Original Research

Variation in Phyto- and Zooplankton of Restored Lake Uzarzewskie

Anna Kozak*, Ryszard Gołdyn

Department of Water Protection, Faculty of Biology, Adam Mickiewicz University,
Umultowska 89, 61-614 Poznań, Poland

Co-financed by National Fund
for Environmental Protection
and Water Management

Received: 1 October 2013
Accepted: 2 April 2014

Abstract

Our paper reports the phyto- and zooplankton changes studied in Lake Uzarzewskie in 2010-12 under the influence of a restoration procedure. It is a small (10.6 ha), not deep (up to 7.3 m) but thermally stratified, natural, kettle-shaped lake fed with waters from the Cybina River. Water of the tributary rich in nutrients was responsible for the hypertrophic state of the lake. To improve the condition of the lake, some restoration measures were applied. They included the iron treatment method used for phosphorus inactivation. The second method used for the lake restoration was transport of the water rich in nitrates flowing from the springs at the bottom of the slope near the lake by special pipes to the deepest part of the lake, to increase the redox potential at the sediments-water interface. The most abundant group of phytoplankton were cyanobacteria, (especially in summer and autumn months), diatoms, cryptophytes, and chrysophytes. Chlorophytes were the most numerous in respect to the number of taxa. The most important taxa were *Planktothrix agardhii*, *Aphanizomenon gracile*, *Pseudanabaena limnetica*, *Limnothrix redekei*, *Cyclotella, Stephanodiscus*, *Rhodomonas lacustris*, *Cryptomonas marssonii*, and *C. reflexa*. Comparing with mean abundance and biomass of phytoplankton in 2010, a small statistically significant decrease was noted in 2011, but an increase in 2012. Some improvement in water quality judged by Shannon-Weaver diversity index and species composition, abundance, and biomass in the lake plankton was observed. Zooplankton was dominated by rotifers. Among cladocerans the most abundant were *Bosmina longirostris* and *Eubosmina coregoni*, which were not effective enough in phytoplankton control.

Keywords: phytoplankton, abundance, biomass, hypertrophic lake, species composition

Introduction

Phytoplankton is an important biological element for ecological assessment of water quality in lakes. Its abundance is dependent, on the one hand, on physico-chemical parameters, while on the other hand on grazing pressure. The response of phytoplankton community in water bodies also depends on the restoration method applied there. Frequently in the restoration experiments it was difficult to establish indirect consequences of restoration treatment

*e-mail: akozak@amu.edu.pl

because of numerous interacting factors (changes in weather conditions, nutrient loading ratios, feeding pressure, etc.) that are responsible for the quantitative and qualitative changes in the plankton community [1]. Usually, spectacular effects are expected. It was shown that the reduction of cyanobacterial bloom is possible using, e.g., a combination of flocculent polyaluminium chloride with the lanthanum-modified bentonite Phoslock®, effectively sedimented cyanobacteria flocks to get substantially cleared water [2]. Phytoplankton changes in composition and abundance are observed as the first response to the restoration treatment [3]. The intensive interference in the ecosystem caused by the restoration produces drastic and rapid changes in the whole ecosystem. Therefore, in the case of Lake Uzarzewskie it was decided to undertake sustainable restoration. At first the procedure of phosphorus inactivation (iron treatment, PIX-112) was applied in 2006 and 2007. In 2008 the method of restoration was changed and hypolimnetic oxygenation started. The spring water was delivered into the hypolimnion using two pipes. This water is fully oxygenated and contains a high concentration of nitrates [4].

Before the restoration in 2005, the concentration of ortophosphates in Lake Uzarzewskie was quite high and reached 0.052-0.089 $mg \cdot l^{-1}$ P in spring and summer to 0.170 $mg \cdot l^{-1}$ P in autumn [5]. In the bottom sediments, the concentration of reactive phosphorus excited 2.41 $mg \cdot l^{-1}$ P of dissolved phosphorus and 2.56 $mg \cdot l^{-1}$ P of total phosphorus [6]. Increased phosphorus amounts favoured high Cyanobacterial growth. The phytoplankton community was dominated by filamentous Cyanobacteria, especially by *Cuspidothrix issatschenkoi* (Usachev) Rajaniemi, *Anabaena spiroides* Kleb., and *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek. Their domination began in June and lasted till November [5]. In that time zooplankton was dominated by rotifers, mainly *Keratella cochlearis* f. *tecta,* which indicates a very high tropic state [7].

During chemical procedure (iron treatment) in 2006 and 2007 the phosphorus internal loading from bottom sediments also was measured. In comparison with 2005 (before restoration), phosphorus internal loading slightly increased in 2006 and decreased in 2007 [8]. This decrease was reported as a positive result of iron treatment. The highest values of released phosphorus were noted in summer and autumn [8]. In the first year of chemical restoration the abundance and biomass of phytoplankton in the lake increased, in comparison with the previous year, while in the second one the values were similar as before restoration. A high abundance and biomass of phytoplankton and the longer-term dominance of cyanobacteria in the first year of restoration may have resulted from high temperatures and sunshine in June and July of that year, with the high availability of ammonium nitrogen, and the growth stimulation of phytoplankton by iron derived from the dosed coagulant [9]. In 2008 (after the restoration method changed into hypolimnetic oxygenation) phytoplankton was still dominated by cyanobacteria such as *Planktothrix agardhii*, *Aphanizomenon flos-aquae* (L.) Ralfs, *Anabaena flos-aquae* Brebisson, ex Bornet et Flahault, and *Limnothrix redeckei* (Van Goor) Meffert [10]. The aim of this study was to analize the phyto- and zooplankton community changes during restoration of a dimictic, hypertrophic lake with the increasing water redox potential in the hypolimnion zone.

Materials and Methods

Lake Uzarzewskie (52º26'53 "N 17º08'00" E) is a small hypertrophic and dimictic lake situated on the River Cybina (Wielkopolska Region), a right tributary of the River Warta in Western Poland. The surface of the lake is 10.6 ha and its maximum depth is 7.3 m. Its average depth is 3.4 m and the average retention time of water in the lake is only 4.5 days [11]. The lake received municipal wastewater in the past, which substantially deteriorated lake water quality. The lake water also is influenced by diffuse water pollution from an agricultural catchment area as well as rich in nutrients and organic compound water drained from the ponds of fish-farms [12], contributing to the hypertrophic state of the lake [13]. The water blooms were recorded in summer, thereby decreasing the transparency to 50 cm and increasing the chlorophyll-*a* concentration up to 200 $\mu g \cdot l^{-1}$. Therefore, the lake had to be closed to recreational use. Water blooms were caused by cyanobacteria species, especially *Planktothrix agardhii*, *Aphanizomenon flos-aquae*, *Anabaena flos-aquae,* and *Limnothrix redeckei* [10]. To improve the water quality for several years restoration procedures have been implemented. One of methods used in 2006-07 to improve the water quality was an iron treatment method used for phosphorus inactivation [14, 15]. In 2008 the water from two small tributaries flowing from the springs at the bottom of the slope near the lake was directed to the hypolimnion. This water was well-oxygenated and rich in nitrates, so it increased the redox potential at the sediment-water interface [16].

Due to the cyanobacterial water blooms, steep slopes, and significant silting, Lake Uzarzewskie is not used for swimming or water sports. The only form of recreational use of the lake is fishing. The lake was stocked with 160 specimens of zander fry and 110 specimens of tench fry in 2006 and 2007 [9].

In 2006-07 the restoration procedure was started with the aim of phosphorus inactivation using iron sulphate (PIX 112). As a result, the sorption capacity of bottom sediments was increased and the intensity of phosphorus internal loading was reduced [8]. Storage of bound phosphorus in the bottom sediments, however, requires a high level of redox potential that would prevent the reduction of iron (III) in the sediments [17, 18]. So, since 2008 the cold waters rich in nitrates and oxygen have been directed from the springs through the pipelines into the deepest site of the lake.

The qualitative and quantitative composition of phyto- and zooplankton in the lake was analyzed in 2010-12. Water for analyses was sampled from a station located in the middle of the lake, at monthly intervals. The samples were taken each time from the surface water layer and from the depths of 1, 2, 3, 4, and 6 m. The analyses were made using an OLYMPUS optical microscope and Sedgwick-

Rafter chamber with a capacity of 0.67 ml. The zooplankton was collected by sieving 10 l of lake water through a 45-µm mesh plankton net. Samples were preserved with Lugol's solution.

The biodiversity index based on species richness determination was used to describe the phytoplankton community composition. Phytoplankton diversity was calculated using the Shannon-Weaver formula for each sample using the software for scientific data statistics analysis Past 3.x – the Past of the Future. Kruskal-Wallis tests were used to compare differences between phytoplankton abundance, biomass, and Shannon -Weaver diversity index in the studied years.

The significance of changes in the physicochemical parameters on the one hand and total biomass and abundance of phytoplankton on the other were determined using Spearman's rank correlation from nonparametric statistics. The correlations between nutrient concentration, zooplankton abundance, and phytoplankton abundance and biomass were checked using the STATISTICA program. The results of physicochemical parameters of Lake Uzarzewskie water from 2010-12 have been published elsewhere [16]. The physicochemical variables of water such as temperature, dissolved oxygen concentration, pH, Secchi depth, phosphorus, and nitrogen published there were used here for checking the correlations with planktonic variables. The correlations between the abundance and biomass of phytoplankton (total abundance of the phytoplankton, as well as that of each group separately) with the abundance of filtering zooplankton (rotifers), Cladocera (without *Leptodora kindtii*), and Calanoida (from copepods and young copepods – nauplii) were tested. Statistical analysis was performed only for the results from epilimnion, i.e. from the surface layer to a depth of 2 m.

Results

In total, 161 phytoplankton taxa were identified in Lake water in the studied period (from 120-131 in each year of the study). As regards the species composition of phytoplankton of Lake Uzarzewskie, the green algae were dominant (67 taxa were noted in the three years of study).

Table 1. Number of taxa noted in Lake Uzarzewskie in the studied period.

	2010	2011	2012	Sum
Cyanobacteria	14	16	13	20
Euglenophyceae	6	4	4	6
Cryptophyceae	8	8	9	9
Chrysophyceae	12	12	10	14
Bacillariophyceae	24	23	20	28
Chlorophyceae	54	57	50	67
Dinophyceae	4	4	7	7
Xantophyceae	3	2	2	5
Conjugatophyceae	4	5	5	5
No. of phytoplankton taxa	129	131	120	161
Rotifera	59	45	41	66
Cladocera	8	8	9	12
Copepoda	11	7	8	15
No. of zooplankton Taxa	78	60	58	93

The next most abundant groups were diatoms, cyanobacteria, and chrysophytes, represented by 28, 20, and 14 taxa, respectively. Other groups were represented by a smaller number of taxa (from 5 to 9, Table 1). The mean abundance of phytoplankton in the studied years reached 7.9×10^3 specimens·ml^{-1} in 2010, 5.2 $\times10^3$ specimens·ml^{-1} in 2011 and 9.9×10^3 specimens·ml^{-1} in 2012 (Fig. 1). As regards the phytoplankton abundance, the most abundantly represented were cyanobacteria, observed mostly in summer and autumn. The other most abundant groups were diatoms, chrysophytes, and cryptophytes. Other taxonomic groups were less abundant. The dominant species were: *Planktothrix agardhii*, *Aphanizomenon gracile*, *Pseudanabaena limnetica*, and *Limnothrix redekei*. After the cyanobacterial water blooms, centric diatoms from the genus *Cyclotella*, *Stephanodiscus*, and pennate *Ulnaria* or *Nitzchia* started to dominate. Large abundances of chryso-

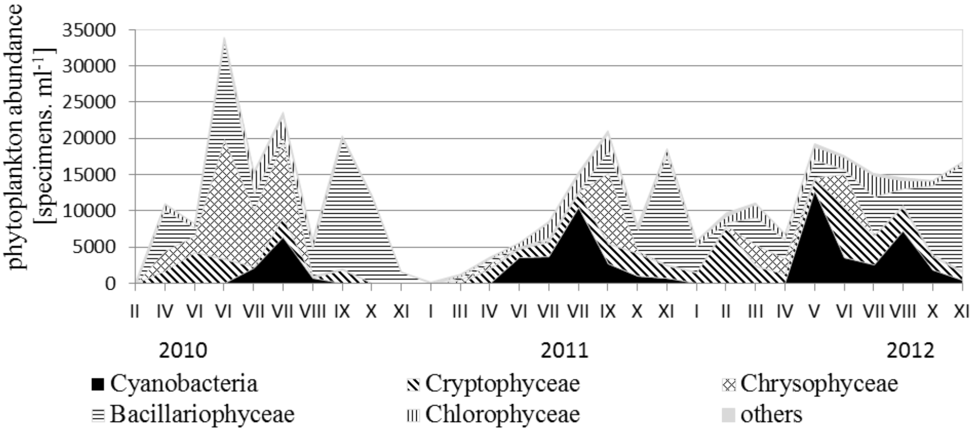

Fig. 1. The abundance of phytoplankton in Lake Uzarzewskie (an example from the surface).

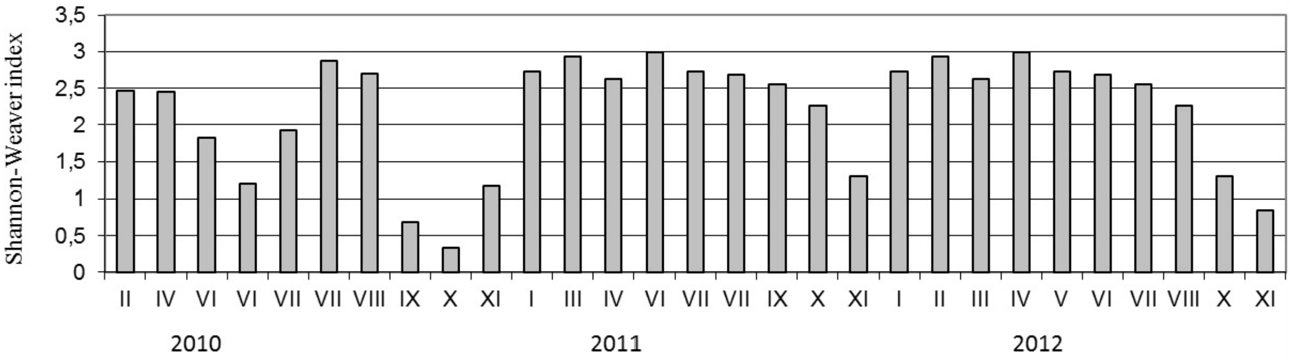

Fig. 2. The diversity index of phytoplankton abundance each month in Lake Uzarzewskie.

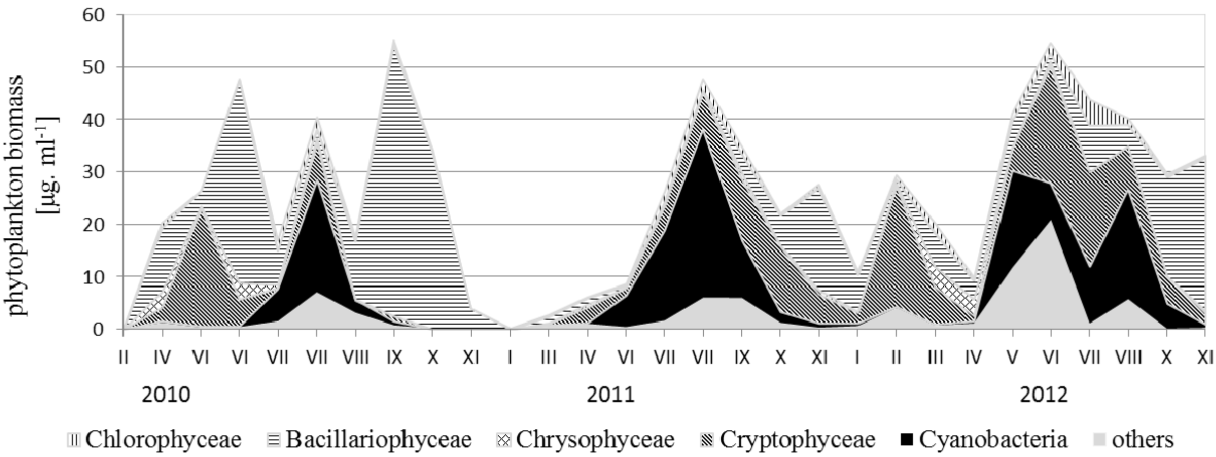

Fig. 3. The biomass of the phytoplankton in Lake Uzarzewskie (an example from the surface).

phytes and cryptophytes were most frequently recorded in winter. Also in late spring and summer, the most abundant were cryptophytes, represented mainly by *Rhodomonas lacustris* Pascher and Ruttner, *Cryptomonas marssonii* Skuja, *C. reflexa* Skuja, and chrysophytes such as *Erkenia subaequiciliata* Skuja. The Shannon-Weaver diversity index in the studied years varied from 0.33-3.00 (Fig. 2). In the first year of the study (2010), the minimum and maximum values of the index were the lowest. They increase in subsequent years (2011-12). The averaged values of the index were 1.75 in 2010, 2.53 in 2011, and 2.36 in 2012.

Seasonal changes in the biomass of phytoplankton were noted in the analyzed period and the most important were diatoms, cyanobacteria, and cryptophytes (Fig. 3). The average values of the biomass from the three studied years were significantly different and reached 17.2 $\mu g \cdot ml^{-1}$, 10.6 $\mu g \cdot ml^{-1}$, and 21.0 $\mu g \cdot ml^{-1}$ in 2010, 2011, 2012, respectively (Fig. 4). However, significant differences (Kruskal-Wallis tests, $p<0.05$) were noted only between values from 2011 and 2012. In 2012 an important group in the aspect of biomass was that of conjugatophytes (Fig. 3). The most important in the group was *Mougeotia* genus because of its large individual cell size. Significant differences were found in the vertical distribution of phytoplankton abundance and biomass. It was the highest abundance or biomass at the surface and the lowest just above the bottom layer (6 m, Fig. 5).

In all years of study zooplankton was represented by 66 taxa of rotifers and 27 of crustaceans from which 12 belonged to the Cladocera and 15 to the Copepoda. In the three-year period, the number of identified rotifer taxa decreased from 59 in 2010 to 49 in 2012. The zooplankton abundance was dominated also by rotifers (Fig. 6) and the maximum of their contribution was 31,500 $ind \cdot ml^{-1}$, reached in July 2012. The most abundant species were:

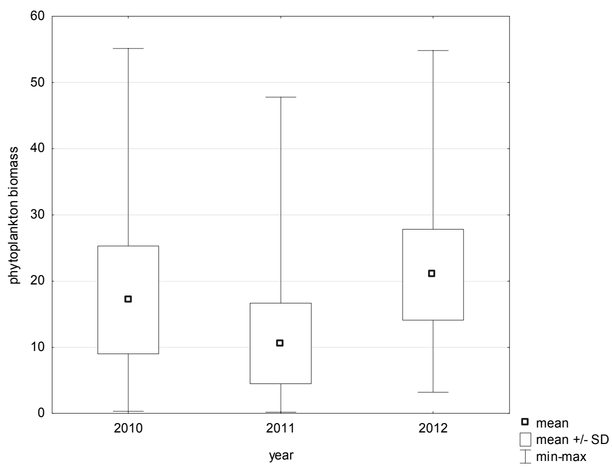

Fig. 4. Mean values of the phytoplankton biomass in the studied years.

Table 2. the correlations of physic-chemical variables and zooplankton abundance with phytoplankton abundance (Spearman's rank correlation coefficient in Lake Uzarzewskie).

	Cyanobacteria	Euglenophyzeae	Cryptophyceae	Chrysophyceae	Bacillariophyceae	Chlorophyceae	Dinophyceae	Xantophyceae	Conjugatophyceae	Phytoplankton abundance
N=63										
Temperature	0.72*	0.02	0.21	-0.10	-0.11	0.52*	0.25*	0.23	0.22	0.54*
pH	0.09	-0.01	0.13	0.17	0.32*	0.25*	-0.01	0.13	0.12	0.35*
Conductivity	-0.43*	-0.11	-0.03	0.23	-0.30*	-0.32*	-0.09	-0.28*	-0.08	-0.48*
Oxygen	-0.16	0.18	0.24	0.33*	0.30*	-0.09	0.17	-0.07	0.05	0.22
The oxygenation	0.14	0.16	0.31*	0.25*	0.23	0.11	0.27*	0.02	0.15	0.42*
Seston	0.68*	0.16	0.27*	-0.09	0.22	0.49*	0.29*	0.23	0.08	0.71*
Chlorophyll-*a*	0.43*	0.41*	0.16	0.11	0.29*	0.29*	0.35*	0.35*	-0.09	0.55*
$N-NH_4$	0.06	0.32*	0.17	-0.13	0.19	0.03	0.08	-0.06	-0.04	0.20
$N-NO_2$	0.15	-0.21	0.55*	-0.10	-0.07	0.59*	-0.02	-0.12	0.39*	0.35*
$N-NO_3$	0.46*	-0.10	-0.02	-0.14	0.21	-0.01	0.13	-0.14	0.13	0.38*
N_{org}	-0.06	0.00	-0.12	-0.14	0.45*	-0.24	-0.18	0.00	-0.07	0.12
N_{tot}	-0.51*	-0.22	-0.29*	0.07	0.01	-0.45*	-0.30*	-0.18	-0.09	-0.48*
PO_4	0.11	0.24	0.11	-0.33*	0.34*	-0.06	0.14	0.00	-0.07	0.27*
P_{tot}	0.31*	0.17	0.15	-0.21	0.23	0.07	0.40*	0.01	-0.01	0.39*
Visibility	-0.57*	-0.25*	-0.31*	-0.02	-0.17	-0.45*	-0.33*	-0.19	-0.18	-0.66*
N=70										
Rotifera	0.24*	-0.07	0.36*	-0.01	-0.20	0.53*	-0.08	-0.05	-0.04	0.09
Cladocera	0.39*	-0.18	-0.06	-0.18	-0.22	0.19	-0.10	-0.10	0.00	-0.03
Copepoda	0.72*	-0.22	0.14	-0.30*	-0.36*	0.40*	0.08	-0.04	0.15	0.16
Zooplankton	0.31*	-0.10	0.34*	-0.05	-0.24*	0.54*	-0.08	-0.06	-0.03	0.10
Nauplii	0.68*	-0.23	0.12	-0.29*	-0.38*	0.38*	0.07	-0.05	0.17	0.12

* $p<0.05$

Filinia longiseta (Ehrenberg), *Keratella cochlearis* (Gosse), *K. cochlearis* f. *tecta* (Lauterborn), *Keratella quadrata* (O.F. Müller), *Polyarthra dolichoptera* (Idelson, 1925), *P. longiremis* (Carlin), *P. remata* (Skorikov), and *P. vulgaris* (Carlin). The abundance and percentage of cladocerans and copepods in total zooplankton abundance was much lower. The maximum values were 3,800 ind·l^{-1} for cladocerans and 1,600 ind·l^{-1} for copepods. The most abundant species listed among the cladocerans were *Bosmina longirostris* (O.F. Müller) and *Eubosmina coregoni* (Baird, 1857), while among copepods *Thermocyclops oithonoides* (G.O. Sars, 1863) and youth forms – the copepodites and nauplii. The highest abundances of cladocera were recorded at a depth of 2 m (Fig. 7).

As result of statistical analyses between the abundance and biomass of the phytoplankton and environmental variables, significant correlations were found with temperature, pH, degree of oxygenation, seston content, and chlorophyll-*a* and nutrient concentrations (nitrogen and phosphorus, Table 2). Negative correlations were found between phytoplankton abundance and conductivity, total nitrogen, nitrates, and Secchi depth.

Discussion

During the studied period the total number of 161 taxa belonging to nine taxonomic groups of phytoplankton were identified in Lake Uzarzewskie. The number of taxa in the individual years of the study was stable, as it ranged from 120 to 131. In the previous years (2005-07) before and during iron treatment, the number of taxa was quite similar, as it ranged from 129 to 146 [9]. In 2008, in the first year after using the new method of restoration (pipeline with spring

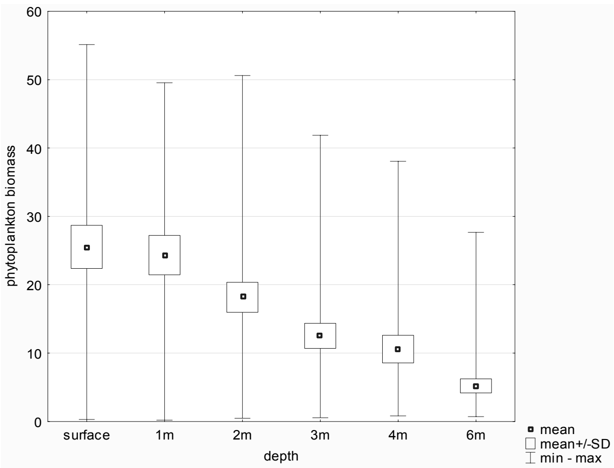

Fig. 5. Changes in the phytoplankton biomass [μg·ml^{-1}] on analized depths in Lake Uzarzewskie in 2010-12.

water rich in nitrates), there was a slight increase in the number of taxa achieving 163 [10].

The values of mean phytoplankton biomass in the analyzed period were slightly higher (10.5-20.9 μg·ml^{-1}) in comparison with the earlier period of 2005-07 (7.8-11.6 μg·ml^{-1}). However, in the first year of iron treatment (2006) the biomass of phytoplankton was much higher, as it increased up to 80 μg·ml^{-1} [9]. Phytoplankton biomass in eutrophic water bodies usually varies within these limits. In the fish ponds it reached 31.5-38.5 μg·ml^{-1} [19]. Average value of phytoplankton biomass noted in the polyhumic eu/hypertrophic dam reservoir Siemianówka was also similar – 12.24 μg·ml^{-1} [20].

The seasonal changes in biomass of phytoplankton were also analyzed in individual years. The maxima of phytoplankton biomass were noted in autumn (September 2010), when a high share of diatoms was observed, or in summer (August 2011), when the phytoplankton was dominated by cyanobacteria and in June 2012, when the highest share of cryptophytes and cojugatophytes was noted. In previous periods the biomass maxima were observed in the similar months (July, August, and September), but each time cyanobacteria was the dominant group [9].

A significant decrease in phytoplankton abundance, expected in connection with the restoration process, was noted only in 2012 ($p < 0.01$). The mean abundance of total phytoplankton in the following years fluctuated and showed no significant trend.

The highest diversity index was found in 2011, when the lowest abundance of phytoplankton and the highest number of taxa were observed. The value of the mean Shannon-Weaver diversity index in this study slightly increased in comparison with the period 2005-07, as it reached 2.53 and 2.36 in 2011and 2012, respectively, while 1.22-1.88 in 2005-07 [9]. An increase in the value of this index may reflect an improvement in the environmental conditions resulting from indirect disturbances caused by the new restoration technique. For comparison, the index was significantly lower in the artificial pond in the Wielkopolska Region, where it ranged from 0.64 to 1.85 [21]. However, the values of this index were higher in Swarzędzkie Lake on the Cybina River (varying from 2.28 to 5.05 in the summer) [22]. Larger values of Shannon-Weaver index indicates less pollution in the water and a healthier ecosystem [23].

Diatoms brought an important contribution to both abundance and biomass of the phytoplankton. It is known that with decreasing phosphorus concentration, the growth of large diatoms intensifies [24]. Supply of additional load of SiO_2 from the catchment area due to high precipitation in spring 2010 was the most probable reason for an intensive growth of diatoms, further enhanced by significant increase in temperature in June [16]. It was also observed that during wet years, silica inputs caused diatom blooms while in dry periods dinophytes dominated [25]. The abundance and biomass of phytoplankton in 2010 was slightly lower than in 2009 (statistically significant difference). This resulted in a visibility increase reported at that time [16].

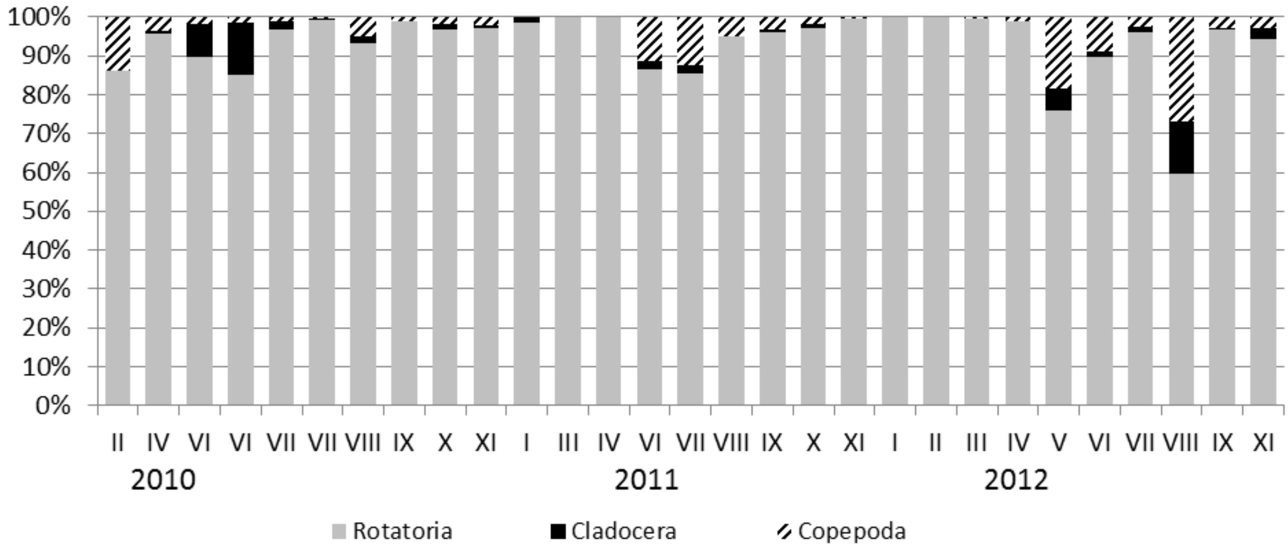

Fig. 6. Percentage of zooplankton groups in general abundance.

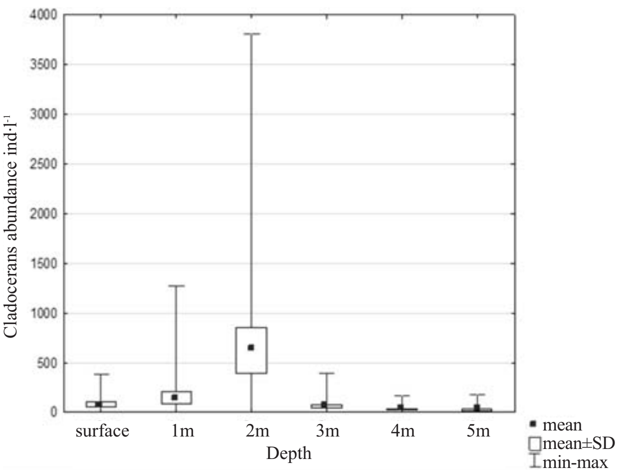

Fig. 7. Changes in cladocerans abundance on analized depths in Lake Uzarzewskie in 2010-12.

Throughout the studied period, phytoplankton grew well in the epilimnion, which was connected with the high availability of natural light. In this lake the lack of light at the deeper layers prevented the growth of submerged macrophytes. The only water macrophyte communities that were present in the lake were nympheids (unpublished data). Macrophytes may play a very important role in preventing re-suspension of phosphorus from sediments and are a refuge for zooplankton and fish [26], but in this case the lack of submerged macrophytes did not limited resuspension.

In the competition for nutrients in the absence of phosphorus and depletion of silicate, cyanobacteria benefit, as shown in the PEG model [24]. There are several other factors that are advantageous for the cyanobacteria blooms in the lake. They include high water temperature, low N:P ratio, high pH, and low CO_2 availability, low light intensity, the buoyancy of cyanobacteria, and grazing of herbivorous zooplankton [27]. These conditions favoured the occurrence of cyanobacteria in Lake Uzarzewskie. There was a significant effect of nitrate concentration on the development of blue-green algae. The maximum values of nitrate were noted in spring months [16]. After exhausting this item the increase in the abundance and biomass of cyanobacteria occurred (correlation coefficient was -0.70, $p<0.05$). The dominant species were *Planktothrix agardhii*, *Aphanizomenon gracile*, *Pseudanabaena limnetica*, and *Limnothrix redekei*. These species were also recorded in this lake in the previous period of 2005-07 [9, 28] and in 2008 [6] so even the iron treatment did not cause the decrease in cyanobacterial abundance. They were also present in other water bodies located in the course of the Cybina River, e.g. Swarzędzkie Lake and Maltański Reservoir [29-33].

It is worth noting that in Lake Uzarzewskie the invasive species of cyanobacteria such as *Cuspidothrix issatschenkoi*, *Anabenopsis milleri*, *A. elenkinii,* and *Raphidiopsis mediterranea* were found. According to de Senerpont Domis et al. [34], an earlier seasonal increase in water temperature due to climate warming causes earlier cyanobacteria germination from resting stages and potentially promotes the growth of invasive cyanobacteria species. Also, climate warming is supposed to be responsible for changes in the plankton community and enhancement in phosphorus loading [35, 36]. In 2012 phytoplankton abundance was not significantly different from that in 2011 ($p> 0.05$). In this year a slightly lower abundance of cyanobacteria was noted and other groups, such as diatoms and chrysophytes, dominated in phytoplankton abundance, especially the species that dominated in cool seasons. Both the small size species and those with long cells were significantly harder to eliminate by the grazing of zooplankton filtrators [37].

In the context of controlling the growth of phytoplankton we also analyzed the composition and abundance of zooplankton. Its grazing determines the structure of phytoplankton [37]. Neither now nor in 2006-08 [9] were there large cladocerans in the lake, which could effectively control the growth of large phytoplankton individuals. This is probably the predation effect of the fish stock living in the lake. In 2006 and 2007 fry of zander were stocked in the lake [9], but in very small numbers, so had no effect on the biomanipulation impact on the population of planktivorous fish. In the present study a small increase in the proportion of Cladocera in 2012 was found in comparison to the previous years, but the results are not so explicit. Water blooms are only present when the grazing pressure on the bloom-forming phytoplankton organisms is low. It has been reported by Lurling et al. [38] that *Daphnia* are less abundant, or absent, in warm regions. Another important fact is that they are generally much smaller than in cool regions. This observation was confirmed in Lake Uzarzewskie in the studied period. The statistically important positive correlations between the abundance (or biomass) of phyto- and zooplankton indicates that zooplankton may represent only one of several potential factors influencing the biomass and abundance of phytoplankton. Zooplankton sometimes can also stimulate the growth of phytoplankton by providing nutrients. The excretion of planktonic animals is an important source of phosphorus in the water of lakes, and in some periods of the year it may be the most important for the growth of phytoplankton [39-41]. The stimulation of the growth of phytoplankton, especially large cyanobacteria, was also reported from Maltański Reservoir. In the water of this reservoir significant correlations were found between the increase in the cyanobacteria abundance and the simultaneous increase in the number of filtering Cladocera [30]. In this study also a positive correlation was found between the abundance of zooplankton and that of cyanobacteria. Similar positive correlations were found between zooplankton and chlorophytes and cryptophytes, while those between zooplankton and chrysophytes and diatoms were negative.

In the period of 2010-12, the analyses of phyto- and zooplankton were made to check the effect of the innovative restoration process on the abundance of phytoplankton and on water quality. Maintaining a high redox potential prevents the release of phosphorus from bottom sediments to the water column. Preliminary analyses indicated a gradual improvement in water quality, which was manifested in a slight but statistically significant reduction of abundance and biomass of phytoplankton in subsequent years of study.

Acknowledgements

This work was supported by The Polish National Science Center as research project No. NN305 372838. The authors are also grateful to Dr. R. Dondajewska and Dr. K. Kowalczewska-Madura for some physico-chemical data of Lake Uzarzewskie, and MSc. W. Romanowicz-Brzozowska for help with zooplankton analyses.

References

1. PADISAK J., REYNOLDS C.S. Selection of phytoplankton associations in Lake Balaton, Hungary, in response to eutrophication and restoration measures, with special reference to the cyanoprokaryotes. Hydrobiologia **384**, (1), 41, **1998**.
2. LÜRLING M., VAN OOSTERHOU F. Controlling eutrophication by combined bloom precipitation and sediment phosphorus inactivation. Water Res. **47**, 6527, **2013**.
3. GOŁDYN R., MESSYASZ B. , DOMEK P., WINDHORST W., HUGENSCHMIDT C., NICOARA M., PLAVAN G. The response of lake Durowskie ecosystem to restoration measures. Carpath. J. Earth Environ. Sci., **8**, (3), 43, **2013**.
4. GOŁDYN R., PODSIADŁOWSKI S., DONDAJEWSKA R., KOZAK A. The sustainable restoration of lakes – towards the challenges of the Water Framework Directive. Ecohydrol. Hydrobiol. **14**, 68, **2014**.
5. GOŁDYN R., KOWALCZEWSKA-MADURA K., DONDAJEWSKA R., BUDZYŃSKA A., DOMEK P., ROMANOWICZ W. Functioning of Hypertrophic Uzarzewskie Lake Ecosystem. In. Sengupta M.Dalwani R. (Eds). Proceedings of Taal2007: The 12th World Lake Conference: pp. 857-860, **2008**.
6. KOWALCZEWSKA-MADURA K., DONDAJEWSKA R. GOŁDYN R. Changes of phosphorus concentration in bottom sediments and in overlying water of two strongly eutrophicated lakes in Wielkopolska Region, Limnol. Rev. **7**, (4), 205, **2007**.
7. EJSMONT-KARABIN J. The Usefulness of Zooplankton as Lake Ecosystem Indicators: Rotifer Trophic State Index. Pol. J. Ecol. **60**, (2), 339, **2012**.
8. KOWALCZEWSKA-MADURA K., DONDAJEWSKA R. GOŁDYN R. Influence of iron treatment on phosphorus internal loading from bottom sediments of the restored lake, Limnol. Rev. **8**, (4), 177, **2008**.
9. BUDZYŃSKA A. Changes in the phytoplankton of two lakes under the influence of restoration with the use of iron sulphate. Ph.D., thesis, manuscript 1-244, **2012** [In Polish].
10. KOZAK A. Community structure and dynamics of phytoplankton in Lake Uzarzewskie. Teka Kom. Ochr. Kszt. Środ. Przyr. – OL PAN, **6**, 146, **2009**.
11. GOŁDYN R., GRABIA J. Protection program of waters in the Cybina River. Program of water protection in the Cybina River, Department of Environmental Protection, Poznań Town's Authority, Poznań **1998** [In Polish].
12. GOŁDYN R., JACKOWIAK B., BŁOSZYK J. Natural values of the Cybina Valley and their protection. Kontekst, Poznań, pp. 96. **2005** [In Polish].
13. KOWALCZEWSKA-MADURA K. GOŁDYN R. DONDAJEWSKA R. The bottom sediments of Lake Uzarzewskie – a phosphorus source or sink? Oceanol. Hydrobiol. Stud. **39**, (3), 81, **2010**.
14. GOŁDYN R., KOWALCZEWSKA-MADURA K., DONDAJEWSKA R., BUDZYŃSKA A., DOMEK P., ROMANOWICZ W. Functioning of Hypertrophic Uzarzewskie Lake Ecosystem Sengupta, M. and Dalwani, R. (Eds). Proceedings of Taal 2007: The 12th World Lake Conference pp. 857-860, **2008**.
15. OSUCH E., PODSIADŁOWSKI S. Efficiency of pulverizing aeration on Lake Panieńskie. Limnol. Rev. **12**, (3), 139, **2012**.
16. DONDAJEWSKA R., GOŁDYN R., PODSIADŁOWSKI S., KOZAK A., KOWALCZEWSKA-MADURA K., KOŹLIK K. Changes in water quality of Uzarzewskie Lake as a result of restoration treatment. Ochrona i rekultywacja jezior, Toruń, Przysiek, VIII Konferencji Naukowo-Technicznej 06-08 June 2013, pp. 47-56, **2013** [In Polish with English Abstract].
17. RIPL W. Biochemical oxidation of polluted lake sediment with nitrate – a new restoration method, Ambio **5**, 132, **1976**.
18. SØNDERGAARD M., WOLTER K-D., RIPL W. Chemical treatment of water and sediments with special reference to lakes. In Perow M.R., Davy A.J. (eds.) Handbook of ecological restoration, Cambridge University Press, pp. 184-205, **2002**.
19. NAPIÓRKOWSKA-KRZEBIETKE A., HUTOROWICZ A., TUCHOLSKI S. Dynamics and Structure of Phytoplankton in Fishponds Fed with Treated Wastewater. Pol. J. Environ. Stud. **20**, (1), 151, **2011**.
20. GRABOWSKA M. Cyanoprokaryota blooms in the polyhumic Siemianówka dam reservoir in 1992-2003. Ocean. Hydrobiol. Stud., **34**, (1), 73, **2005**.
21. MESSYASZ B., KRYSIUK A. Phycoflora composition in an artificial pond subjecting to ecological succession. Teka. Kom. Ochr. Kszt. Środ. Przyr. **3**, 129, **2006**.
22. STEFANIAK K., GOŁDYN R., KOWALCZEWSKA-MADURA K. Changes of summer phytoplankton communities in Lake Swarzędzkie in the 2000-2003 period – Oceanol. Hydrobiol. Stud. **36**, Suppl. 1, 77, **2007**.
23. JUNSHUM P., CHOONLUCHANON S., TRAICHAIYAPORN S. Biological indices for classification of water quality around Mae Moh power plant, Thailand. Mj. Int. J. Sci. Tech. **2**, (1), 24, **2008**.
24. SOMMER U., GLIWICZ Z.M., LAMPERT, W., DUNCAN A. The PEG-model of succession of planktonic events in fresh waters. Arch. Hydrobiol. **106**, 433, **1986**.
25. CUGIER P., BILLEN G., GUILLAUD J.F., GARNIER J., MENESGUEN A., Modelling the eutrophication of the Seine Bight (France) under historical, present and future riverine nutrient loading. J. Hydrol. **304**, 381, **2005**.
26. MEIJER M-L. Biomanipulation in the Netherlands. 15 years of experience. RIZA, the Netherlands, pp. 208, **2000**.
27. SOMMER U. Plankton Ecology, Springer Verlag, Berlin, Heidelberg, New York, pp. 369, **1989**.
28. BUDZYŃSKA A., GOŁDYN R., ZAGAJEWSKI P., DONDAJEWSKA R., KOWALCZEWSKA-MADURA K. The dynamics of a Planktothrix agardhii population in a shallow dimictic lake, Oceanol. Hydrobiol. Stud. **38**, (2), 7, **2009**.
29. KOZAK A. Seasonal changes occurring over four years in a reservoir's phytoplankton composition. Pol. J. Environ. Stud. **14**, (4), 451, **2005**.
30. KOZAK A., GOŁDYN R. Zooplankton versus phyto- and bacterioplankton in the Maltanski Reservoir (Poland) during an extensive biomanipulation experiment J. Plankton Res. **26**, (1), 37, **2004**.

31. KOZAK A. Changes in the structure of phytoplankton in the lowest part of the Cybina River and the Maltański Reservoir. Oceanol. Hydrobiol. Stud. **39**, (1), 85, **2010**.
32. PIETRZAK A., KOZAK A. A quantitative study of Swarzędzkie Lake phytoplankton in the cold water season. In: Rosińska J., Neumann M. (Eds) The Functioning and protection of water ecosystems. Threats, protection and management of water resources. Poznań, Dept. of Water Protection, Faculty of Biology, Adam Mickiewicz University: pp. 41-52, **2013**.
33. KOZAK A., DONDAJEWSKA R., GOŁDYN R., KOWALCZEWSKA-MADURA K. The efficiency of restoration treatment in Maltański Reservoir in the last four years. In: Wiśniewski R. (Ed.) Ochrona i rekultywacja jezior. PZITS Oddz. Toruń, 1-8, **2013** [In Polish with English Abstract].
34. DE SENERPONT DOMIS L.N., ELSER J.J., GSEL A.S., HUSZAR V.L.M., IBELINGS B.W., JEPPESEN E., KOSTEN S., MOOIJ W.M., ROLAND F., SOMMER U., VAN DONK E., WINDER M., LURLING M. Plankton dynamics under different climate conditions in tropical freshwater systems. Freshwater Biol. **58**, 463, **2013**.
35. JEPPESEN E., KRONVANG B., MEERHOFF M., SØNDERGAARD M., HANSEN K.M., ANDERSEN H.E., LAURIDSEN T.L., LIBORIUSSEN L., BEKLIOGLU M., OZEN A., OLESEN J.E. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. J. Environ. Qual. **38**, (5), 1930, **2009**.
36. ÖZEN A., ŠORF M., TROCHINE C., LIBORIUSSEN L., BEKLIOGLU M., SØNDERGAARD M., LAURIDSEN T. L., JOHANSSON L. S., JEPPESEN E. Long-term effects of warming and nutrients on microbes and other plankton in mesocosms, Freshwater Biol. **58**, (3), 483, **2013**.
37. LAUGASTE R., HABERMAN J., KRAUSE T., SALUJIE J. Significant changes in phyto- and zooplankton in L. Peipsi in recent years: what is the underlying reason? Proc. Estonian Acad. Sci. Biol. Ecol. **56**, (2), 106, **2007**.
38. LÜRLING M., ESHETU F., FAASSEN E. J., KOSTEN S.. HUSZAR V. L. M. Comparison of cyanobacterial and green algal growth rates at different temperatures. Freshwater Biol. **58**, 552, **2013**.
39. IKEDA T, CARLETON JH, MITCHELL AW., DIXON P. Ammonia and phosphate excretion by zooplankton from the inshore waters of the Great Barrier Reef. Austral J Marine Freshwater Res. **33**, (4), 683, **1982**.
40. KOWALCZEWSKA-MADURA K., GOŁDYN R., SZYPER H. Zooplankton phosphorus excretion in Swarzędzkie Lake (Western Poland) and its influence on phytoplankton. Oceanol. Hydrobiol. Stud. **36**, (1), 3, **2007**.
41. GOŁDYN R., KOWALCZEWSKA-MADURA K. Interactions between phytoplankton and zooplankton in the hypertrophic Swarzędzkie Lake in western Poland. J. Plankton Res. **30**, (1), 33, **2008**.