relatively high values of EC. DO in water ranged from 2.1 mgO_2 L^{-1} at station D7 to 8.4 $mgO_2 L^{-1}$ at station D1. Similar variability was observed in oxygen saturation, which ranged from 21% to 73%. The TSS ranged widely from 2.9 mg L^{-1} (station D1) to 124 mg L^{-1} (station D2), but usually did not exceed 40 mg L^{-1} (Table 2).

Ammonium nitrogen concentrations varied significantly from 0.50 mgN-NH_4 L^{-1} at station D8 to 2.46 mgN-NH_4 L^{-1} at station D3. The highest mean value was observed at station D7—1.81 mgN-NH_4 L^{-1} and the value was slightly lower at site D3—1.64 mgN-NH_4 L^{-1}. A wide range of nitrate nitrogen concentrations was noted. The highest content was found in D1—up to 19 mgN-NO_3 L^{-1}. Relatively high values were also observed in D8—maximally 7.7 mgN-NO_3 L^{-1}. In other watercourses they did not exceed 1.5 mgN-NO_3 L^{-1}. The highest concentrations of mineral N were found in D1, with maximum of 19.9 mgN L^{-1}, while slightly lower at station D8 (max 8.4 mgN L^{-1}), and less than 2.7 mgN L^{-1} in the rest of watercourses. Higher concentrations of organic N were observed at sampling stations D1, D2, D3 and D4, reaching up to 2.9 mgN L^{-1}, while the highest content of TN was characteristic for inflow D1, reaching a maximum of

21.6 mgN L^{-1}. Slightly lower values were noted at station D8, where the maximum was 8.9 mgN L^{-1}.

High concentrations of SRP were observed in D1 and D8—1.31 mgP L^{-1} and 1.24 mgP L^{-1}, respectively. Similar trend was observed for TP—it reached 1.9 mgP L^{-1} in D1. Relatively high values were also found at the sampling station D8—1.3 mgP L^{-1} (Table 2).

Kamionka River had slightly higher temperature and pH in comparison with inflows. On the other hand, EC was much lower than that found at sites D1–D8 and reached maximally 488 µScm^{-1}. DO reached 10.1 mgO_2 L^{-1} at 86% of oxygen saturation. TSS content ranged from 11.00 to 12.30 mgL^{-1}. Contents of ammonium nitrogen were quite high, reaching maximally 2.54 mgN-NH_4 L^{-1}, while nitrate nitrogen concentrations were low, up to 0.31 mgN-NO_3 L^{-1}. The average concentration of mineral N was 2.14 mgN L^{-1}, but higher concentrations were found in organic form—mean 2.1 mgN L^{-1}. Mean SRP concentration was 0.10 mgP L^{-1} and TP 0.32 mgP L^{-1} (Table 2).

The temperature of stormwater showed clear seasonal variability and ranged from 9.5 °C to 21 °C. EC values were considerably lower than at stations D1–D8 and at the outflow and ranged from 103 µScm^{-1} to 134 µScm^{-1}. TSS content during the study period varied from 3.6 mgL^{-1} to 182 mgL^{-1} and was higher than at the other sampling stations. The pH of stormwater was nearly neutral, ranging from 6.8 to 7.4, and DO was low, varying from 1.94 mgO_2 L^{-1} to 4.04 mgO_2 L^{-1}, corresponding to oxygen saturation of 21% and 43%. Mineral N concentrations were high, reaching up to 7.5 mgN L^{-1}. Ammonium nitrogen was the dominant form, with concentrations ranging from 1.4 mgN-NH_4 L^{-1} to 2.4 mgN-NH_4 L^{-1}. Once (in August), nitrates were predominant and their concentration reached 5.9 mgN-NO_3 L^{-1}, while in the remaining months they did not exceed 2.0 mgN-NO_3 L^{-1}. TN concentrations in the stormwater runoff reached a maximum of 8.2 mgN L^{-1} and the mineral form dominated throughout the study period. SRP concentrations ranged from 0.03 mgP L^{-1} to 0.23 mgP L^{-1}, whereas TP concentrations ranged from 0.13 mgP L^{-1} to 0.35 mgP L^{-1} (Table 2).

Table 2. Minimum, maximum and mean value of parameters in the inflows (D1–D8), outflow (KR) and stormwaters (SW) (*—only one measurement).

	D1	D4 *	D5	D6	D7	D8	KR	SW
Temperature (°C)	5.0–16.2 (11.8)	7.2	9.1–18.1 (14.4)	7.6–14.5 (12.1)	6.8–15.6 (11.2)	6.1–18 (13.3)	7.4–19.5 (4.1)	9.5–21.0 (15.1)
EC (μS cm^{-1})	540–637 (589)	697	695–871 (789)	540–651 (589)	837–870 (853)	692–724 (707)	457–488 (472)	103–134 (113)
pH	6.32–8.25	6.94	6.28–8.07	7.60–7.90	7.35–7.77	7.08–7.96	7.43–8.19	6.82–7.38
DO (mgO_2L^{-1})	5.54–8.40 (6.32)	7.25	3.27–5.56 (4.17)	4.29–5.98 (5.21)	2.13–6.16 (4.15)	3.67–6.12 (4.82)	1.55–10.13 (4.71)	1.94–4.04 (3.21)
TSS (mgL^{-1})	2.9–30.8 (11.4)	12.9	9.8–28.0 (19.1)	8.8–36.5 (19.3)	12.7–30.0 (21.3)	7.0–35.3 (13.7)	11.0–12.3 (11.5)	3.6–182 (47.3)
Ammonium N (mg N-NH_4 L^{-1})	0.85–1.39 (1.08)	0.67	0.58–1.20 (0.84)	0.58–1.55 (0.96)	1.72–1.89 (1.81)	0.50–0.82 (0.66)	1.25–2.54 (1.86)	1.40–2.43 (1.68)
Nitrate N (mgN-NO_3 L^{-1})	7.30–19.1 (12.7)	2.30	0.23–0.48 (0.32)	0.13–0.39 (0.27)	0.16–0.30 (0.23)	1.88–7.67 (4.42)	0.20–0.31 (0.25)	0.34–5.89 (1.75)
Mineral N (mgN L^{-1})	8.50–19.9 (13.9)	2.95	0.99–1.51 (1.18)	0.77–1.93 (1.24)	2.02–2.09 (2.05)	2.72–8.35 (5.14)	1.51–2.85 (2.14)	1.95–7.48 (3.56)
Organic N ($mgNL^{-1}$)	0.99–1.91 (1.53)	2.25	0.13–1.28 (0.79)	0.11–1.46 (0.79)	0.26–2.05 (1.15)	0.41–1.33 (0.82)	1.65–2.49 (2.09)	0.03–2.41 (0.85)
TN ($mgNL^{-1}$)	10.3–21.6 (15.4)	5.20	1.22–2.49 (1.97)	1.08–2.85 (2.03)	2.28–4.14 (3.21)	3.22–8.89 (5.96)	4.01–4.51 (4.23)	2.37–8.23 (4.42)
SRP ($mgPL^{-1}$)	0.65–1.31 (1.04)	0.004	0.02–0.15 (0.07)	0.04–0.15 (0.09)	0.04–0.06 (0.05)	0.54–1.24 (0.79)	0.08–0.12 (0.10)	0.03–0.23 (0.11)
TP ($mgPL^{-1}$)	0.82–1.88 (1.26)	0.037	0.09–0.26 (0.17)	0.09–0.32 (0.22)	0.11–0.17 (0.14)	0.57–1.31 (0.88)	0.18–0.58 (0.32)	0.13–0.35 (0.230

3.2. External Loading

3.2.1. The Catchment of Raczyńskie Lake

The total area of the natural catchment of Raczyńskie Lake is 9.32 km^2 and was increased on the northwest by the stormwater system in Zaniemyśl by an additional 15.6 ha, giving 947.95 ha or nearly 9.5 km^2 in total. The drainage basins of the 8 studied watercourses have a total area of 265.5 ha, so they drained 28.5% of the total natural catchment of the lake. The D5 watercourse had the largest catchment area, while the D8 watercourse had the smallest. The catchments of five of the eight watercourses had a surface area of less than 17 ha (Figure 2). The catchment area directly draining into the lake is 666.9 ha.

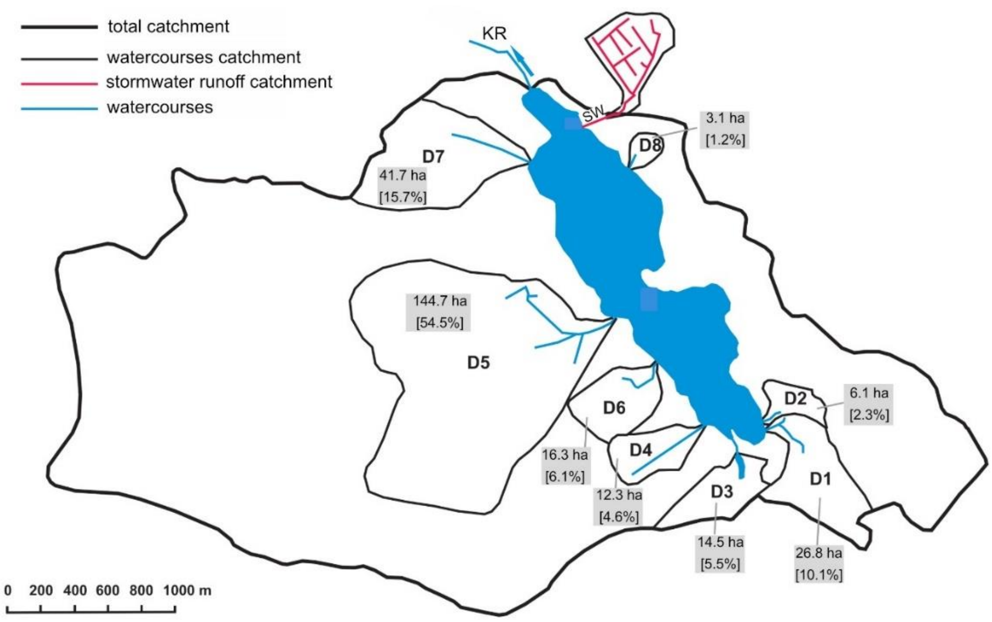

Figure 2. The total catchment area of Raczyńskie Lake and the partial catchments of its tributaries and stormwater (compiled on the basis of topographic map 1:10,000).

3.2.2. Loads of Nutrients and TSS in Natural Watercourses (D1–D8 and KR)

TN daily loads showed significant variability, depending on the changing discharge. At D5 and D6, nitrogen loads increased to about 0.3–0.4 kgN d^{-1} in May and June, and slightly higher at D8, reaching a maximum of 0.67 kgN d^{-1} (Figure 3). In drying watercourses (D1, D4 and D7), in the second part of the study period, they decreased to zero. The highest N loads were noted in Kamionka River, with a maximum of 28.4 kgN d^{-1} in the spring.

The tributaries D1–D7 carried low TP loads, not exceeding 0.05 kgP d^{-1}, while in D8 they increased to nearly 0.15 kgP d^{-1} in August. The highest TP loads were outflowing from the lake via Kamionka River, reaching up to 1.5 kgP d^{-1} (Figure 3) in spring.

In the case of mean N loads, the highest values were recorded for the D8 tributary. The annual nitrogen load introduced into the lake reached 160 kgN (Table 3). The load for the D6 stream was half as high. Other tributaries supplied less than 55 kgN per year. The annual TP load deposited to the lake by D8 reached almost 30 kgP y^{-1}, while in the other tributaries it did not exceed 8 kgP y^{-1}. The highest TSS loads were carried by D6, and quite high loads were also carried by D5 and D8 (above 400 kg y^{-1}). In total, watercourses supplied the lake with about 0.92 kgN d^{-1}, less than 0.12 kgP d^{-1} and nearly 5 kg of TSS per day. Annually, these loads increased to 336 kgN, over 42 kgP and over 1800 kg of TSS (Table 3). The highest loads in the D8 watercourse were connected with the occurrence of the highest concentrations of nitrogen and phosphorus in D8 in comparison with the other watercourses.

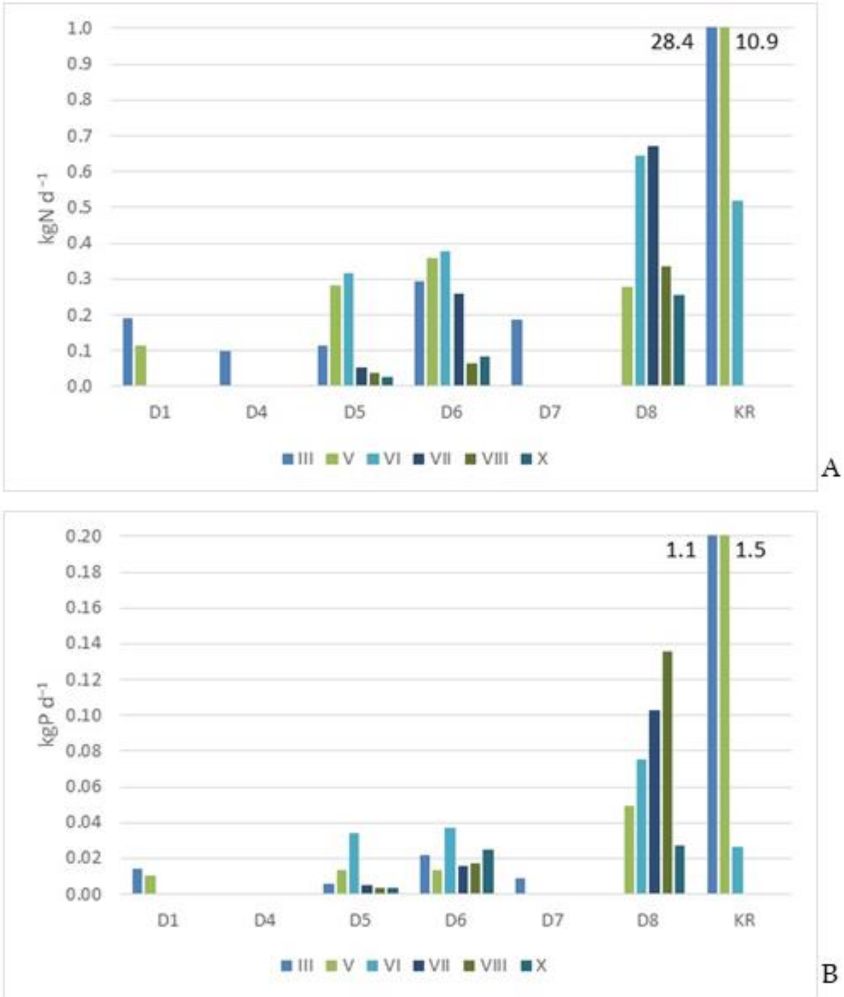

Figure 3. Changes of TN (**A**) and TP (**B**) loads in tributaries of Raczyńskie Lake and in Kamionka River.

Table 3. Mean daily and annual loads of nitrogen (N), phosphorus (P) and total suspended solids (TSS).

	Daily Loading [kg d^{-1}]			Annual Loading [kg y^{-1}]		
	N	P	TSS	N	P	TSS
D1	0.052	0.004	0.100	18.91	1.49	36.65
D4	0.017	0.000	0.014	6.13	0.04	4.95
D5	0.139	0.011	1.247	50.91	3.92	455.02
D6	0.242	0.022	2.063	88.49	7.96	752.90
D7	0.031	0.002	0.414	11.49	0.55	151.06
D8	0.439	0.078	1.122	160.07	28.56	409.41
Total	**0.920**	**0.117**	**4.960**	**336.00**	**42.52**	**1810.00**

Due to the fact that the study was carried out in an exceptionally dry year with little precipitation (431.7 mm in comparison to 538.9 mm as a mean in 1991–2020) and after an exceptionally snowless winter, the loads of nutrients and suspended solids found in the watercourses were probably much lower than those found in a typical year. To assess the loads for typical climate conditions, loads were calculated according to the multiannual average unit outflow, estimated on 2 L·s^{-1} km^{-2} [37]. For this purpose, average concentrations for particular watercourses were multiplied by the average amount of water outflowing from the defined catchment areas (Table 4).

Table 4. Annual nitrogen (N), phosphorus (P), and total suspended solids (TSS) loads discharged to the lake, calculated on analyzed concentrations, catchment area and multiannual average unit outflow.

Inflow	Mean Concentration [kg d^{-1}]			Annual Load [kg y^{-1}]		
	N	P	TSS	N	P	TSS
D1	15.37	1.26	11.4	260.23	21.32	193.69
D2	3.33	0.17	34.5	12.71	0.64	131.65
D3	3.55	0.36	9.5	32.44	3.31	87.08
D4	5.20	0.04	12.9	40.19	0.29	99.93
D5	1.97	0.17	19.1	179.81	15.30	1740.47
D6	2.02	0.22	19.3	20.82	2.23	198.08
D7	3.21	0.14	21.3	84.31	3.68	560.42
D8	5.96	0.88	13.7	11.65	1.73	26.81
Total				**642.16**	**48.50**	**3038.13**

Significantly higher loads of nutrients and TSS were calculated for most of the tributaries. The exceptions were D6 and D8, with loads much lower than calculated only according the water flow rate in 2015.

In order to more accurately reflect the conditions in an average year, the values calculated for the D6 and D8 in Table 4 were replaced by the values calculated from our own studies in Table 3. These corrected data are summarized in Table 5. The largest loads of nutrients enter the lake with D1 and D8, due to the high concentrations found in these tributaries. The largest amounts of TSS, but also quite high loads of N and P, reach the lake from D5, which results from the large area of the catchment and the relatively large amount of inflowing waters. The other tributaries are of minor importance, becoming active after heavy rains and after winter. Total loads reached almost 860 kgN per year, over 80 kg P per year and almost 4000 kg of TSS annually.

Table 5. Corrected annual loads of nitrogen (N), phosphorus (P), and total suspended solids (TSS) entering the lake for average conditions.

Inflow	Annual Load [kg y^{-1}]		
	N	P	TSS
D1	260.23	21.32	193.69
D2	12.71	0.64	131.65
D3	32.44	3.31	87.08
D4	40.19	0.29	99.93
D5	179.81	15.30	1740.47
D6	88.49	7.96	752.90
D7	84.31	3.68	560.42
D8	160.07	28.56	409.41
Total	**858.25**	**81.06**	**3975.55**

3.2.3. Loads of Nutrients and TSS in the Stormwater Runoff

The calculated volume of stormwater discharged to the lake was 23,096 m^3 per year (for the average multiannual precipitation). Thus, 102 kg of N, 5.3 kg of P and over a ton of TSS flowed into the lake. In the case of a heavy rain (56.2 mm rainfall), the load may reach 20 kg of N, nearly 1 kg of P and 454 kg of TSS (Table 6).

The comparison of loads flowing into the lake through natural tributaries with those supplied by stormwater indicates a particularly large impact of suspended solids through stormwater system, ca. 20% of the total load, while for N it is about 10% and for P only about 6%.

Table 6. Annual loads of nitrogen (N), phosphorus (P) and total suspended solids (TSS) entering lake waters with stormwater runoff.

Parameter	Mean Concentration in Storm Water (III-X 2015) [mg L^{-1}]	Annual Loading [kg y^{-1}]	Maximum Concentration in Stormwater (III-X 2015) [mg L^{-1}]	Load in Heavy Rainfall [kg d^{-1}]
N	4.42	102.1	8.24	20.6
P	0.23	5.3	0.35	0.87
TSS	47.3	1092	182	454

3.2.4. Loads of Nutrients Supplied from Direct Catchment

The load of nutrients also infiltrates groundwater and surface runoff from the direct catchment of the lake along the entire shoreline from the direct catchment covering 666.9 ha. The highest loads entered the lake from croplands. Total N loads reached over 4800 kg per year, while total P load was almost 200 kg per year (Table 7).

Table 7. Nitrogen and phosphorus loads from the direct catchment of the lake.

Catchment Cover	Area [ha]	Standard Unit Load (after Giercuszkiewicz-Bajtlik [36])		Annual Loading	
		[kgN y^{-1} ha^{-1}]	[kgP y^{-1} ha^{-1}]	[kgN y^{-1}]	[kgP y^{-1}]
Croplands	286.8	10	0.4	2868	114.7
Forests	313.4	5	0.1	1567	31.3
Meadows	20.0	8	0.3	160	6.0
Built-up areas	46.7	6	0.9	280	42.0
Total	**666.9**			**4875**	**194**

3.2.5. Total External Loading

The comparison of all external nutrient and TSS sources indicated that the Raczyńskie Lake is supplied with the largest loads from the direct catchment area (Table 8). They account for more than 80% of the total N load, and for 67% of the total P load. Almost 30% of TP was entering the lake via watercourses.

Table 8. External load of nitrogen (N), phosphorus (P) and total suspended solids (TSS) to Raczyńskie Lake from different sources in a typical year.

Source	N [kgN y^{-1}]	P [kgP y^{-1}]	TSS [kg y^{-1}]
Tributaries (D1-D8)	858.3	81.1	3976
Stormwater runoff	102.1	5.3	1092
Direct catchment	4875.0	194.0	-
Total	**5835.4**	**280.4**	**6115.8**

3.3. Bottom Sediments

3.3.1. Sediment Composition

The mean water content in the sediments of Raczyńskie Lake was similar at both sampling stations, namely 94.5% at station I and 94.6% at station II. Similar results were observed for dry matter, namely respectively 54.4 g kg^{-1} wet weight (WW) and 53.6 g kg^{-1} WW, respectively.

The content of TP in the bottom sediments ranged from 1.5 to 2.8 mgP g DW^{-1}. The minimum was observed at station II in June and the maximum at station I in September. Slightly lower values were noted between May and August and higher ones in spring and autumn. Organic matter content in the bottom sediments of the studied lake ranged from 33.8% (station II—July) to 38.9% (station II—May) (Table 9).

Table 9. Concentration of total phosphorus, percentage share of its individual fractions, organic matter in bottom sediments and soluble reactive phosphorus and total phosphorus in interstitial waters at two sampling stations in Raczyńskie Lake.

Parameter		Unit	Station I			Station II		
			Min-Max	Mean	SD	Min-Max	Mean	SD
Total phosphorus		$mgPg^{-1}$ DW	1.71–2.83	2.32	0.47	1.54–2.56	1.96	0.39
Fractions of TP	**NH_4Cl-P**	%	2.50–2.97	2.81	0.21	2.94–10.7	4.69	2.96
	BD-P	%	0.07–0.88	0.38	0.38	0.23–1.56	0.79	0.51
	NaOH-P	%	3.08–7.12	4.46	1.83	1.56–5.74	3.59	1.74
	NaOH-NRP	%	18.6–28.3	25.1	4.53	12.7–30.5	18.8	7.38
	HCl-P	%	5.19–8.71	7.36	1.61	4.17–15.3	10.22	4.36
	Res-P	%	55.9–69.1	60.1	6.09	54.5–76.1	61.9	7.94
Organic matter		%	34.2–37.4	36.3	1.48	33.4–38.9	37.4	2.11
Interstitial water	**SRP**	$mgPL^{-1}$	0.50–2.63	1.28	0.94	0.44–4.74	2.98	1.47
	TP	$mgPL^{-1}$	0.68–2.91	1.62	0.94	0.56–5.28	3.23	1.62

In interstitial water of bottom sediments, a slightly higher concentration of both SRP and TP was found at station II. SRP concentrations ranged from 0.3 to 7.65 mgP L^{-1} while TP content ranged from 0.56 to 8.32 $mgPL^{-1}$ (Table 9).

TN content in the bottom sediments of profundal was on average 10.7 gN kg^{-1}, sulfate 1.6 gSO_4 kg^{-1}, calcium 128.9 gCa kg^{-1}, and magnesium 1.6 gMg kg^{-1}. Iron concentrations in the sediments of this lake were low, at 1.9 gFe kg^{-1}.

The analysis of individual TP fractions in the bottom sediments showed that they were similar at both analyzed sampling stations. The dominant phosphorus fraction was Res-P (55.9–76.1%), i.e., phosphorus practically biologically inaccessible. The second fraction was the NaOH-NRP (phosphorus bound to organic matter) with an average share of 21.3%. The fraction with the lowest contribution (0.07% to 1.6%) was the BD-P (iron-bound phosphorus). The sum of fractions with the highest bioavailability (NH_4Cl-P, BD-P, NaOH-P) was on average 7.6% at station I and 8.6% at station II. The fraction of phosphorus found in compounds with calcium (HCl-P) was characterized by a low contribution of up to 15% (Table 9).

3.3.2. Internal Loading of Phosphorus from Bottom Sediments

P supply to the water body from bottom sediments of the profundal of Raczyńskie Lake was a process that varied both in time and in space. The lowest predominance of P release to the overlying water was observed in early spring (March), when it was 0.73 mgP $m^{-2}d^{-1}$ at station I. On the other hand, at station II the dominance of P accumulation in bottom sediments (0.92 mgP $m^{-2}d^{-1}$) was observed at the same time. In the subsequent months of the study a significant predominance of P release from bottom sediments over its accumulation was observed. In May it reached 7.0 mgP $m^{-2}d^{-1}$ (station I) and 8.02 mgP $m^{-2}d^{-1}$ (station II), decreasing to less than 7.4 mgP $m^{-2}d^{-1}$ in July. P internal loading increased at station II in autumn to 11.2 mgP $m^{-2}d^{-1}$, while at station I it reached 4.5 mgP $m^{-2}d^{-1}$ (Figure 4).

Mean internal P loading was higher at station II (6.43 mgP $m^{-2}d^{-1)}$ than at station I (3.86 mgP $m^{-2}d^{-1}$). Higher internal loading of phosphorus was found only in a small area of the bottom (of about 4.4 ha) where oxygen deficits were periodically observed, approximately separated by a 5 m isobath. The annual release of P from the lake bottom was calculated assuming that station II represents the deepest areas of the lake (ca 4.4 ha), while station I corresponds with the rest of the lake bottom. Approximately 1127.2 kg P is released annually from the bottom up to a depth of 5 m, while 103.3 kgP is released from the bottom below 5 m. The total internal loading to the lake is therefore 1230.5 kg of phosphorus.

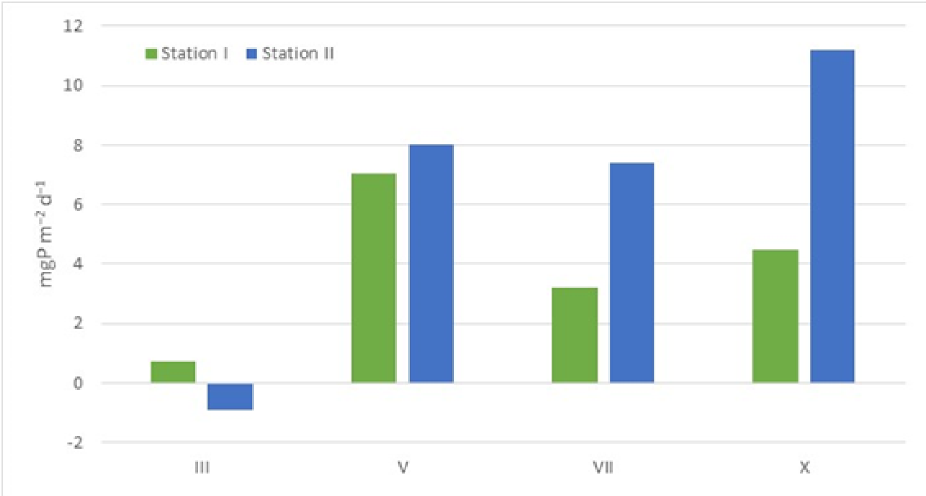

Figure 4. Seasonal changes of domination of phosphorus release (positive values) or accumulation in bottom sediments (negative values) of Raczyńskie Lake at both sampling stations.

3.4. External vs. Internal Phosphorus Loading

P supply to Raczyńskie Lake included an external load from the catchment (280.4 kgP y^{-1}) and an internal loading from bottom sediments (1230.5 kgP y^{-1}). The total P load was therefore 1510.9 kgP y^{-1}, and internal sources were responsible for 81.4% of this total load. The permissible load, calculated according to the criteria given by Vollenweider [35] is 0.045 gP $m^{-2}y^{-1}$, whereas the critical load is 0.091 gP $m^{-2}y^{-1}$. The calculated TP load of 1510.9 kgP y^{-1} divided by the lake area (84.4 ha) gives an annual load of 1.79 gP m^{-2}. The permissible phosphorus load is thus exceeded 40 times, while the critical load, causing rapid degradation of the lake, is exceeded 19.7 times. The external phosphorus load from the catchment, which is 280.4 kg P y^{-1}, exceeds the critical load of the lake 3.6 times.

4. Discussion

Excessive nutrient loads flowing into lakes primarily contribute to increased trophy, deterioration of water quality and the appearance of nuisance cyanobacterial blooms, which becomes problematic especially for reservoirs used for recreation and contributes to environmental and economic impairments in the watershed [38]. This is especially important for shallow lakes where nutrient loading has taken place for an extended period, as both internal and external nutrient sources can contribute to the deterioration of the water quality [39]. Raczyńskie Lake was heavily polluted already in the 1990s. It was characterized by strong cyanobacterial blooms, low transparency and high concentrations of biogenic compounds, which significantly limited its ecosystem services [32].

4.1. External Loading from the Catchment Area

The study of the tributaries of Raczyńskie Lake showed that they delivered relatively high N loads to the reservoir, which were characterized by distinct variability over the year, depending on changing flow intensity in the watercourses. In the second part of the study period N loads decreased even to zero in drying up watercourses. Lack of water in small watercourses in summer, on one hand, limits nutrient runoff from the catchment, but on the other hand, indicates the growing problem of drought. This may lead to accumulation of pollutants in the catchment and then their increased inflow to the lake during heavy rainfall after a dry period. It influences the intensity of N leaching from croplands, so according to the climate change scenario a reduction in N inflow might be expected in spring in the future, but there is also legacy N within the watershed accumulated over decades of excess application of fertilizers [40].This indicates that management practices should cover the entire catchment, and buffer strips around the lakes will not be sufficient to control N loads to the lake. A large single runoff of nutrients may contribute to bloom in the lake and further deterioration of water quality [41].

The highest nitrogen and phosphorus loads supplying the lake were from a small tributary called D8, flowing from green areas in the village of Zaniemyśl. The fact that the water flows permanently, while other minor tributaries have dried, indicates underground loading, while quite high N and P concentrations prove that this load is under influence of wastewater effluents, probably from the leaky septic tanks in the surroundings. At the moment the village is connected to a sewage system, and most of the wastewaters are directed to sewage treatment plant outside the lake catchment.

Nutrient legacy in the ground still exerts an impact on lake water quality, and thus immediate solutions are required to reduce this source. A nature-based solution was proposed and constructed at the inflow of stream D8 to the lake. A gabion filled with dolomite in a shape of a semi-circle was situated near the shoreline creating a small water pool to retain sediments together with nutrients, and to decrease the concentration of P as well by binding with Ca and Mg, present in dolomite. Additionally, it was surrounded by macrophytes from the lake side to increase the uptake of nutrients and its incorporation in plant biomass. This solution should result in the reduction of N and P impact on lake by their natural transformations: sedimentation, chemical binding and biological uptake [42].

Distinct N and P loads were also noted in tributaries D5 and D6. In the case of D5, the share of agricultural areas in the watercourse catchment was mainly responsible. As was proved by Szpakowska et al. [43], the greater is the farmland share in the watershed and the closer it is situated to small waterbodies, the more deteriorated is the watercourse, with high chlorophyll-a concentrations and lack of submerged vegetation. Tributary D6 on the other side was affected by catchment covered by forest and build-up areas. Many summer houses are located in that part of the lake watershed, and not all of them are connected to the sewage system, which was constructed over the past years. The legacy nutrients will again affect stream and finally lake water quality in following years, without proper solutions aiming at their reduction. The nature-based solution mentioned before was also implemented at the inflow of D5 to Raczyńskie Lake as a large part of nutrients flowing from croplands are transported via ditches to the stream, so they can be reduced before they enter the lake. In case of subsurface loads from the catchment of D6, the structuring role of buffer strips needs to be implemented. There is not enough space to create typical buffer zones of several hundred meters in width [44], but as was indicated by Szpakowska et al. [45], a 20 m wide buffer strip consisting of trees may reduce the nutrient loads by 70–80%. Nevertheless, buffer strips of bushes and high grasses should accompany the entire length of the streams, to decrease the surface runoff of N and P. According to the Common Agricultural Policy of EU, buffer strips are mandatory practice [46]; however, it should be underlined that their efficiency in nutrient removal varies and depends on many factors besides width, such as plant composition, nutrient input, local hydrogeological conditions and climate [47]. To mitigate the nutrient loads, constructed wetlands (CWs) might be considered as it was proved that phosphorus removal efficiency by in-stream CWs treating agricultural runoff may reach about 30%; however, the size of the CW as well as presence of vegetation is crucial for successful operation [48].

The highest loads of N and P were recorded in waters flowing out of the lake along the Kamionka River in spring, which indicates that the waters in the outflow are supplied with nutrients from lake sediments. This was confirmed by the comparison of inflow and outflow loads from the lake and the study of internal supply from bottom sediments. Moreover, in the summer period, the Kamionka River flowing out of the lake tends to dry up and therefore the nutrient loads from the sediment accumulate in the system, stimulating cyanobacterial blooms. The most abundant among this group of phytoplankton were *Aphanizomenon gracile*, *Cuspidothrix issatschenkoi*, *Raphidiopsis raciborskii*, *Planktolyngbya limnetica* and *Planktothrix agardhii*, which are known as toxin producers [31].

Therefore, restoration aimed at decreasing the importance of these sources of N and P is crucial for Raczyńskie Lake.

Catchment characteristics affected not only nutrient concentrations in tributaries and the outflowing Kamionka River, but also other water quality features, such as oxygen content and EC. Fine sediment accumulation in beds of slowly flowing watercourses influences oxygen regimes and sediment oxygen demand, which are usually lower and higher, respectively, in streams fed by runoff from croplands [49]. Higher EC values found in tributaries D4, D5, D7 and D8 may indicate an impact of pollution of anthropogenic origin, either infiltrating from the catchment or introduced directly to the waters of the tributaries. Their inflow was also indicated by elevated concentrations of ammonium nitrogen in D7 tributary.

The largest amounts of TSS, but also quite high loads of N and P reached the lake with the waters of the tributary D5, which was a result of the large catchment area of this watercourse and relatively large amount of inflowing water. As it was mentioned, the catchment is covered mainly by croplands, which increases the risk of soil erosion, especially when no plant cover occurs. Implementing cover/catch crops might decrease the leaching of nutrients as is observed in Finland, where winter plant cover may reduce erosion and nutrient leaching by 10–15%. Another solution is to mitigate tillage impacts by proper cultivation as well as no-till farming [50]. The remaining tributaries were of minor importance, becoming active mostly after heavy rains and during thawing in early spring (corrected loads).

The largest loads of N and P reached Raczyńskie Lake directly from croplands via the shoreline, which is typical for lowland catchments used for agriculture [51,52]. The comparison of all external sources of pollution showed that N and P loads originating from the direct catchment, penetrating the entire shoreline of the lake, accounted for the largest share. In the case of N they accounted for more than 80% of the total N load from external sources, while in the case of P they accounted for 67% of the total P load. Many strategies mitigating the adverse effect of agricultural land use on water quality of lakes have been proposed worldwide, since they were developed in the 1950s to combat soil erosion and nutrient loss e.g., [53,54]. Some of them are implemented into legislative regulations in EU countries (see Living Water Exchange, EU database of Best Practices, 2015); however, there is still a need for studies documenting their efficiency in nutrient reduction [46]. In the case of Raczyńskie Lake, the Polish Code of Good Agricultural Practice should be implemented, especially in the western part of the lake's catchment area.

Stormwater runoff flowing into water bodies can provide a variety of pollutants, including biogenic compounds. Rainwater discharged into Raczyńskie Lake contributed the most significant amount of TSS and quite high concentrations of mineral N. The concentrations of SRP and TP found in rainwater feeding Raczyńskie Lake clearly exceeded the value of 0.1 mgP L^{-1}, considered to be the threshold for causing water blooms [55]. Moreover, stormwater runoff feeds the lake with other, undetected contaminants such as heavy metals or oil products, which have a particularly negative effect on the ecosystem, including macrophytes and benthic invertebrates [16]. This potential impact should be eliminated by the diversion of stormwater sewer overflows, e.g., into the outflowing Kamionka River, excluding the lake from being a receiver. This change might be extended with additional purification of stormwater in retention ponds to decrease the content of dissolved nutrients before it enters the receiver [56,57].

It was already observed in many European countries, that the implementation of regulations has led to improved sewage management and as a result has apparently reduced the external P loading to streams and lakes. Nevertheless, in spite of significant reduction in external loads, the ecological state of water bodies did not improve as much as it was expected. There are two main factors responsible for this, i.e., intensified agricultural practices resulting in high P loads and high internal P loading [58].

4.2. Internal Phosphorus Loading from Bottom Sediments

The ex-situ tests showed that supply of phosphorus from bottom sediments in Raczyńskie Lake was a spatially and temporally varied process. The internal loading of phosphorus to the lake is a resultant of two processes occurring at the same time, i.e., sedimentation of phosphorus together with suspended organic matter and undissolved minerals as well as sorption of phosphorus on bottom sediment particles on the one hand and mineralization of organic matter and release of dissolved phosphorus compounds to the overlying water on the other hand [59].

The internal loading of phosphorus from bottom sediments depends on many factors, including oxygen concentration and temperature in the over-bottom zone. The depth of the lake is also one of them. Shallow lakes are very susceptible to internal loading because nutrients in their bottom sediments have a greater impact on water quality than in deeper lakes. In shallow water bodies, factors affecting the intensity of phosphorus release from bottom sediments can change dramatically in a very short time [60,61]. In a shallow Raczyńskie Lake, the occurrence of oxygen deficits at the deepest place (station II) was observed during summer, which contributed to the predominance of phosphorus release over its accumulation in bottom sediments. Anaerobic conditions are one of the most important causes of a significant release of phosphorus from bottom sediments [59]. However, the highest intensity of this process was observed in autumn despite the improvement of oxygen conditions in the over-bottom zone, which could be due to a more rapid temperature decrease in water than in sediment [62]. Such a phenomenon has already been observed in other highly eutrophicated lakes in Wielkopolska [63,64]. At station I where oxygen conditions were better the intensity of internal loading of phosphorus was lower. Phosphorus release is also observed under conditions of good oxygenation [65]. In spring, at station I there was a slight predominance of phosphorus release and at station II there was a predominance of phosphorus accumulation which was the result of good oxygenation in the over-bottom zone and low temperature.

Raczyńskie Lake belongs to the category of highly eutrophied lakes [32]. The internal loading of phosphorus from bottom sediments depends on the trophic state of the water body. This was confirmed, among others, by studies of other hypereutrophic lakes [63,64]. In highly eutrophic lakes, intensive primary production of phytoplankton is observed, which results in intensive sedimentation of organic matter into bottom sediments. Raczyńskie Lake is characterized by a significant content of organic matter in bottom sediments, which may be the cause of intensive internal phosphorus loading [65,66]. Intensive organic matter mineralization due to higher temperature caused phosphorus release to prevail over its sorption and accumulation. High primary production in the lake and phosphorus-rich organic matter sedimentation affect the increase of total phosphorus content in bottom sediments. The intensity of phosphorus release from bottom sediments depends on the contribution of particular phosphorus fractions in bottom sediments [67].

The highest share of total phosphorus in the bottom sediments of Raczyńskie Lake is held by the Res-P fraction, which represents biologically inaccessible phosphorus [68], which is a positive aspect from the point of view of internal loading possibilities. The factor which determined phosphorus release is the amount of three most mobile fractions (NH_4Cl-P, BD-P, NaOH-P), which equalled less than 9%. Thus, these values were lower than those found in hypereutrophic Swarzędzkie Lake and similar to those observed in Uzarzewskie Lake [64,69]. The significant potential for phosphorus release from the bottom sediments of the study lake is also indicated by higher phosphorus concentration in interstitial waters, because it is commonly regarded as an indicator of the intensity of its transport across the sediment-water interface [70]. The physico-chemical parameters of the bottom sediments of Raczyńskie Lake as well as the results of ex situ tests indicate that there is significant potential for internal loading to the lake. The observed values of phosphorus release from bottom sediments of Raczyńskie Lake were higher than those found in the lakes with lower trophic state and similar to those observed in eu- and hypereutrophic lakes [71].

The importance of internal loading from bottom sediments of Raczyńskie Lake must be decreased by restoration activities. Removal of bottom sediments is the most radical and the most effective method, but it is a very expensive procedure [72]. Easier will be the application of sediment compacting agents such as lanthanum modified bentonite clay (Phoslock) or drinking water treatment residue [73,74], and P inactivation in the water column with the use of chemicals like aluminum sulphate, iron sulphate or magnesium chloride [31,75]. Excessive nutrient content in water will be reduced by increased binding in sediments [75,76]. The use of the so-called sustainable restoration method is especially recommended. This approach involving the simultaneous application of several complementary pro-ecological, non-aggressive methods to prevent ecosystem feedbacks has already been applied in many lakes [77–79]. P inactivation using iron sulphate or magnesium chloride at low doses (<15 kg ha^{-1}), supported, if necessary, by technical methods, e.g., over-bottom water aeration, and by biological methods, e.g., biomanipulation, is the most common. The use of sustainable restoration reduces the concentration of phosphates and ammonium nitrogen in the water column, decreases the proportion of cyanobacteria in phytoplankton and increases the light transparency, and above all reduces the internal nutrient loading from bottom sediments. The use of this method for a long time contributes not only to the reduction of the amount of phosphorus released from sediments, but also to increasing the periods when phosphorus accumulation has an advantage over its release [64,69,80]. This method is aimed at gradual reconstruction of the structure and functioning of the ecosystem without the need for excessive interference. The chemicals used in small doses do not harm the fauna of benthic macroinvertebrates or macrophytes and as a result of such restoration biodiversity is increased as an important factor influencing the adaptation of the ecosystem to the changes caused [78,81,82]. The number and size of chemical doses depends on the external and internal load (internal load in summer), which exerts a constant pressure on the phytoplankton communities. This enables its gradual reconstruction, and above all, the reduction of the biomass of cyanobacteria, which will cease to limit the safe use of lake waters by humans [83].

5. Conclusions

Raczyńskie Lake is a highly degraded, hypereutrophic lake with cyanobacterial blooms. A significant impact on water blooms is caused by P released from the bottom sediments. This can be observed especially in summer in dry years, when the influence of the catchment area decreases and due to the temperature rise of bottom sediments the process of organic matter mineralization and release of mineral P into water column intensifies. In the cold months, the internal loading is insignificant, but the role of the catchment area in supplying the lake with mineral nutrients increases, especially after dry years when the accumulated nutrients in the soil are released.

The introduction of protective measures only, to limit the inflow of biogenic compounds from external sources, will certainly be insufficient. Studies conducted in Raczyńskie Lake proved that the main reason for poor water quality is internal loading, and so lake management strategies must be directed to a reduction of nutrient release from bottom sediments. At the same time, spring nutrient supply from the catchment area requires mitigation as it may induce water bloom before the sediments increase their role in summer. The proposed measures necessary to reduce the inflow of external load include measures throughout the catchment area, i.e., application of the Code of Good Agricultural Practice, buffer strips in the vicinity of the lake shoreline and tributaries, special water pools construction in front of the tributaries' mouths and stormwater diversion from the lake.

In order to reduce internal P loads, it will be necessary to introduce restoration measures in the lake. They should be oriented to elimination of sediments as a source of biogenic compounds, thus dredging. Due to the semi-liquid nature of the sediment (high water content), high cost of such treatment and lack of a suitable site for sediment storage, this method seems unavailable. At this moment, the best solution in the case of Raczyńskie Lake will be the application of sediment compacting agents and P inactivation with the use of chemicals. To avoid drastic changes in the ecosystem, one possible method would be a sustainable restoration, mainly based on P inactivation using low doses of chemicals, which effectively reduces the internal phosphorus source and also reduces cyanobacterial blooms. This method is effective but requires a longer time. Improving the water quality will certainly contribute to the recovery of the lake's ecosystem services. The scale of climate changes predicted in the future will apparently modify the functioning of shallow lakes, including the role of bottom sediments as a source of nutrients, thus actions should be undertaken immediately and planned as a multi-annual strategy for lake management.

In conclusion, it can be stated that for the proper management of a lake showing symptoms of progressive eutrophication, it is necessary to apply an appropriate research scheme. Apart from permanent monitoring of the lake waters (both its biotic elements and physicochemical parameters), it is also necessary to analyse the loads of nutrients flowing in from various sources. First of all, it is necessary to assess the temporal and spatial variability of the loads flowing not only with the waters of natural tributaries, but also with stormwater collectors and those permeating the entire shoreline of the lake. It is also extremely important to analyze the internal phosphorus loading, which in the case of shallow lakes is often of paramount importance in supplying the water column with nutrients, especially in the summer season. Only after all important sources of nutrients have been identified can protective measures in the lake's catchment area and restoration measures in the lake itself be planned.

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