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Sustainable Restoration as a Tool for the Improvement of Water Quality in a Shallow, Hypertrophic Lake

Katarzyna Kowalczewska-Madura *, Anna Kozak, Natalia Kuczyńska-Kippen, Renata Dondajewska-Pielka and Ryszard Gołdyn

Department of Water Protection, Faculty of Biology, Adam Mickiewicz University, Uniwersystetu Poznańskiego 6, 61-614 Poznań, Poland; anna.kozak@amu.edu.pl (A.K.); kippen@hot.pl (N.K.-K.); gawronek@amu.edu.pl (R.D.-P.); rgold@amu.edu.pl (R.G.)

* Correspondence: madura@amu.edu.pl; Tel.: +48-61-829-58-77

Abstract: Sustainable restoration treatments were implemented with the simultaneous application of pro-ecological methods that complement each other to improve water quality in the shallow and heavily polluted Raczyńskie Lake. Phosphorus inactivation with magnesium chloride and Phoslock® was introduced along with biomanipulation. Physico-chemical and biological parameters were studied in 2015 (before restoration) and throughout 2018 and 2019 (during restoration). Water quality improved in the first year of treatment. An increase in water transparency, oxygen concentration above the bottom, a decrease of chlorophyll-a concentration and a reduction in cyanobacteria were observed. In the second year of treatment, a slight deterioration of water quality was recorded, probably caused by fewer phosphorus inactivation treatments and a shortened period of application. However, the deterioration of conditions is also characteristic of sustainable restoration at the beginning of the restoration process. The obtained results showed that sustainable restoration requires more than two years, and its scope and intensity should strictly depend on the pace of changes, determined on the basis of monitoring. In addition, improved water quality will have a positive impact on the recreational use of this reservoir.

Keywords: restoration; lake; phosphorus inactivation; nitrogen; phytoplankton; zooplankton

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1. Introduction

Poor water quality is one of the most important issues for water resources management. It is especially significant in the case of shallow lakes in a turbid state, in which the presence of intensive phytoplankton blooms, most frequently caused by cyanobacteria, and the associated low water transparency contribute to a decrease of overall biodiversity of aquatic ecosystems, their recreational potential and fishery production [1–3]. The main causes of poor water quality are uncontrolled discharge of external pollutants like surface runoff from urban or agricultural areas, stormwater discharge, and neglected sewage management in the lake catchment area (domestic sewage) [4,5]. Moreover, internal loading from bottom sediments [6] affects lake metabolism and seriously lessens the possibility of achieving at least good lake status, which is highly desirable for social and legal reasons [7]. Hence, there is an urgent need to improve the quality conditions of water through the application of appropriate restoration measures.

One of the innovative solutions used to improve lake water quality is sustainable restoration, which consists of the simultaneous application of several complementary methods that are so-called nature-based solutions. They are environmentally friendly, use internal mechanisms for changing the ecosystem in the expected direction and make them stable and useful for delivering ecosystem services [8,9]. In order to improve water quality, it is essential to apply treatments that stimulate the natural regulatory capability of the lake's ecosystem without changing it radically. Such a semi-ecological approach prevents feedback in the ecosystem and tends to gradually reconstruct the structure and functioning of the ecosystem without drastic and expensive human intervention. These alternative methods are relatively inexpensive, easy to use, energy efficient and not destructive for most of the biota [10,11]. According to the European Commission, such solutions bring more and more diverse nature and natural features and processes into cities, landscapes and seascapes through locally adapted, resource-efficient and systemic interventions.

The main method used for sustainable restoration is the inactivation of phosphorus in the water body using low, non-aggressive doses (<15 kg ha^{-1}) of chemicals such as magnesium chloride ($MgCl_2$) and iron sulphate ($Fe_2(SO_4)_3$), and, less often, aluminium salts (e.g., $Al_2(SO_4)_3 \cdot 14H_2O$) [8,12]. They are applied with the use of a special mobile vehicle which spreads them as a solution over the entire lake surface. The dose is adjusted to the present phosphorus concentration in the lake waters [13]. Iron and aluminium sulphate adsorbs phosphorus on oxyhydroxides and chemically binds phosphorus, while magnesium chloride binds phosphorus and ammonium ions to form insoluble struvite [14,15]. Limiting the availability of phosphorus to algae is an overriding priority of restoration [16], and the use of coagulants also increases the sorption capacity of the bottom sediments and reduces the internal loading [17].

Biological methods, especially biomanipulation, are also used in sustainable restoration, based on the removal of cyprinids and the stocking of lakes with predatory fish, resulting in an increase of the density of the large cladoceran zooplankton. Their grazing during summer can reduce the numbers of certain species of planktonic algae and diminish algal water turbidity [18,19]. Submerged macrophytes are also important in sustainable restoration, as they have a significant impact on the improvement of water quality [20,21].

Restoration measures applied directly to a lake are designed to reduce the impact of internal loading. In order to realise a long-term improvement of water quality, they must be supported by protective measures that will limit the impact of external sources of pollution [22–24]. One of these measures is the construction of biofiltration and sedimentation systems on the outlets of tributaries to the lake, consisting of gabions filled with dolomite and surrounded by a zone of hydromacrophytes, contributing to the reduction of external nutrient loading [25,26].

Methods related to the protection and restoration of lakes using nature-based solutions have become increasingly popular in many parts of the world [8,27,28], but evidence of their effective application is still needed. Therefore, the aim of our research was to determine the changes in the functioning (improving water quality, changes in the cyanobacteria densities, increasing the possibilities of recreational use) of the shallow and strongly eutrophied Raczyńskie Lake as a result of a two-year sustainable restoration compared to the period before restoration. Because sustainable restoration, taking advantage of natural internal mechanisms of the ecosystem to improve the ecological status of the lake, is a slow process and takes a long time, we hypothesized that: (i) a two-year application of several sustainable restoration methods will show whether changes have been initiated in the ecosystem that improve water quality, and (ii) the obtained results of the changes will make it possible to indicate the directions of further actions which will help to achieve the expected stable result of the improvement of the water quality.

In order to achieve this aim, we conducted research on:

(1) changes of individual physico-chemical and biological parameters (chlorophyll-a content and plankton abundance) in time and space;
(2) differences in the functioning of the lake ecosystem in both study periods (before and during the treatments);
(3) identification of the most important factors influencing changes taking place in the ecosystem as a result of sustainable restoration treatments.

2. Materials and Methods

2.1. Study Area

Lake Raczyńskie, located in Western Poland in the village of Zaniemyśl (52°08′36″ N 17°09′56″ E), is a spring area for the river Kamionka, which flows through a group of eight lakes—the so-called 'Kórnickie Lakes Chanel'. The River Kamionka flows out of the lake in its north-western part. This ribbon-type lake has an area of 84.4 ha and a polymictic character. The maximum depth (5.8 m) is situated in the central part of the lake (station II) and the second deepest place (4.5 m) is located in the southern part (station I) (Figure 1). There are two islands in the lake. The larger of them, with an area of 3.1 ha, includes a park and catering facilities. The lake is supplied with water by eight small periodic tributaries. In terms of fishing, Raczyńskie Lake belongs to the zander type lakes [29,30].

The total catchment area of Raczyńskie Lake is 9.15 km^2 and the direct catchment area is 1.54 km^2. Over the last 45 years, there has been a gradual transformation of the land use of the direct catchment area from agricultural to recreational. At present, its largest area is covered by forests (44.9%) and fields (34.9%), while built-up areas account for 11.7% and water bodies 8.9%. Raczyńskie Lake is characterised by significant tourist pressure and strong recreational use, and 13% of the shoreline was bordered by recreation resorts [31]. One source of nutrients flowing into Raczyńskie Lake (in the north-eastern part) (Figure 1) is stormwater from an area of about 2.45 ha (partly from the streets of Zaniemyśl). The sewage from the buildings on the island is discharged to the Zaniemyśl sewage system and then to the sewage treatment plant located away from the lake.

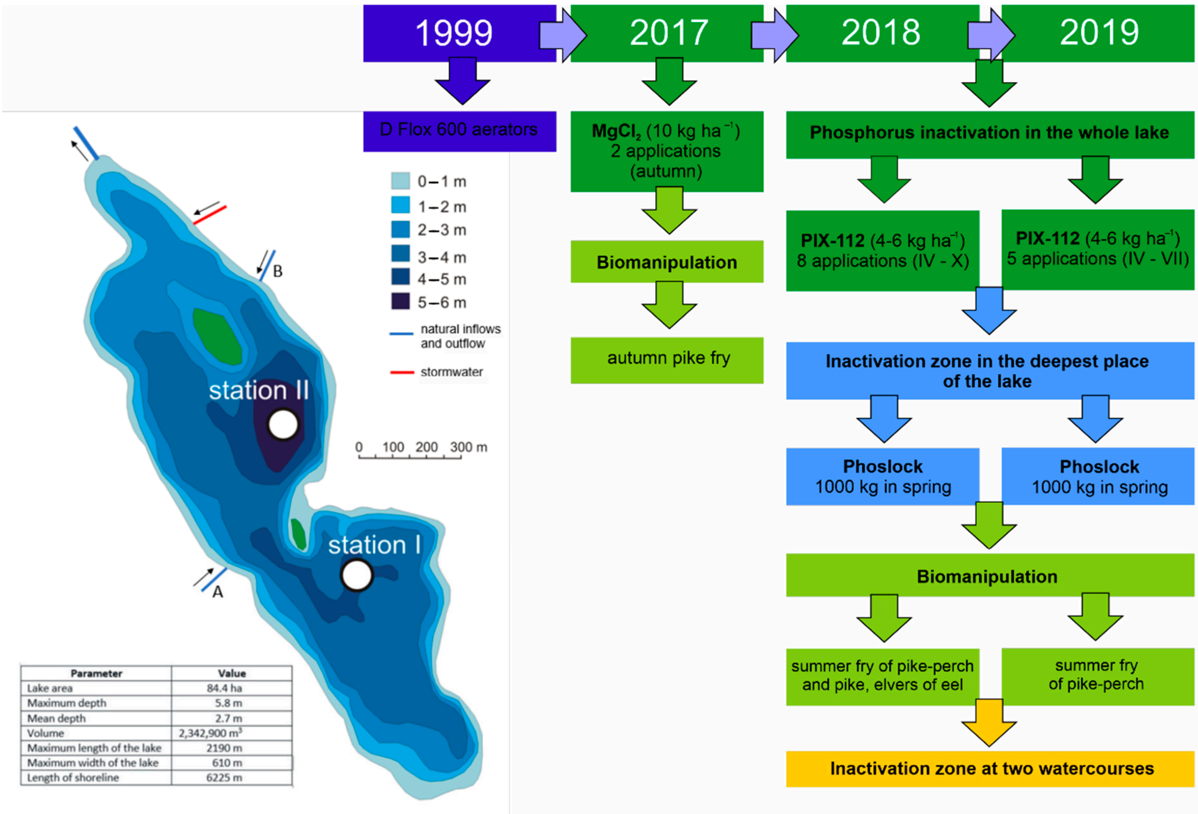


Figure 1. Bathymetric map, location of sampling stations and sustainable restoration scheme in Raczyńskie Lake (after [32], modified) (A, B—tributaries with gabions).

Raczyńskie Lake is a highly polluted, hypereutrophic lake. In the 1970s, the lake was in the β-mezosaprobic group, but by the 1990s, the waters had become very polluted due to high concentrations of nitrogen and chlorophyll-a, low water transparency and oxygen deficits in the bottom zone. In addition, water blooms caused by cyanobacteria were observed with dominating species such as *Aphanizomenon flos-aquae*, *Jaaginema subtilissimum*, *Coelomoron pusillum* and *Planktothrix agardhii* [32]. Further studies on lake water quality conducted in 2001 confirmed the bad state of the waters with domination of cyanobacteria: *Planktolyngbya limnetica* and diatoms *Aulacoseira granulata* var. *angustissima* [33]. In 2014, studies showed the persistence of cyanobacterial blooms, with the dominant species *Dolichospermum affine*, *Limnothrix planctonica* and *Microcystis aeruginosa* [34].

The number of plant communities in Raczyńskie Lake has fallen from 24 to 15 over the last 45 years. Due to strong phytoplankton blooms, no submerged vegetation was observed in 2015, while the reed belt (*Phragmites australis* and *Typha angustifolia*) expanded its area [31].

2.2. Restoration Treatments of Raczyńskie Lake

As a result of the poor quality of water in Raczyńskie Lake and the restriction of recreational use, restoration began in 1999 with 10 D-Flox 600 aerators, which in summer dosed air to a depth of 5 m, with an efficiency of 720 $m^3\ h^{-1}$. At the same time, the construction of a waste water system in Zaniemyśl was started [33].

Because of the lack of a significant improvement in water quality, sustainable restoration was applied in Raczyńskie Lake in 2018–2019. The restoration treatments consisted of precipitation of phosphorus from the water column with low doses of chemicals, and reduction of the number of carp family fish dominating the lake while increasing the density of predatory fish through biomanipulation (Figure 1). Aeration treatment was not applied during this time.

Phosphorus inactivation in the waters of Raczyńskie Lake was carried out by three complementary methods: (i) the inactivation of phosphorus in the whole lake by dosing iron sulphate ($Fe_2(SO_4)_3$) and magnesium chloride ($MgCl_2$) into the water, (ii) consideration of a phosphorus inactivation zone on the bottom part deeper than five metres using Phoslock®, Melbourne, Australia), and (iii) the construction of phosphorus inactivation zones on two watercourses flowing into the lake with the application of magnesium chloride.

Iron sulphate application ranged from 340 to 510 kg per lake, depending on the phosphorus concentration in the water. In 2018, eight applications were made in the period from April to October and in 2019, five applications were made in the months of April-July. Magnesium chloride was applied twice in autumn in 2017 at 10 kg ha^{-1}. Bentonite clay (Phoslock®) was dosed in the deepest place of the lake in the spring of 2018 and 2019 at a dose of 1000 kg (each year).

On two tributaries of the lake (A, B) (Figure 1), gabions filled with crushed dolomite rock were made, into which magnesium chloride was applied once a month at a dose of 20–25 kg.

As part of biomanipulation, stocking of the lake with autumn pike fry (200 kg) took place in autumn 2017. In 2018, the lake was stocked with the summer fry of pikeperch (13,000 psc), elvers of eel (7 kg) and summer fry of pike (40,000 psc). In June 2019, the lake was stocked with the summer fry of pikeperch (13,000 psc).

2.3. Field and Laboratory Research

The study of water quality changes in Raczyńskie Lake was conducted in two time periods: (1) in 2015 (before restoration) and (2) in 2018 and 2019 (during sustainable restoration). Water samples in both study periods were collected in the water column at every metre six times in each year of the study (in March or April, May, June, July, August, and October) at two sampling stations located in the two deepest places of the lake using a bathometer sampler (Figure 1). The total number of samples counted for analyses was 180. Water samples from station I were sampled from the surface to a depth of 3 m and from station II from the surface to a depth of 5 m. The obtained results were divided into two groups: epilimnion (samples from the depth from surface to 3 m) for both sampling stations, and metalimnion for the samples from 4 and 5 m of station II.

The physico-chemical parameters of the water (temperature, pH, conductivity and dissolved oxygen concentration) were measured in situ every 1 m in the depth profile from the surface to the bottom using a YSI 556 meter (Yellow Springs, OH, USA). Water transparency (SD) was measured with the use of a Secchi disk. The samples were analysed for nitrogen and phosphorus concentration using spectrophotometric methods on a Shimadzu UV Mini 1240 (serial number 206-24000-38, Kyoto, Japan): for ammonium nitrogen ($N\text{-}NH_4$)—by the method with Nessler's reagent (PN-C-04576-4:1994); for nitrite nitrogen ($N\text{-}NO_2$)—with sulphanilic acid (PN-EN 26777:1999); for nitrate nitrogen ($N\text{-}NO_3$)—with sodium salicylate (PN-82/C-04576.08); for soluble reactive phosphorus (SRP)—with ascorbic acid and for total phosphorus (TP)—with ascorbic acid after mineralization (PN-EN ISO 6878:2006). For organic nitrogen (Norg), Kjeldahl's method was applied (PN-EN 25663:2001). Total nitrogen was the sum of organic and mineral nitrogen. All analyses were done according to Polish Standard Analytical Methods [35].

Total suspended solids (seston) were analysed by weight after filtration on GF/C glass fibre filters (ø 47 mm, Sartorius, Goettingen, Germany). The same filters were used for the analysis of chlorophyll-a concentration by the Lorenzen method (spectrophotometric method with 90% acetone extraction) (PN-ISO 10260:2002).

Water samples were fixed with Lugol's solution for phytoplankton and with 96% ethanol for zooplankton analyses. Samples of phytoplankton were collected directly, while zooplankton samples were obtained by filtration of 10 Litres of water through a plankton net (45 µm). Qualitative and quantitative analyses of plankton were done using an Olympus CX 21 LED microscope. Phytoplankton abundance was determined in a chamber with a volume of 0.67 cm^3 according to Utermöhl's procedure [36]. Zooplankton were first determined and afterwards counted in a 1.0 cm^3 chamber, which was equal to 1 L of lake water, and finally fixed.

Trophic conditions were estimated with criteria proposed by Carlson [37] based on summer values in the epilimnion for chlorophyll-a (TSI ChL), transparency (TSI SD) and total phosphorus (TSI TP).

2.4. Statistical Analyses

Statistical analyses were made using STATISTICA version 10.0 software. A non-parametric Kruskal-Wallis test was used to determine the significance of value changes through the analysed years. The Pearson correlation coefficient was used to determine relationships between variables. To relate the data set to the environmental parameters and to establish the variables with the most explanatory power, a canonical variates analysis (CVA) was performed using CANOCO 5.0 software [38].

3. Results

3.1. Water Chemistry

The water temperature of Raczyńskie Lake varied from 5.3 °C in March 2015 above the bottom to 24.4 °C in June 2019 in the surface layer. No full thermal stratification in summer and only the presence of metalimnion was observed, which indicated its polymictic character. Considering changes of this parameter in the subsequent years, it was found that at both sampling stations the highest mean temperature in the surface layer (18.6 °C) was observed in 2018, i.e., in the first year of restoration treatments. However, the differences between analysed years were not statistically significant ($p > 0.05$).

The dissolved oxygen concentration in Raczyńskie Lake during the study period was quite similar in the depth profile in both spring and autumn. On the other hand, in summer, a decrease in oxygen concentration with depth and the formation of an anaerobic zone (<1 $mgO_2\ L^{-1}$) were observed, especially at station II. At the surface, the oxygen concentration reached a maximum of 23.1 $mgO_2\ L^{-1}$ in the summer 2019 (270% of saturation). When analysing the seasonal variability of this parameter, it was found that in the subsequent years of the study there was a gradual increase in the mean oxygen concentration in the surface layer, while above the bottom, concentrations varied. The changes were not statistically significant.

The pH changed both seasonally and vertically, and ranged from 6.56 in summer 2019 above the bottom to 9.24 at the surface in summer 2015. A statistically significant decrease was found between the value of this parameter in subsequent years of the study, both in the epilimnion (0–3 m) and in the metalimnion of the lake (4–5 m) (Figure 2a).

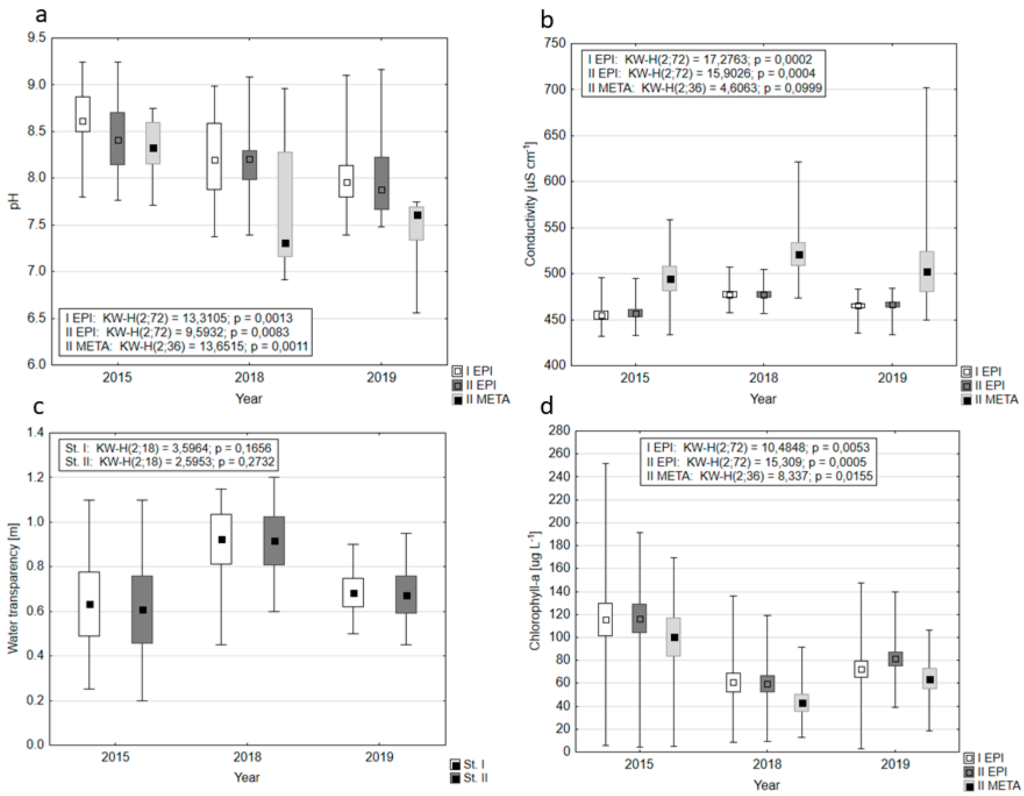


Figure 2. The mean values of pH (**a**), conductivity (**b**), water transparency (**c**) and chlorophyll-a (**d**) in the epilimnion (0–3 m station I and II) and metalimnion (4–5 m station II) in Raczyńskie Lake in years: 2015 (before restoration) and 2018–2019 (during sustainable restoration) [box—mean ± standard deviation in case of chlorophyll-s, transparency and conductivity; median ± 25–75 percentile in the case of pH; whiskers—minimum and maximum].

Electrolytic conductivity differed significantly from year to year, ranging from 432 µS cm^{-1} to 702 µS cm^{-1}. A significant increase was documented in the epilimnion between 2015 and the period of restoration. In the metalimnion, these changes were less pronounced (Figure 2b).

The transparency in the waters of Raczyńskie Lake was similar at both analysed sampling stations and ranged from 0.2 m in August 2015 to 1.2 m in June 2018. In the first year of restoration, an increase in the average value of this parameter was found, but in the second year it decreased again. However, these values were slightly higher than those found in the year before restoration (Figure 2c).

Concentrations of chlorophyll-a ranged widely, from 4.3 µg L^{-1} to 251.9 µg L^{-1}. The highest mean content of this pigment was recorded in 2015 (before the restoration). In the first year of restoration, a significant decrease in the mean chlorophyll-a concentration was observed. In the second year, it increased both in the epilimnion and metalimnion, but the values were lower than in the period before the restoration. The changes obtained between the subsequent years of the study were statistically significant (Figure 2d).

Total suspended solids showed similar variability to chlorophyll-a between subsequent years, ranging from 5.0 mg L^{-1} in autumn 2019 to 48.5 mg L^{-1} in summer 2015. The changes between subsequent years were statistically significant.

The lake waters were characterised by a high concentration of nutrients, especially nitrogen. Ammonium nitrogen ranged from 0.32 mgN-NH_4 L^{-1} (in 2018) to 3.1 mgN-NH_4 L^{-1} (in 2015). In both years of restoration it decreased significantly compared to the year before restoration, especially in the epilimnion, and these changes were statistically significant. On the other hand, a decrease of average concentration in the metalimnion was observed in 2018, but there was a slight increase in 2019. These changes were not statistically significant (Figure 3a).

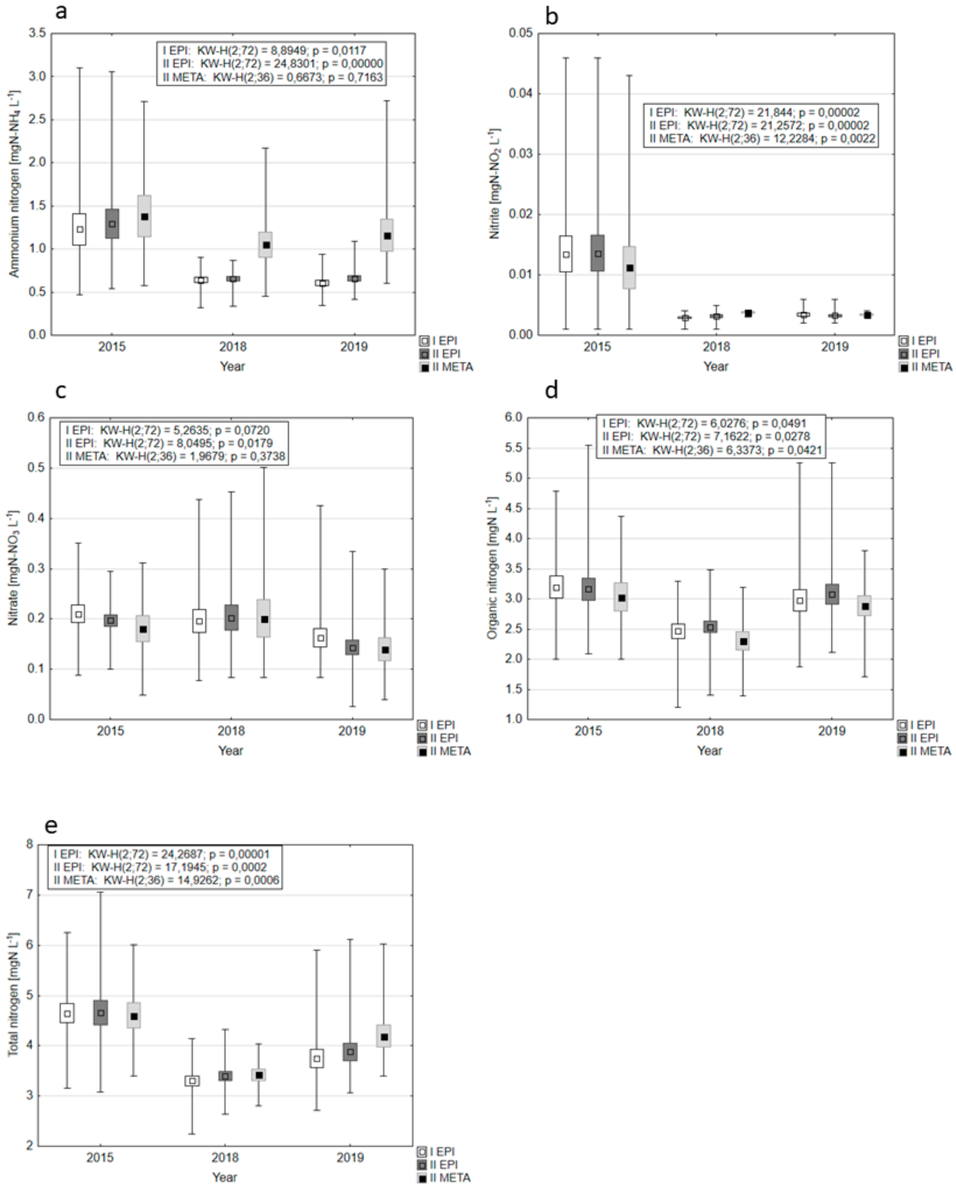


Figure 3. The mean, minimum and maximum concentration of ammonium nitrogen (**a**), nitrite (**b**), nitrate (**c**), organic nitrogen (**d**) and total nitrogen (**e**) in epilimnion (0–3 m station I and II) and metalimnion (4–5 m station II) in Raczyńskie Lake in 2015 (before restoration) and 2018–2019 (during sustainable restoration) [box-mean ± standard deviation; whiskers—minimum and maximum].

A significant decrease during restoration was also observed in the case of nitrite nitrogen. Before the treatments in 2015, it reached 0.046 mgN-NO_2 L^{-1} and in 2018–2019 it did not exceed 0.006 mgN-NO_2 L^{-1} (Figure 3b). Nitrate nitrogen ranged from 0.026 mgN-

NO_3 L^{-1} to 0.50 mgN-NO_3 L^{-1}. The lowest mean values in both epi- and metalimnion were recorded in the last year of the study, although significant differences were only documented in the epilimnion at station II (Figure 3c).

Statistically significant changes in both epi- and metalimnion between subsequent years of the study were observed for organic nitrogen, and its concentrations ranged from 1.39 mgN L^{-1} to 5.55 mgN L^{-1}. In the first year of restoration, a significant decrease in its mean concentration was observed, but in the second year it increased again to the values close to those noted in the initial year (Figure 3d).

The concentrations of total nitrogen also decreased markedly at both sampling stations in 2018. On the other hand, in the second year of restoration, they increased but were still lower than in the period before the restoration. Throughout the study period, total nitrogen concentrations ranged from 2.25 mgN L^{-1} to 7.07 mgN L^{-1}, reaching their highest values in 2015 (Figure 3e).

Soluble reactive phosphorus (SRP) showed slightly higher values at station II, especially in the metalimnion, reaching a maximum of 0.23 mgP L^{-1}. Considering changes in average concentration of this form of phosphorus in successive years, it was found that in 2015 it was similar in all layers. On the other hand, in the first year of restoration treatments, it decreased slightly in the epilimnion, while in the metalimnion it increased. In the second year of restoration, average values rose, both in the epi- and metalimnion, compared to the previous year. The changes found between subsequent years of the study were not statistically significant (Figure 4a). Similar variability both in the depth profile and between subsequent years of the study was observed in the case of total phosphorus (TP) (Figure 4b).

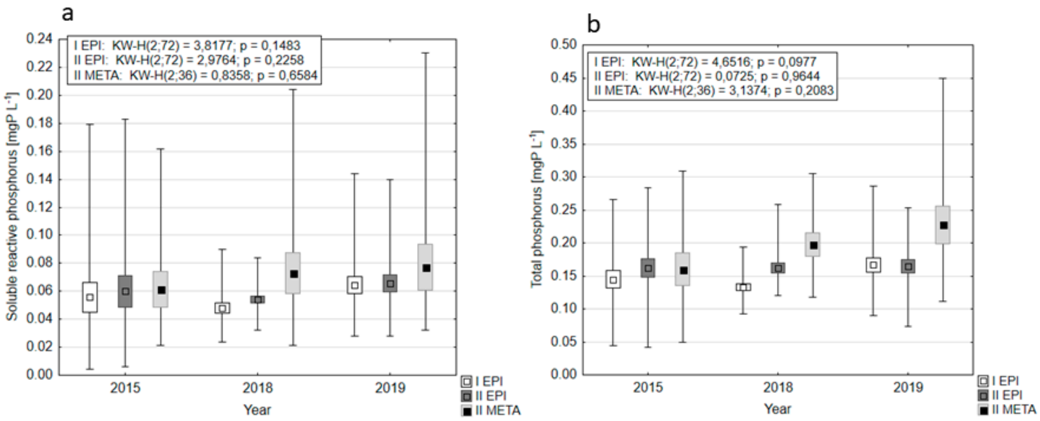


Figure 4. The mean, minimum and maximum concentration of soluble reactive phosphorus (SRP) (**a**) and total phosphorus (TP) (**b**) in epilimnion (0–3 m station I and II) and metalimnion (4–5 m station II) in Raczyńskie Lake in years: 2015 (before restoration) and 2018–2019 (during sustainable restoration) [box-mean ± standard deviation; whiskers-minimum and maximum].

The ratio of total nitrogen to phosphorus reached its highest mean value of 42.01 in 2015 in the epilimnion at station I. During the restoration in 2018–2019, it decreased in both layers to 26.2 in the epilimnion and 21.3 in the metalimnion, although this decrease was not statistically significant.

Trophic state index calculated according to the Carlson formulas indicated a slight decrease in trophic status. However, the obtained values classified the lake throughout the whole research period as hypereutrophic. The highest TSI index of 75.31 was observed in 2015, before restoration treatments (Table 1).

Table 1. Trophic state index for the epilimnion in Raczyńskie Lake in 2015 (before restoration) and 2018–2019 (during sustainable restoration).

Year	TSI (SD)	TSI (TP)	TSI (ChL)	Mean
2015	76.90	68.91	80.13	75.31—Hypereutrophy
2018	66.21	75.34	73.80	71.78—Hypereutrophy
2019	70.29	73.10	75.32	72.90—Hypereutrophy

3.2. Plankton Abundance

The mean total abundance of phytoplankton in the epilimnion of Raczyńskie Lake clearly changed in subsequent years of the study. In the initial year, the maximum phytoplankton abundance was 43,106 specimens mL^{-1} (Figure 5a). In spring, groups such as cryptophytes, chrysophytes, diatoms and green algae dominated in numbers. In summer and autumn, the highest share was held by cyanobacteria, whose abundance exceeded 32,000 spec. mL^{-1} (Figure 5b). In the first year of sustainable restoration, a distinct increase in the total phytoplankton abundance was observed, accompanied by a decrease in the abundance of cyanobacteria. The maximum of the total abundance was 66,959 spec. mL^{-1} and 24,260 spec. mL^{-1} in the case of cyanobacteria. In the second year of restoration, the maximum of abundance of both total phytoplankton specimens and cyanobacteria decreased (27,178 spec. mL^{-1} and 16,538 spec. mL^{-1}, respectively). However, the mean share of cyanobacteria slightly increased (Figure 5a,b). During summer, cyanobacteria taxa proliferated, including *Aphanizomenon gracile* and *Planktothrix agardhii*.

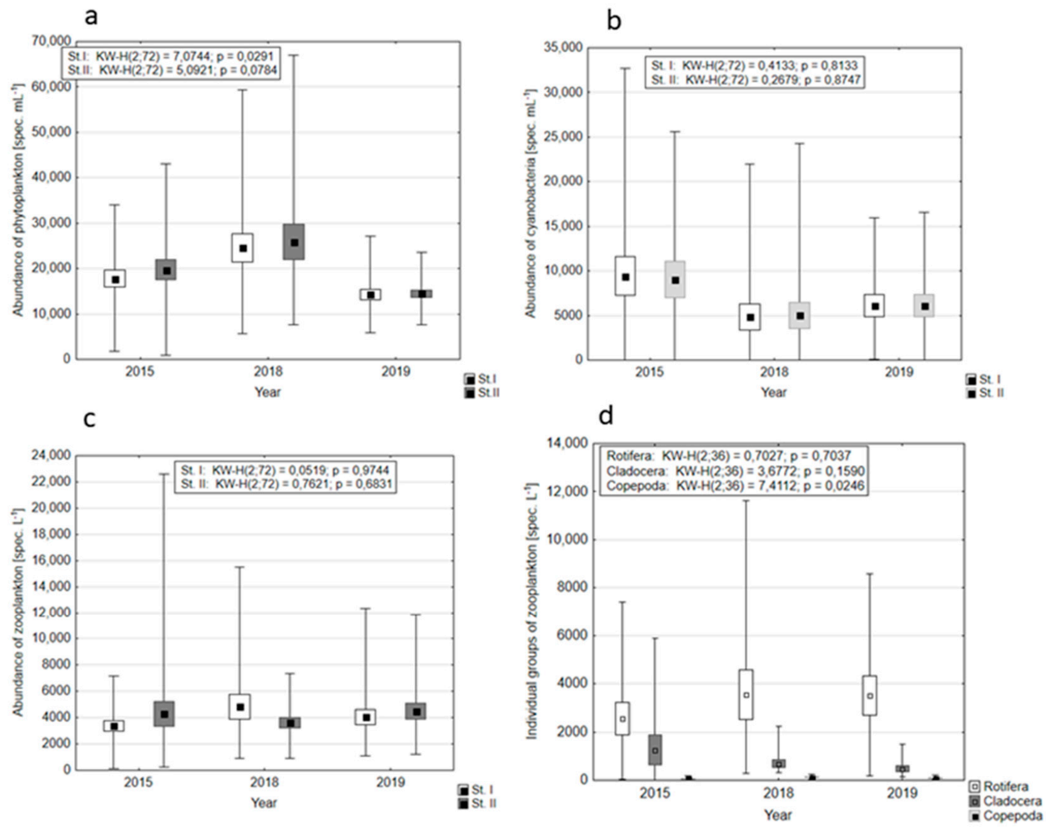
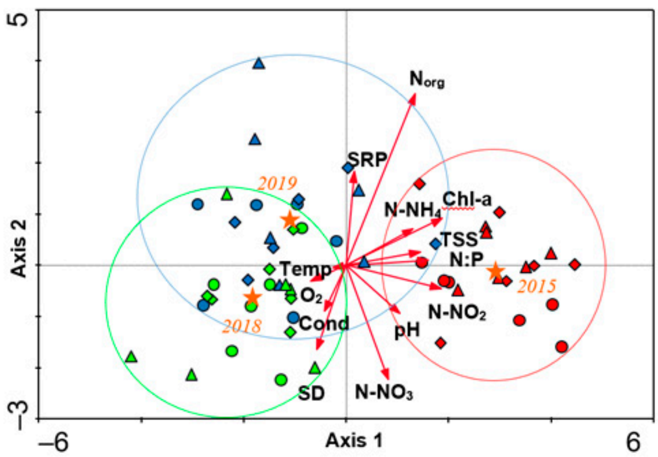


Figure 5. The mean abundance of phytoplankton (**a**), cyanobacteria (**b**), zooplankton (**c**) and individual groups of zooplankton (**d**) in the epilimnion (0–3 m station I and II) of Raczyńskie Lake in years: 2015 (before restoration) and 2018–2019 (during sustainable restoration) (box—mean ± standard deviation; whiskers—minimum and maximum).

In the case of zooplankton, minor differences in the mean total abundance were observed over the study period. Both the minimum (105 spec. L^{-1}) and maximum (22,628 spec. L^{-1}) values of total abundance were found in 2015. In the years when sustainable restoration treatments were applied, the average abundance of cladocerans in the epilimnion decreased, while the number of rotifers increased (Figure 5c,d); however, these differences were not statistically significant.

3.3. CVA Analyses

The CVA identified three groups of pools based on environmental variables and three periods of research (Figure 6). There were three groups including the year 2015, corresponding to the period before restoration, and two periods during sustainable restoration: 2018 and 2019. Among the environmental variables considered, chlorophyll-a (Chl-a), nitrite (N-NO_2), organic nitrogen (Norg) and oxygen (O_2) had the greatest influence in defining these groups (Figure 6). The first group, 2015—before restoration, was clearly separated from the two remaining periods, and the high amount of ammonium (N-NH_4), chlorophyll-a and nitrites had the strongest impact. On the contrary, the two other groups—2018 and 2019, which were strongly separated from the first group (2015), were characterised by increasing water transparency (SD) and a decrease of both ammonium nitrogen, chlorophyll-a and nitrite values (Figure 6).



Variable	Lambda A	P	F
Chl-a	0.27	**0.002**	8.10
N-NO_2	0.32	**0.002**	11.79
Norg	0.12	**0.030**	4.35
SRP	0.06	0.118	2.39
N-NO_3	0.06	0.098	2.57
N-NH_4	0.05	0.158	2.05
SD	0.03	0.330	1.19
pH	0.04	0.234	1.62
O_2	0.07	**0.046**	3.23
Temp	0.06	0.062	2.83
N:P	0.01	0.662	0.38
Cond	0.00	0.694	0.32
TSS	0.01	0.760	0.21

Figure 6. Triplot of the canonical variate analysis (CVA) based on Euclidean distance (Hill's scaling option) and the results of Monte Carlo test. Environmental vectors present the direction along which each variable changes the most: conductivity (Cond), temperature (Temp), oxygen (O_2), pH, water transparency (SD), nitrates (N-NO_3), nitrites (N-NO_2), ammonium nitrogen (N-NH_4), organic nitrogen (Norg), soluble reactive phosphorus (SRP), seston (TSS), chlorophyll-a (Chl-a) and N:P; red colour—samples collected in 2015 before restoration; green—samples collected during restoration in 2018, blue—samples collected during restoration in 2019; o—station I surface; ◊—station II surface; Δ—station II 5 m.

4. Discussion

Sustainable restoration has been previously applied in several lakes in the Wielkopolska region: Durowskie Lake, Uzarzewskie Lake, Swarzędzkie Lake and the Maltański Reservoir [8,11,14,15,39,40]. Two of these lakes, Durowskie and Uzarzewskie Lakes, have shown a gradual improvement of water quality [11,39,40]. In Swarzędzkie Lake, however, only a short-term effect was achieved due to the short-term application of the all complementary methods [15]. Long-term and combined restoration treatments should therefore be used to achieve a permanent improvement in water quality [41,42].

4.1. The Impact of Restoration on the Basic Variables of Water Quality

As predicted, the two-year restoration treatments on Lake Raczyńskie allowed only the initiation of the process of improving water quality. One of the main parameters determining water quality in the lake is transparency [37]. An increase of water transparency was noted in the first year of treatment. Additionally, a decrease in chlorophyll-a concentration was observed together with a decrease in pH and TSS, which resulted from changes in phytoplankton structure. The total abundance of phytoplankton in the epilimnion of Raczyńskie Lake increased in the first year of the treatment, despite the decrease in chlorophyll-a concentration. This was related to the transformation of the phytoplankton composition, with reference to the reduction in the number of large, colonial cyanobacteria containing higher amounts of chlorophyll-a and the increase of the number of small organisms from other taxonomic groups (cryptophytes, chrysophytes, diatoms and green algae). This was probably due to the lowering of nutrient concentration in the epilimnion, especially phosphates and ammonium nitrogen, as a result of chemicals dosing in the restoration process. Cyanobacterial blooms were stimulated by high concentrations of both phosphorus and ammonium nitrogen prior to the restoration, thus the decrease in nutrient content influenced the changes in phytoplankton composition [43–45]. As emphasized by Paerl et al. [46], it is important to change the previous focus from P limitation to a dual N and P co-limitation in the management strategy. This is met by the dosage of magnesium chloride, which inactivates both phosphorus and ammonium nitrogen in the water column, creating insoluble struvite, i.e., magnesium ammonium phosphate ($NH_4MgPO_4 \cdot 6H_2O$) [47], which was confirmed by the statistically significant changes in ammonium nitrogen concentration in the epilimnion in subsequent years of the study.

In the second year of treatment, transparency decreased and the concentration of chlorophyll-a, abundance of cyanobacteria and TSS increased again. However, these values were lower than in the initial year, before restoration. These data were correlated with each other, as confirmed by statistical correlations between SD and chlorophyll-a ($r = -0.839$, $p < 0.05$) and the abundance of cyanobacteria ($r = -0.881$, $p < 0.05$). This demonstrates more intense proliferation of cyanobacteria in 2019 than in 2018, and their effects on chlorophyll-a, TSS and transparency. Changes in the Raczyńskie Lake ecosystem functioning under the influence of restoration treatments were also confirmed by the CVA analysis, which showed the separation of these parameters in 2018–2019 compared to 2015.

At the same time, a further decrease, especially in the epilimnion, was observed in total phytoplankton abundance and pH. A slight deterioration of water quality in the second year of restoration was caused by fewer chemical applications (five instead of eight) and a shorter application period until July instead of October, as in 2018. This proves that the conditions for the proliferation of cyanobacteria from August were much better because the phosphorus concentration increased again. The use of iron sulphate for phosphorus inactivation may also be significant; it probably caused a successive increase in iron concentration in water, stimulating the growth of cyanobacteria and negatively affecting other groups of algae, especially green algae, as previously reported by [48,49]. The increase of transparency was not high enough for the re-establishment of submerged macrophytes throughout the littoral of the lake, although a small area with a patch of *Potamogeton crispus* was found in the north-eastern part near the swimming area. Such a delayed return of macrophytes to restored lakes is frequently observed [21,50,51].

Changes in oxygen concentration were also observed during the study period. In the epilimnion, oxygen content increased in successive years of the sustainable restoration measures. This was confirmed by a statistically significant relationship between phytoplankton abundance and oxygen concentration in the epilimnion (r = 0.482, $p < 0.05$), which suggested that the increase was due to the increased production of oxygen by phytoplankton. On the other hand, however, no correlation was found with the distribution of cyanobacteria, which dominated in summer, creating water bloom. In addition, the increase in phytoplankton abundance was observed only in 2018, and it decreased significantly in 2019. Chlorophyll-a in both years of restoration was statistically significantly lower than before restoration. Thus, the increase in oxygen concentrations in the following years proves that it was unusually low in 2015, disproportionate to the value of chlorophyll-a. This probably resulted from the high oxygen consumption in 2015, occurring as a result of the microbiological biodecomposition of the suspended organic matter present in epilimnetic water due to the re-suspension of bottom sediments. During the restoration the TSS content clearly decreased, which may confirm the lower resuspension of sediments and therefore lower oxygen consumption. This was probably related to the operation of the aerators located near the bottom in the deepest place of the lake and mixed the water column, which only worked in the summer of 2015 and was not switched on in 2018–2019, and the increase in the thermal stability of the water column. It may also indicate an increase in the thermal stability of the water column preventing sediment resuspension as a result of an increase of water temperature at the surface. The water temperature in 2015 was not as warm as during the years 2018–2019 [52]. The confirmation of these assumptions was a clear increase in the range of water temperature between the surface and the bottom in subsequent years of the research (Figure 2a). This may also partly explain the increase in abundance and biomass (as chlorophyll-a) of phytoplankton in the second year of restoration, as according to Donis et al. [53], stronger stratification promotes phytoplankton growth within the euphotic zone.

Electrolytic conductivity increased in both the epi- and metalimnion of the lake under the influence of the applied restoration treatments. This may be related to the accelerated mineralization of organic matter in both the catchment soils and shallow bottom sediments as a result of higher temperatures in 2018–2019. It may also be partly due to the lower consumption of minerals present in the water due to the lower biomass of phytoplankton.

4.2. Influence of Chemicals Used on Nitrogen Concentration

One of the aims of restoration treatments is to limit the availability of nutrients to phytoplankton in order to prevent blooms [54]. The application of sustainable restoration in Raczyńskie Lake resulted in changes in the concentration of nutrients. The concentration of nitrogen in lake water and its seasonal variation is extremely important for phytoplankton proliferation [55]. The greatest reduction in concentration compared to the initial year was noted for ammonium nitrogen, especially in the epilimnion of the lake. This was influenced by the application of magnesium chloride, which led to the formation of struvite deposited in sediment [47]. The reduction of this nitrogen form in the epilimnion persisted in both years of the sustainable restoration. CVA analysis also indicated that the two treatment years were separate from the year before restoration, when higher concentrations of ammonium nitrogen were noted. In turn, the formation of an anaerobic zone in the metalimnion and high temperature above the bottom in summer 2015 contributed to a reduction of nitrification and an increase of ammonium nitrogen concentration in this zone. In the first year of restoration, as a result of increased oxygen concentration above the bottom, there was a predominance of nitrification over denitrification, which contributed to the decrease of ammonium nitrogen concentration. On the other hand, in 2019 there was an increase in the concentration of this form of nitrogen in relation to the previous year, although these values were still lower than before the restoration. This was mainly owing to lower oxygen concentration in the over-bottom zone which was conducive to denitrification, as confirmed by the marked decrease in nitrate concentration in 2019. The reduction in the concentrations of ammonium and nitrate nitrogen undoubtedly had an impact on decreasing the abundance and biomass of phytoplankton, as well as the reconstruction of the species composition [56]. More intensive nitrification and denitrification processes in 2018–2019 favoured a notable reduction in the concentration of nitrites in the entire water column.

The analysis of changes in organic nitrogen concentration showed that in the first year of the restoration it decreased in the whole water column. This resulted in a less intensive phytoplankton growth as indicated by a decreased abundance of cyanobacteria, lower chlorophyll-a concentration, and increased transparency, and was confirmed by the statistically significant relationship between chlorophyll-a and organic nitrogen concentration ($r = 0.809$, $p < 0.05$) and cyanobacteria abundance and concentration of this nitrogen form ($r = 0.759$, $p < 0.05$). In 2019, the amount of organic nitrogen in lake waters increased to a value similar to that observed before restoration, which due to the internal loop had an impact on the increase of the phytoplankton biomass, including cyanobacteria [57]. The decrease in the content of organic nitrogen in the water as a result of restoration, as well as the differences in its concentration in both years of the treatments, probably resulted from the precipitation of dissolved organic matter under the influence of the iron sulphate coagulant. In the process of drinking water treatment [58], also during the restoration of lakes using iron or aluminium coagulants, flocs are formed in the coagulation process, on which dissolved organic compounds present in the water are adsorbed. Fewer phosphorus inactivation treatments in 2009 probably also resulted in a lower reduction in organic nitrogen content.

Thus, sustainable restoration caused a clear decrease in total nitrogen in the first year of treatments and a slight increase again in the second year, although these values were still lower than in the year before the restoration. This had a clear impact on the growth of phytoplankton, especially cyanobacteria, as evidenced by a statistically significant relationship between total nitrogen concentration and cyanobacteria abundance in the epilimnion ($r = 0.491$, $p < 0.05$).

4.3. Influence of Chemicals Used on Phosphorus Concentrations

One of the main goals of the phosphorus inactivation in the process of restoration of lakes is the precipitation of phosphorus from the water column to the bottom and the slowing of its release from sediments [59]. The result is a reduction in phosphorus availability for phytoplankton. Cyanobacteria are particularly sensitive to this process, which leads to a decline of their abundance and the reduction of water blooms [8,17]. Quite high concentrations of both forms of phosphorus were observed in the water column of Raczyńskie Lake before the restoration. As a result of the application of chemicals in 2018, a reduction in the concentrations of both SRP and TP in the epilimnion of the lake was observed. This contributed to a decrease in phytoplankton productivity, as evidenced by lower chlorophyll-a concentration and a higher transparency than in 2015. The share of cyanobacteria in the lake phytoplankton also decreased. The effect of reduced P inactivation treatments in 2019 was to increase the concentrations of both forms of phosphorus in the epilimnion up to values close to those before the restoration. Increased SRP availability for phytoplankton contributed to the return of cyanobacteria blooms, which consequently increased chlorophyll-a, TSS and reduced transparency. These changes confirmed statistically significant relationships between cyanobacteria abundance and SRP and TP concentrations in the epilimnion ($r = -0.531$ and $r = -0.656$, respectively, $p < 0.05$). However, in the metalimnion of the lake, an increase in SRP and TP concentrations was observed in 2018 and 2019. An increase in phosphorus concentration in the over-bottom zone is often observed in the initial phase of sustainable restoration, which is probably related to the release of phosphates due to the reduction of dosed iron compounds in deeper layers of water and sediments, which is periodically deoxidized [8,14]. In order to bind this phosphorus load released from the bottom, it was decided to dose Phoslock to the part of the lake where the water overlying bottom sediments is deoxidized, i.e., the bottom at a depth greater than 5 m. The calculated Phoslock dose of 1 ton turned out to be too small to bind the released phosphorus, which was probably related to its dosing to the lake surface [60]. Water currents in the lake meant that the applied dose not only reached the deepest part of the lake, but also spread to the shallower bottom, where it was not needed because the bottom was not deoxidized there. Therefore, it is important in the future to dose Phoslock more precisely to the deeper parts of the lake, or to increase its dose in relation to stoichiometric amounts.

4.4. Influence of Biomanipulation

The effects of lake restoration are often very clear when analysing the community structure of inhabiting organisms. Biomanipulation was the method used to support technical treatments in improving water quality. Its aim was to increase cladoceran occurrence in the lake, and particularly to enhance their grazing pressure on phytoplankton [61,62]. Filter-feeding cladocerans, especially *Daphnia* spp., are responsible for the creation of clear water periods in biomanipulated lakes [63]. Thus, the results of some studies [64] indicate that a regime shift of zooplankton communities may be recorded following biomanipulation. However, in the analysed lake, generally no increase in either the numbers of cladocerans or daphnids was noted. A lack of a significant shift towards large-bodied effective filtrators is usually explained by insufficient fish reduction in the restored lakes leading to weak enhancement in the food web interactions [65]. An overwhelming participation of small pelagic taxa such as e.g., *Bosmina longirostris*, *Chydorus sphaericus*, *Diaphanosoma brachyurum*, *Eubosmina coregoni* and *Daphnia cucullata* along with predominating rotifers were noted frequently in Raczyńskie Lake. Small cladocerans are known to be less vulnerable to fish predation than the large-sized taxa [66,67], and their prevalence over large forms and co-occurrence with small-bodied rotifers is a typical phenomenon of the eutrophic character of water [68,69].

There are also other so-called feedback mechanisms [19,70] that are responsible for the lack of a spectacular effect of restoration. Some decreases of cladocerans in subsequent years may also be noted as a consequence of the occurrence of toxic cyanobacteria [71]. In case of the examined Raczyńskie Lake, potentially toxic species of cyanobacteria forming the water bloom were recorded every summer. 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 [72,73]. This bloom was more intense in 2019 compared to 2018, possibly leading to the higher concentration of cyanobacterial toxins in the water. It is worth underlining that their numbers were lower in the years following restoration in relation to the period before restoration. This might be a positive sign of restoration measures in this lake. A reduction in the abundance of cyanobacteria and an increase in the share of other phytoplankton groups, such as chrysophytes, green algae, diatoms and cryptophytes, has also been observed in other lakes that have undergone sustainable restoration, such as Durowskie Lake [40,74], Swarzędzkie Lake [14,51,75,76], and Uzarzewskie Lake [77].

5. Conclusions

The research undertaken has confirmed that achieving satisfactory results of sustainable restoration in improving water quality requires a time period longer than two years. However, the two-year simultaneous application of several methods of sustainable restoration showed that the ecosystem responded positively to the measures taken, as an increase in transparency and a decrease in chlorophyll-a concentration were observed. Moreover, the abundance of cyanobacteria was almost two-fold lower than before restoration. There was also a significant decrease in nitrogen concentration, especially ammonium and organic nitrogen. Differences in the analyzed parameters between the period before and during restoration were also confirmed by the CVA analysis. The obtained results showed that the treatments should last for several more years. They should cover the entire growing season, and their frequency and scope should strictly depend on the pace of changes.

This indicates the importance of ongoing monitoring and tracking changes taking place in the ecosystem, which confirms the second research hypothesis. Studies have shown that at the beginning of sustainable restoration (the first two years), the improvement effect is not spectacular, but the processes responsible for improvement of water quality have been initiated. The ecosystem responds slower than during intensive restoration; however, the applied treatments do not destroy the biocenosis, but rather rebuild it. Within two years, it was impossible to decrease phosphorus concentration from 0.15 mg P L^{-1} to the required 0.10 mg P L^{-1} to achieve a significant improvement in water quality, but the observed changes indicate that the restoration methods used, after some adjustments, may be successful within a few years, because the initiated changes go in the right direction. The slow improvement of water quality as a result of long-term restoration treatments will contribute to establishing a balance in this ecosystem and to achieving an environmental effect as well as increasing its recreational potential. Sustainable restoration is a long-term activity and brings positive results in terms of improved water quality.

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