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RESPONSE OF PLANKTONIC CYANOBACTERIA AND PERIPHYTON ASSEMBLAGES TO PHYSICOCHEMICAL PROPERTIES OF STORMWATER IN A SHALLOW URBAN LAKE

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Abstract

The aim of this study was to determine the response of planktonic cyanobacteria and periphyton assemblages (periphytic algae in the separator pipes, epilithon and epiphyton) to lamella separator-treated stormwaters in urban Lake Jeziorak Mały in 1997-2003 and 2005. Relationships between periphyton and phytoplankton assemblage and water chemistry variables were analyzed by calculating the Spearman's rank correlation coefficient, and then with canonical correspondence analysis (CCA).

The basic factors favouring the cyanobacterial growth were water temperature and iron, while high chloride concentration limited their development. Cyanobacterial abundance recorded at the separators was half that of the pelagic zone because of a lower water temperature and higher Cl concentration, indicating high algal sensitivity to the considerable velocity and disturbances caused by stormwater effluents. Higher silicon and calcium concentrations at the separators and orthophosphates at sites with stones and gravel showed connection with the growth of diatoms, especially *Fragilaria leptostauron* var. *martyi*, *Diatoma vulgaris* and *Navicula gregaria*. The richness of the dominant cyanobacteria, *Aphanizomenon gracile* and *Limnothrix redekei*, was related with the water temperature, conductivity, pH, and TN. Similarities in the periphyton dynamics in separator pipes and epilithon between the years covered by the study suggest significant influence of separator-treated stormwater on these assemblages, in contrast to epiphyton and phytoplankton in the pelagial zone, where these waters had limited influence.

Key words: rainwater, pollution, algae, nutrients, CCA.

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INTRODUCTION

The growing industrial development of urban areas and the twnetieth-century agriculture contributed to water eutrophication, which accelerates in urban agglomerations when domestic sewage and nutrient-rich stormwater enter shallow lakes (Guzkowska, Gasse 1990, Wichelen et al. 2007). Excess primary nutrient production causes massive growth of some algal species, particularly cyanobacteria, resulting in algal blooms (Reynolds 1984), which deteriorates the ecological status of some lakes (Napiórkowska-Krzebietke et al. 2012). These processes are effectively limited by reducing the nutrient inflow, using lake-basin restoration methods, including hypolimnetic withdrawal (Olszewski 1961, Wichelen et al. 2007) combined with artificial aeration and mixing of bottom waters (Steinberg 1983, Moore et al. 2012), plus the removal of bottom sediments and chemical deactivation of phosphorus (Lossow et al. 2004). Effective lake restoration must take into the lake's morphological and hydrological conditions, pollution sources, catchment use and technical methods appropriate for local conditions (Bernhardt 1987). Polluted stormwaters are often discharged directly into lakes in urbanized catchments where sewerage systems and pipes to collect overland flow and waste water are absent (Guzkowska, Gasse 1990). Separators can be used for stormwater organic substance pretreatment to protect urban lake water.

Owing to their role in aquatic ecosystem, phytoplankton and plant periphyton are good indicators of eutrophication changes in lakes, caused by nutrient inflow. Ecologically, phytoplankton and periphyton contribute to the nutrient cycling and biological productivity of aquatic systems by linking the "bottom-up" and "top-down" processes (Reynolds 1984).

Jeziorak Mały is a eutrophic lake dominated by planktonic cyanobacteria. In 1997, protective restoration measures were implemented, including the installation of lamella separators for stormwater pretreatment. The aim of this paper was to determine the response of cyanobacteria (plankton) and periphyton assemblages to the influx of stormwaters in the urban lake Jeziorak Mały, in 1997-2003 and in 2005. The general problem was whether stormwaters flowing through the separators affected the growth of cyanobacteria (plankton) and periphyton assemblages in this lake. Answers to the following questions were sought to verify it:

(1) Did storm water inflows significantly change the water chemical composition in Jeziorak Mały Lake?

(2) Do differences occur in succession of cyanobacteria at the separator sites and in the pelagic zone?

(3) Are there relationships between periphyton assemblages in the separator pipes and in the epilithon, epiphyton and phytoplankton?

(4) Have the environmental requirements of the dominant periphyton and phytoplankton assemblages changed after the installation of the separators?

MATERIAL AND METHODS

Jeziorak Mały is a typical, shallow (mean depth 3.4 m), eutrophic, urban lake lying in the Mazurian Lakeland, in northeastern Poland (Figure 1). The 26-ha lake is situated in a temperate climate zone. It is connected to Jeziorak Duży Lake (3219 ha area) by a narrow canal (4 m width and 4 m depth). For decades, Jeziorak Mały received untreated municipal sewage from the town of Iława, but since 1991, the effluent has been treated in a local wastewater treatment plant. The ongoing lake water quality improvement began in 1997 and included the installation of separators for pretreatment of stormwater influent and a fountain-based water aeration system. The construction of on the Unicon System lamella separators in the lake's littoral zone started in 1996 and was completed in spring 1997, now preventing untreated stormwater from entering the lake. These separators contain 16 blinder sections, 1200 mm diameter inlet and outlet pipes, and a 10,000 l sedimentation tank to remove petroleum compounds, silt and sand in a separate rainwater sewer system. The efficiency of the separation petroleum products was 97% at the nominal discharge of 160 l s^{-1}. This stormwater pretreatment covered the 70-ha catchment area of Jeziorak Mały Lake (Puh Ekol 1995). The amount of stormwater flowing through the separators depends on monthly precipitation in Warmia and Mazury (Grzesiak, Domańska 1998-2004, 2006). The highest mean total monthly rainfall recorded during the study (1997-2003 and 2005) was 79 mm in summer and 116 mm following torrential rains in July (Figure 2).

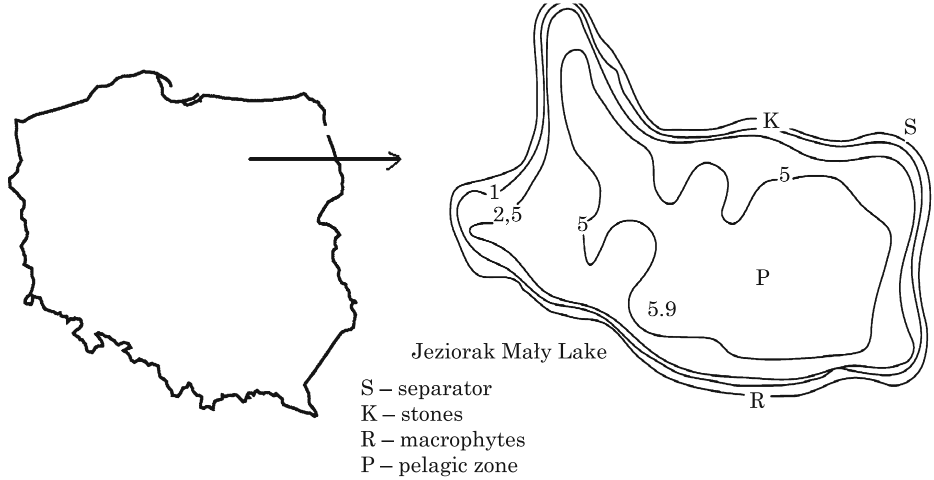

Fig. 1. Morphometric map of Jeziorak Mały Lake

Periphyton samples were collected monthly from April to October in 1997-2003 and 2005, from 3 substrates in the littoral zone, and phytoplankton from the pelagic area of Jeziorak Mały Lake:

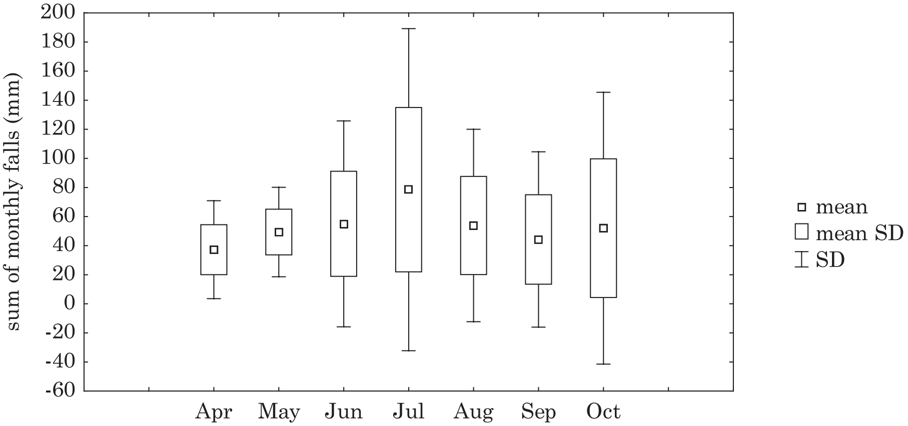

Fig. 2. Sum of monthly rainfalls in Warmia and Mazury (mean and standard deviation – SD) in 1997-2003 and 2005 (Grzesiak, Domańska 1998-2004, 2006)

1) periphyton from the separator pipes draining stormwater (S);
2) epilithon accumulated on stone surfaces in 1997 (K);
3) epiphyton from *Acorus calamus* L. vascular plant leaves (R);
4) phytoplankton from the 1 m euphotic area of the pelagic zone, where the average water transparency in 1997-2003 and 2005 was 0.80 m (P).

Periphyton was scraped from the pipes, from stones (1 cm^2 surface area), and from macrophyte leaves (5 cm lengths). The pipes and stones were often found to be overgrown with *Cladophora glomerata* (L.). Kűtzing filamentous green algae formed a natural substratum for periphytic algae. The periphyton was shaken carefully in distilled water to separate algae from chlorophytic thalli, and the remains were scraped from macrophyte leaves with a knife. Samples were rinsed and preserved in ethanol and formaldehyde solution. Phytoplankton samples were collected from a one-meter surface layer of the pelagic zone using a 5 l Toń plankton sampler, filtered through a 25 µm mesh plankton net, and preserved in Lugol and 4% formaldehyde solution. In total, 124 periphyton and phytoplankton samples were collected. The basic physical and chemical water parameters were measured directly at the sampling sites. The water temperature was exactly 0.1^{o}C, the oxygen content was measured at 0.01 mg dm^{-3} using an HI 9143 oxygen meter, and the pH and conductivity were 1 and 1500 µS cm^{-1} as checked with a CONMET 1 conductometer *in situ.* In the laboratory, the Spectroquant Merck test and a NOVA 400 spectrophotometer were used to determine the following nutrient contents: orthophosphates (0.05-5.00 mg dm^{-3}), silicon (0.005-5.0 mg dm^{-3}), calcium (10-250 mg Ca dm^{-3}), total nitrogen (0.5-15 mg dm^{-3}), iron (0.05-4.0 mg dm^{-3}) and chlorides (2.5-250 mg Cl dm^{-3}).

Phytoplankton and plant periphyton were inspected to determine their qualitative and quantitative characteristics under an Alphaphot YS2 optical microscope at magnifications of lens 10x, 20x, 40x and 100x. These phytoplankton and periphyton samples were composed of prokaryotic (cyanobacteria) and eukaryotic organisms, including diatoms, chlorophytes, dinoflagellates, chrysophytes, and cryptophytes. Diatoms were prepared following the methods of Battarbee (1979). Algal biomass was calculated for bio-volume by comparing the algae with their geometric shapes (Rott 1981). The mean biomass was calculated for 10 individuals of each planktonic and periphytic algal species. Counts in 1 ml samples of periphyton and phytoplankton were determined in 5000 fields of vision with 200× magnification in each planktonic chamber to account for differences in organism densities and their abundance and biomass expressed in identical, basic 1 cm^3 volumes.

The cyanobacterium abundance and species dominance in phytoplankton and periphyton assemblages were correlated with the physical and chemical water parameters using non-parametric methods because these data are not normally distributed. Relationships were confirmed by calculating the Spearman's rank correlation coefficient in a Statistica version 8.0, and then with canonical correspondence analysis (CCA) to relate water chemistry variables to periphyton and phytoplankton dominant species in assemblages. Finally, these relationships were presented on a biplots graph using Canoco for Windows 4.5 software.

RESULTS

In this study, the mean proportion of cyanobacteria in total phytoplankton in the pelagic zone was 72%, ranging from 60% in 1998 to 88% in 2003. The share decreased to 66.02% at the separators in the littoral zone, ranging from 34.15% in 2000 to 87.48% in 1997 (Figure 3*a*). A higher mean abundance of cyanobacteria occurred in the pelagic zone at 48,522 ind. cm^{-3} in 2002, compared to 30,843 ind. cm^{-3} at the separators in 2003 (Figure 3*b*). Statistically positive correlation was shown between the richness of cyanobacteria and both water temperature ($r = 0.46$, $N = 119$, $p < 0.05$) and iron concentration ($r = 0.57$, $N = 36$, $p < 0.05$), while negative correlation was detected with chlorides ($r = -0.38$, $N = 36$, $p < 0.05$). A rapid increase in cyanobacteria was observed in the pelagic zone in June, with 19°C water temperature, maximum total nitrogen of 3.5 mg dm^{-3} and maximum iron concentration of 5.13 mg dm^{-3}. The maximum abundance of cyanobacteria was noted in July at 49,895 ind. cm^{-3}, when the highest water temperature was 25.1°C and the lowest orthophosphate concentration was 0.14 mg dm^{-3}. Cyanobacterial abundance at the separators in the littoral zone was 20,534 ind. cm^{-3} in July, less than half the abundance in the pelagic zone. The littoral zone had a lower water temperature of 20.3°C but a higher maximum chloride concentration of 63 mg dm^{-3} (Figure 4).

Periphytic algal assemblages had the highest mean abundance for periphyton in the pipes (70,535 ind. cm^{-3}) and the lowest for epiphyton

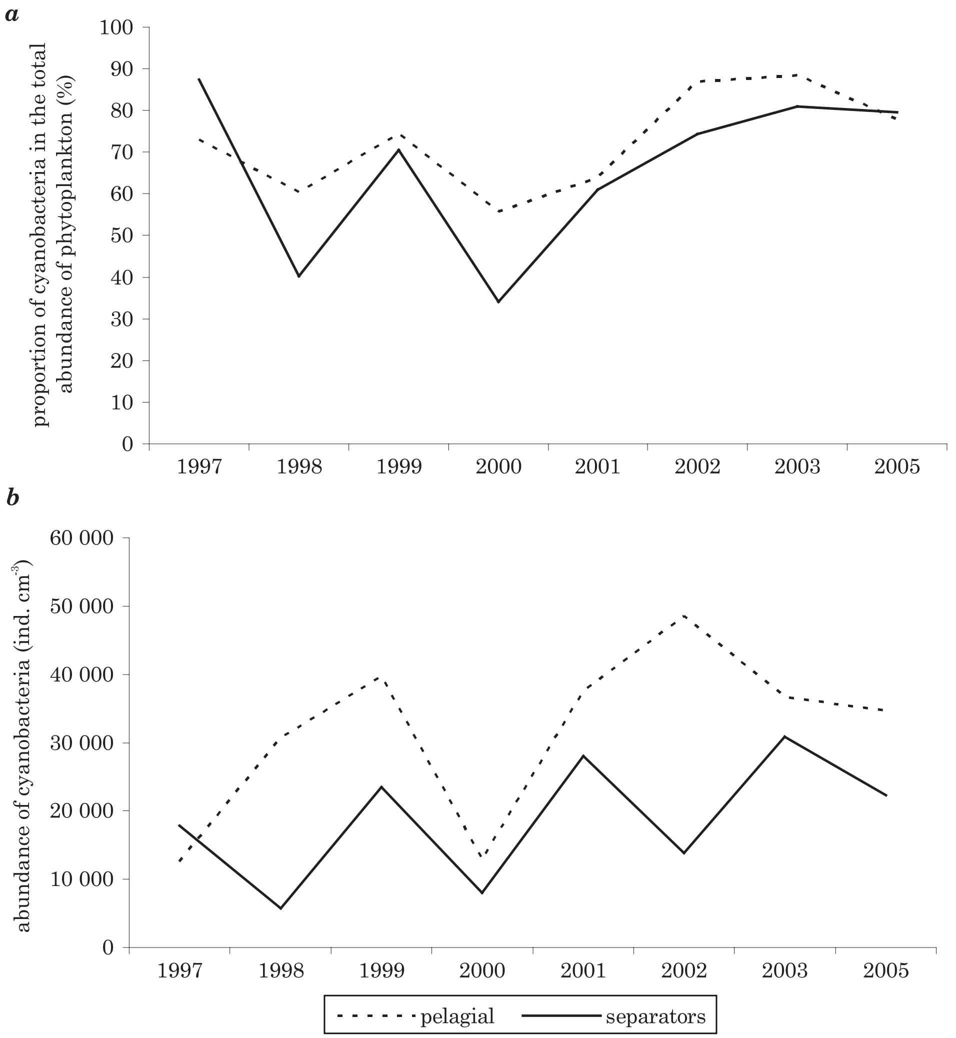

Fig. 3. Proportion of cyanobacteria in total abundance of phytoplankton (*a*) and abundance of cyanobactera (*b*) in 1997-2003 and 2005, in the pelagic zone and at sites with separators in Jeziorak Mały Lake

(39,821 ind. cm^{-3}), and the highest mean biomass for epilithon (0.226 mg cm^{-3}) and the lowest for epiphyton (0.067 mg cm^{-3}). The mean abundance of phytoplankton in the pelagic zone was 31,272 ind. cm^{-3} and its biomass was 0.065 mg cm^{-3} (Table 1). Diatoms dominated periphyton (max. 86% - S), and cyanobacteria outnumbered phytoplankton in both abundance and biomass (73%). Chlorophytes had a significant share in periphyton, with the maximum percetange of 42% in the epilithon, versus 32% of diatoms and 14% of dinoflagellates found in the total phytoplankton.

The following values were recorded (Table 1):

Table 1

Characteristics of periphyton and phytoplankton assemblages and physicochemical parameters of water in Jeziorak Mały Lake (means for the 1997-2003 and 2005 period)

Parameters	Pipes of separators (S)	Stones (K)	Macrophytes (R)	Pelagic zone (P)
Abundance of periphyton/ phytoplankton (ind. cm^{-3})	70,353	65,173	39,821	31,272
Biomass of periphyton/ phytoplankton (mg cm^{-3})	0.175	0.226	0.067	0.065
Water temp (°C)	16.8	19.3	19.2	19.4
Oxygen concentration (mg dm^{-3})	8.17	8.17	8.06	10.33
pH	8.85	8.87	8.98	9.30
Conductivity (mS cm^{-1})	577	469	443	417
PO_4 (mg dm^{-3})	0.41	0.56	0.24	0.32
Si (mg dm^{-3})	1.56	0.77	0.71	1.30
Ca (mg dm^{-3})	136	103	97	82
TN (mg dm^{-3})	3.5	2.8	2.3	1.9
Fe (mg dm^{-3})	2.99	4.36	4.01	3.33
Cl (mg dm^{-3})	51	38	31	23

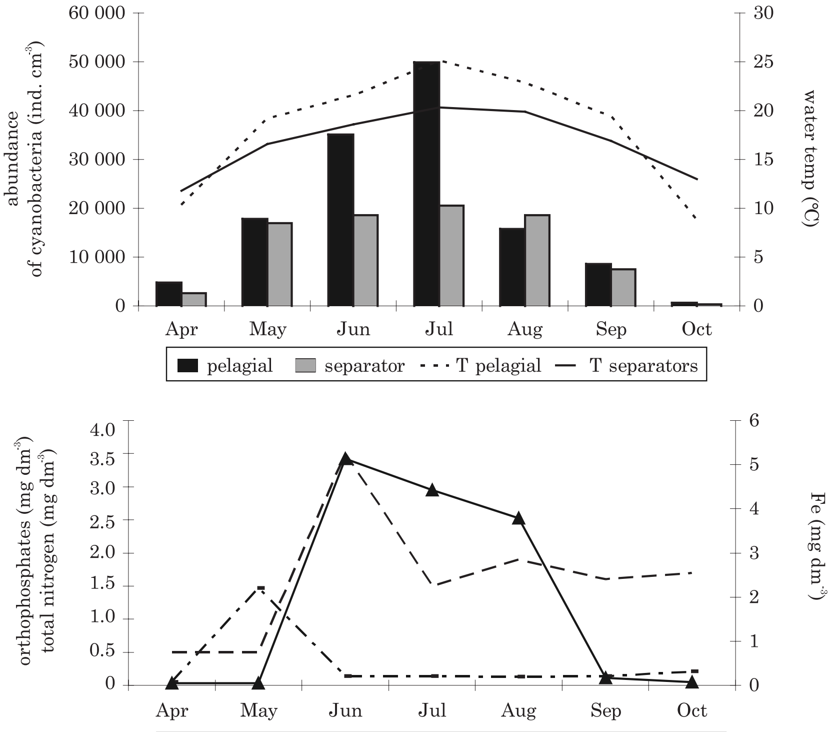

Fig. 4. Changes in abundance of cyanobacteria and water physicochemical parameters from April to October in the pelagic zone and at sites with separators in Jeziorak Mały Lake (means from 1997-2003 and 2005)

(1) at the separators, the lowest mean water temperature was 16.8°C, and the highest water electrolytic conductivity was 577 μS cm^{-1}; additional concentration values were determined for silicon (1.56 mg dm^{-3}), calcium (136 mg dm^{-3}), total nitrogen (3.5 mg dm^{-3}) and chlorides (51 mg dm^{-3});

(2) at sites with stones, the highest mean PO_4 and Fe concentrations were 0.56 mg dm^{-3} and 4.36 mg dm^{-3}, respectively;

(3) in the surface layer of the pelagic zone, the maximum pH values were recorded at 9.3, with 10.33 mg O_2 dm^{-3} of oxygen concentration.

Changes in periphytic assemblages as well as in the phytoplankton abundance and biomass occurred at different orthophosphate concentrations during 1997-2003 and in 2005 (Figure 5a-c). Similar algal dynamics was observed in periphyton sampled from the separator pipes and epilithon. Although the maximum abundance of epilithon (134,644 ind. cm^{-3}) and maximum biomass of both periphytic assemblages (0.648 mg cm^{-3} and 0.521 mg cm^{-3}, respectively) were recorded in 1997, a rapid decrease occurred thereafter. The maximum abundance of periphyton in the pipes was 135,177 ind. cm^{-3} in 2000, at the highest orthophosphate concentration of 0.68 mg dm^{-3}. Changes in PO_4 levels during the study were similar to the changes recorded for periphyton abundance in the separator pipes. Similar dynamics of algal growth were noted between epiphyton and phytoplankton, with the maximum abundance in 2001.

The following diatom species dominated periphytic assemblages: *Navicula gregaria* Donkin, *Nitzschia frustulum* (Kützing) Grunow and *Gomphonema olivaceum* (Hornemann) Brébisson. In turn, the cyanobacterium *Planktolyngbya brevicellularis* Cronberg & Komárek dominated phytoplankton. *Diatoma vulgaris* Bory dominated periphyton biomass in the separator pipes and epilithon; and the epilithon contained the filamentous chlorophytes *Ulothrix tenuissima* Kützing and *Stigeoclonium* sp.

Some correlations between counts of dominant species and water physicochemical parameters were statistically significant at $p < 0.05$):

(1) *G. olivaceum*: a positive correlation with water temperature ($r = 0.42$) in separator pipes, and with PO_4 and Si ($r = 0.52$ and $r = 0.57$) in epilithon;

(2) *F. leptostauron* var. *martyi*: a positive correlation with Si and PO_4 ($r = 0.59$ and $r = 0.40$) in separator pipes;

(3) *D. vulgaris*: a positive correlation with TN in epilithon ($r = 0.59$) and a negative correlation with PO_4 ($r = -0.61$) in separator pipes;

(4) *N. gregaria*: a positive correlation with oxygen ($r = 0.40$) in epiphyton;

(5) *N. frustulum*: a negative correlation with PO_4 ($r = -0.69$) in epiphyton;

(6) *A. gracile*: a positive correlation with pH and TN ($r = 0.71$ and $r = 0.58$), *L. redekei*: with conductivity ($r = 0.64$), and *Peridinium inconspicuum* and *Cryptomonas erosa*: with water temperature

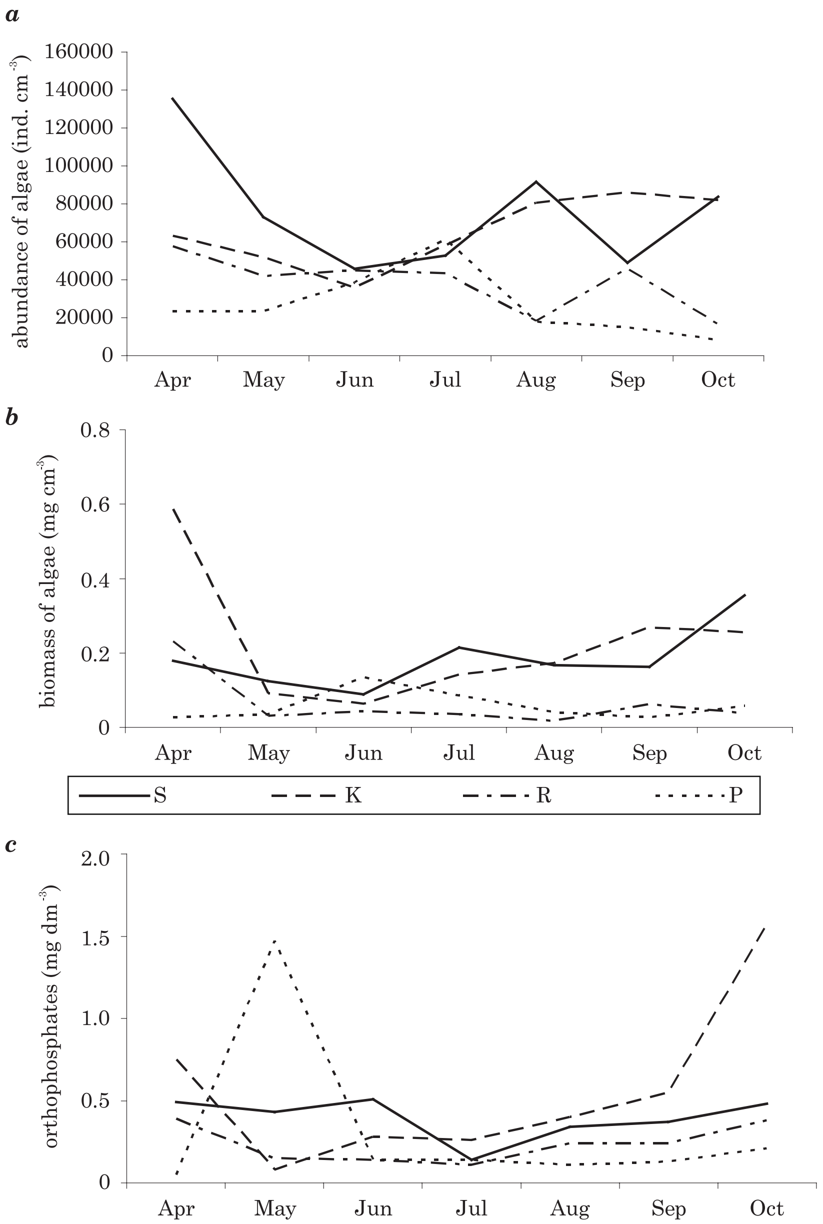

Fig. 5. Relationships between the abundance (*a*) and biomass (*b*) of periphyton assemblages (S – periphyton in separator pipes, K – epilithon, R – epiphyton) and phytoplankton (P) and orthophosphates (*c*), at these sites in Jeziorak Mały Lake in 1997-2003 and 2005

(r = 0.62 and r = 0.59) and negatively correlated with PO_4 (r = -0.62 and r = -0.64) in phytoplankton.

The periphyton and phytoplankton CCA also showed significant relationships between dominant species and the physicochemical parameters of water (Figure 6).

The statistical analysis used a dataset of 124 samples, 14 dominant species and 9 environmental variables, with the first axis accounting for 49% of the total periphyton species variation in separator pipes, 50% for epilithon, 55% for epiphyton, and 53% for phytoplankton. In the separator pipes, *F. leptostauron* var. *martyi* correlated with PO_4 and *G. olivaceum* – with water temperature. In addition, conductivity promoted the occurrence of *D. vulgaris*. Correlations were found between *D. vulgaris* and TN, and *G. olivaceum* and Si and PO_4 in the epilithon, while *N. gregaria* correlated only with oxygen in epiphyton. In phytoplankton, *A. gracile* correlated with pH, *L. redekei*

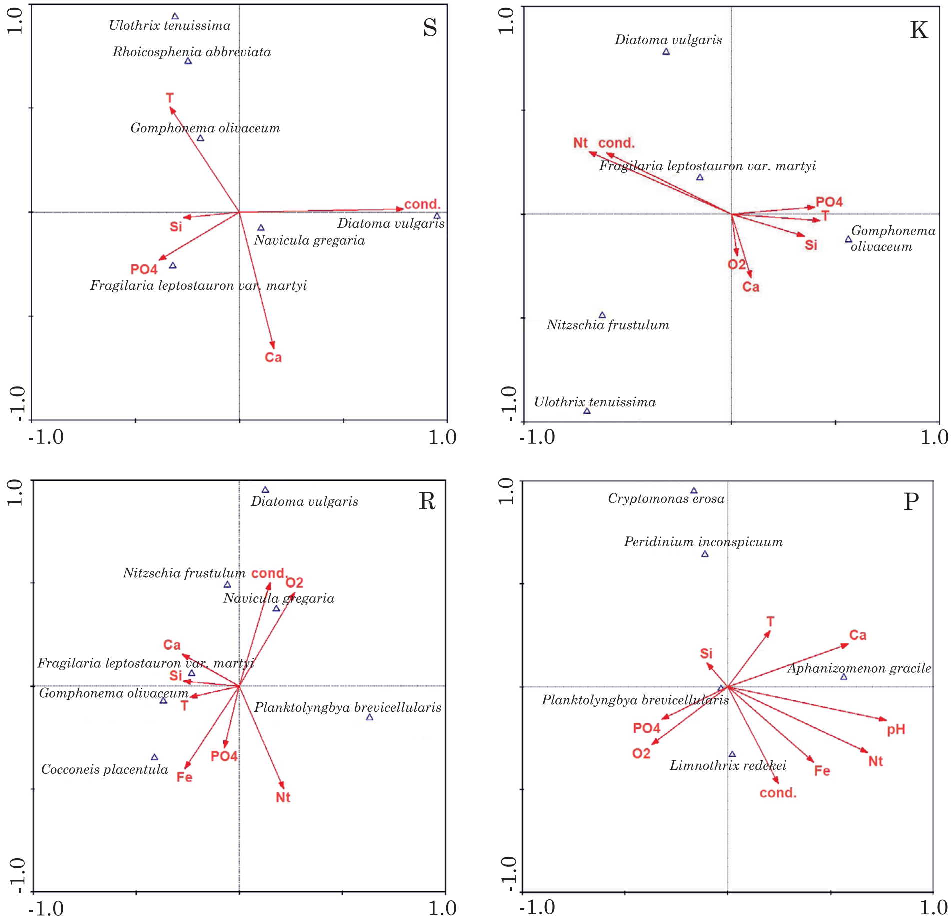

Fig. 6. Biplots of the canonical correspondence analysis (CCA) showing the relationships between dominant species in the periphyton assemblages (S – periphyton in separator pipes, K – epilithon, R – epiphyton) and phytoplankton (P) and the physical and chemical water parameters. (cond. – electrolytic conductivity)

with conductivity, and *Peridinium inconspicuum* and *Cryptomonas erosa* with water temperature.

DISCUSSION

The phytoplankton studies in 1978 showed that Jeziorak Mały was a polytrophic lake, where cyanobacteria dominated, making up over 90% of the total phytoplankton biomass in summer (SPODNIEWSKA 1986). Before the implementation of protective and restoration measures in the pelagic zone in 1996, the average percentage of cyanobacteria was above 90% (ZĘBEK 2009), thereafter decreasing to 72% in 1997-2003 and 2005, when stormwater was pretreated by the separators. The share and abundance of cyanobacteria were lower at the separator sites than in the pelagic zone over this period. According to GUZKOWSKA, GASSE (1990), stormwaters environmentally shock the algal growth, especially diatoms, suggesting that cyanobacteria in Jeziorak Mały Lake response to separator-treated stormwater. Analogously to other examinations on urban lakes (BOBIN et al. 1989), the impact of stormwaters could be related to precipitation levels, especially in summer, when the highest sum of monthly rainfalls was recorded around this lake.

The mass cyanobacterial growth depends not only on water temperature, nutrient resources, the degree of exposure to wind and water mixing, phosphorus resuspension from sediments and iron accessibility (REYNOLDS 1984, BERMAN-FRANK et al. 2007), but also on the specific iron, nitrogen, and phosphorus ratio (BURCHARDT et al. 2007). In this study, high water temperature and iron concentration affected the cyanobacterial growth in the pelagic zone, as supported by the positive correlation between the abundance of these microorganisms and the said water parameters. Additionally, the water temperature of 19°C was identified as the treshold temperature for cyanobacterial growth in the lake, i.e. the temperature at which the abundance of these prokaryotic organisms begin to grow most rapidly (ZĘBEK 2005). The chemical composition of water changed abruptly with a rapid decrease in PO_4, TN and Fe after cyanobacteria attained the maximum number at water temperatures above 19°C, suggesting that the cyanobacterial development is affected by interrelated Fe, TN, and PO_4 concentrations in addition to being dependent on the water temperature.

As observed in other urban lakes, the influence of stormwater flowing through Jeziorak Mały Lake from the separators is so strong that it environmentally shocks aquatic organisms, including cyanobacteria. The changes in water quality in urban lakes are often rapid and extreme because of inflows, which vary in quantity, chemistry and seasonality. This situation is exacerbated by unpredictable occurrences such as building construction and road salting in surrounding catchments (GUZKOWSKA, GASSE 1990). Disturbances in the cyanobacterial biomass growth are also caused by environmental stress, including decreased water temperature and strong mixing (Bobin et al. 1989, Burchardt, Pawlik-Skowrońska 2005, Vincent et al. 2014), as well as the influx of chlorides after winter. In this study, the cyanobacterial abundance recorded at the separators was half that of the pelagic zone because of the lower temperatures from cooler catchment waters and severe water disturbances at the separators. Additionally, the high Cl concentration induced stress in cyanobacterial growth. The stormwater flow from the catchment affected the growth of both cyanobacteria and other algae (Bobin et al. 1989) e.g. periphyton assemblages. In this study, the separators supported the most varied environmental conditions compared to the other sites (Guzkowska, Gasse 1990, Vincent et al. 2014), including the lowest mean water temperature, the highest water electrolytic conductivity and the highest concentrations of Si, Ca, TN, and chlorides. Thus, the flow of polluted stormwater from the catchment area significantly affected the lake water chemistry. Beside increased nutrient concentrations, rainwater had also high levels of Pb, Cu, Zn, Cd, heavy metals and other chemical elements (Szpakowska et al. 2014, Sapek 2014, Zębek 2014). Different changes occurred in the abundance and biomass of periphytic assemblages and phytoplankton related to the PO_4 concentration in 1997-2003 and 2005. Periphyton in the separator pipes and epilithon had similar maximum biomasses, unlike the previously rapid decrease in its abundance and biomass after the separators had been installed. Hence, stormwaters flowing through the separators meant creating environmental conditions similar to those in the pelagic zone and sites with macrophytes, with differences in the algal dynamics resulting from the limited influence of separator-treated stormwater in deeper waters.

After the separators in Jeziorak Mały Lake began operating in 1997, the dominant cyanobacterium species in phytoplankton changed from *Limnothrix redekei* to *Plaktolyngbya brevicellularis*, similarly to other eutrophic lakes (Cronberg, Komarek 1994, Zębek 2005). The periphytic assemblages were dominated by species from genera typical of natural and artificial substrata in eutrophic lakes such as diatoms *Diatoma* spp., *Fragilaria* spp., and *Gomphonema s*pp., *Cocconeis* spp., and also filamentous chlorophytes *Stigeoclonium* sp. and *Ulothrix* sp. (Bohr, Miotk 1979, Danilov, Ekuland 2001, Jobgen et al. 2004, Raeder et al. 2010). The periphyton assemblages in the separator pipes, epilithon, and epiphyton were dominated by *N. gregaria*, *N. frustulum*, and *G. olivaceum* diatoms. In addition, *N. gregaria* grew well in the separator pipes because of its mobile form classified as an α-meso-saprobe, which tolerates large amounts of organic matter (Zębek et al. 2012). The CCA showed that changing environmental conditions caused differences in environmental preferences of the dominant and accompanying taxa in the periphytic and phytoplankton assemblages. The periphytic species *F. leptostauron* var. *martyi, G. olivaceum*, and *D. vulgaris* preferred nutrient-rich waters with high concentrations of Si, and PO_4, and TN in the separator pipes and epilithon. The low water temperature at the separator pipes is another factor stimulating the growth of *G. olivaceum*. However, the planktonic species preferred high water temperature, pH and conductivity. Moreover, the negative correlation of *D. vulgaris* in the separator pipes, and *P. inconspicuum* and *C. erosa* in the pelagial with orthophosphates may indicate intensive uptake of this nutrient by these species.

In conclusion, stormwater significantly influenced the development of phytoplankton and periphyton by changing the environmental conditions in Jeziorak Mały Lake, and this led to the reconstruction of the structure and function of the analyzed algal assemblages, with the stronger influence in the littoral than in the pelagic zone. These results highlight the response of planktonic and periphytic algal trophic indicators to stormwater, domestic runoff and sewage, as well as the possibilities to limit toxic cyanobacterial blooms in shallow lakes. These findings are especially important because a massive growth of cynaobacteria is threatening to the water quality of urban water bodies worldwide. As demonstrated by this study, stormwaters also influence the growth of these prokaryotic organisms by changing environmental conditions, such as decreasing water temperature and increasing Cl concentration. These results suggest that the above phenomenon should be incorporated in future management strategies for urban lakes.

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