INTENSITY AND THRESHOLDS OF CYANOBACTERIAL BLOOMS – AN APPROACH TO DETERMINE THE NECESSITY TO RESTORE URBAN LAKES

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Abstract: Cyanobacterial blooms are broadly recognized as a global problem for aquatic ecosystems, health and economics. This study focused on determining the intensity and main contributors of cyanobacteria blooms, and identifying the cyanobacteria-environment based recovery potential of impaired urban lakes. Based on physicochemical parameters, nutrient-rich (especially excess of nitrogen and phosphorus) conditions were recognized in the majority of lakes. In summer Cyanobacteria formed biomass on average from 2.5 to 88.8 mg L^{-1}. The WHO-designed low risk threshold (summer average > 2 mg L^{-1}) for cyanobacterial blooms was significantly exceeded in all lakes, while the WHO-designed moderate risk threshold (> 10 mg L^{-1}) was exceeded in five lakes. In two lakes, cyanobacterial biomass exceeded even the WHO high risk threshold specified for surface scums or the newly-proposed very high risk threshold of 40 mg L^{-1} connected with possibly high potential toxin risk. Cyanobacteria assemblages were then dominated by potentially toxic species, mainly from the genera *Microcystis*, *Cuspidothrix* (*Aphanizomenon*), *Dolichospermum* (*Anabaena*), *Limnothrix* and *Planktothrix*, which considerably restricted the recreational use of these lakes. The response of cyanobacteria and dominant species to environmental variables (especially *Microcystis*), positively correlated with N and P enrichment, should also be very useful to determine the main water management targets for urban lakes.

Key words: biomass; cyanobacteria; freshwaters; health alert; nutrients; potential toxicity

1. INTRODUCTION

Cyanobacteria are prokaryotic organisms of special attention due to their possibly great impact on recreational or drinking used waters. They can develop and form blooms or surface scum under suitable conditions of high temperature, lights and nutrient enrichment (phosphorus and nitrogen) (Chorus & Bartram 1999). Algal blooms including cyanobacteria aspects have been defined, e.g. by a deviation from the normal cycle of phytoplankton biomass or observations with statistical unusually high biomass (Parker 1980). The literature includes various threshold values of algal blooms. For example, Nebaeus (1984) proposed a total phytoplankton biomass of 3 mg L^{-1} or chlorophyll *a* content of 20 μg L^{-1}, whereas others described a total biomass exceeding 8 or 10 mg L^{-1} (Heinonen 1980; Oliver & Ganf 2000). According to the World Health Organization (Chorus & Bartram 1999), the density of 20,000 cyanobacterial cells per mL in 0 – 4 m in a water column was recognized as a low risk threshold – LRT (low risk level or low probability of adverse health effects) of cyanobacterial blooms for recreational waters. However, 100,000 cyanobacterial cells per mL corresponded to moderate risk threshold – MRT (moderate risk level or moderate probability of adverse health effects). When they were transposed to biomass (assuming that the density of algal cells in water was 1.0 g mL^{-1}) they constituted 2 and 10 mg L^{-1} for low and moderate risk thresholds, respectively. Furthermore, 10,000,000 and 100,000,000 cells per mL in the top 4 cm of surface layer were given for high and very high risk thresholds associated with

scum occurrence and possibly high and very high cyanotoxin risk (Chorus & Bartram 1999).

The Water Framework Directive (WFD) seeks to ensure the sustainable management of all water bodies mainly by deterioration prevention, appropriate use, protection and improvement of the water environment where eutrophication processes have contributed to water quality problems (European Commission 2009). Eutrophication, defined by nutrient enrichment, has become a cause of an accelerating growth of algae constituting a significant undesirable disturbance to the balance of aquatic organisms and to water quality (adverse ecological changes). This undesirable disturbance caused mainly by massive cyanobacteria development may be harmful to human health, e.g. by cyanobacterial toxins in the recreational or drinking waters in urban lakes (Messineo et al., 2009), including the Pomerian Province in northern Poland (Mazur-Marzec et al., 2008; Kobos et al., 2013). Cyanobacteria associated with enriched conditions causing a high biomass of potentially toxic species significantly limited the recreational or even drinking use of freshwaters. From an ecological point of view, a permanent cyanobacterial bloom should not be present in the water bodies being at the WFD required good ecological status because of e.g. health hazard and the sustainable use of that water. Expanding the knowledge of cyanobacteria-environment specific relations can also be very useful for setting targets of water management.

Therefore, the aims of this study were (1) to determine the intensity and main contributors of cyanobacterial blooms including the health risk possibility; (2) to identify a recovery potential of urban lakes based on cyanobacteria-environment characteristics and relations.

2. METHODS

2.1. Study site

This study concerned the seven temperate lakes in the Vistula River basin (Poland), i.e. drainage basin of the Baltic Sea, belonging to the Western Europe Unit. Four lakes are situated within the borders of the town of Kartuzy (c.a. 15,000 inhabitants) in the Pomerian Province, and they belong to flow-through lakes with mutual connections as follows: Lake Mielenko – Lake Karczemne – Lake Klasztorne Małe – Lake Klasztorne Duże (Fig. 1, Table 1).

The other similarly connected lakes: Lake Święte – Lake Skępskie Małe – Lake Skępskie Wielkie, are situated within the borders of the town of Skępe (c.a. 3,700 inhabitants) in the Dobrzyński Lake District within the Mień River catchment. Additionally, they belong to the Protected Landscape Area of Skępskie Lakes. The majority of these lakes have a glacial origin. Their surrounding regions include urban infrastructure (mainly residential buildings and recreational centers), meadows, pastures, fallow lands or forest areas. For many years, such catchment management and fishing-angling economy have been a serious anthropogenic source of direct (e.g. pollutants from storm water drainage) or indirect pollution (Mazur-Marzec et al., 2008; unpublished data of Department of Water Protection Engineering, UWM in Olsztyn). For example, lakes Klasztorne Małe, Klasztorne Duże and Karczemne were treated as sewage-receiving water bodies in the past (Januszkiewicz 1969). The similar sewage management could be led also in Skępe. From the 1970s (Kartuzy) and the 1990s (Skępe), the municipal sewage have been treated at the local wastewater treatment plants and then discharged into the rivers Radunia and Mień (outside the towns), respectively. Despite this fact, the sediments of almost all surveyed lakes are currently an endless source of nutrients.

2.2. Sample collection and analysis

The cyanobacteria study was carried out in these seven urban lakes including 2 deep, dimictic and 5 shallow, polymictic (Table 1). The samples were collected during the growing season from April to November in 2013. Samples were taken from the euphotic zone in spring/autumn and epilimnion in summer from dimictic lakes, while in polymictic lakes they were collected from the whole water column. These samples were taken at one-meter or a half-meter intervals and then integrated. The quantitative analysis of cyanobacteria was conducted according to generally accepted standard methods (using an inverted microscope, Utermöhl technique) (CEN 2006). The cyanobacterial biomass was calculated by the method of cell volume measurements. Additional samples for qualitative analyses were taken using a plankton net no. 25 with 55–60 μm mesh, from the same water layers as those for quantitative samples. This gave mixed material with net plankton (meso- and microplankton) which was analyzed both live and after preservation using a light microscope. The taxa identification included species level.

Water samples for chemical analyses were taken at the same time as cyanobacteria samples. The concentrations of total nitrogen (TN), total phosphorus (TP), phosphates, nitrates, ammonium nitrogen and chlorophyll *a* (Chl-*a*) using colorimetric and chromatographic methods were determined

Figure 1. Map of the surveyed urban lakes within towns Kartuzy and Skępe (Poland).

Table 1. Morphometrical features of urban lakes, situated in the administrative borders of two towns: Kartuzy and Skępe.

Lake, code	Water-flow direction	Mictic type*	Surface area (ha)	Depth (m)		Volume (10^3 m^3)
				Max.	Mean	
Mielenko, M		P	7.8	1.9	1.3	102.9
Karczemne, K		P	40.4	3.2	2.0	798.3
Klasztorne Małe, KM		D	13.7	20.0	8.1	1106.0
Klasztorne Duże, KD		D	57.5	8.5	4.8	2780.0
Święte, Ś		P	32.1	2.1	1.5	492.0
Skępskie Małe, SM		P	15.8	2.0	1.0	157.0
Skępskie Wielkie, SW		P	120.0	4.2	2.8	3349.0

*D – dimictic, P – polymictic

according to standard methods (PN-EN ISO 6878:2006p.7; PN-EN 25663:2001; PN-ISO 10260:2002), whereas total organic carbon (TOC) content was analyzed with high-temperature combustion on Shimadzu TOC analyzer.

2.3. Numerical analyses

The trophic state of the lakes was determined based on the Trophic State Index (TSI) including summer data on SDV, Chl-*a*, TP (Carlson 1977) and TN (Kratzer & Brezonik 1981). Additionally, TOC was used to calculate TSI_{TOC} (Dunalska 2011). The WHO risk thresholds (Chorus & Bartram 1999) for cyanobacterial biomass and possible microcystin content (if e.g. *Microcystis* dominate) were used to compare bloom intensity and to calculate the potential toxin risk – PTR including:
low risk threshold:

(1) LRT = 20,000 cyanobacterial cells per mL ≈ 2 mg L^{-1} biomass ≈ 10 μg L^{-1} Chl-*a* ≈ 2-4 μg L^{-1} microcystins (up to 10 μg L^{-1})

moderate risk threshold:

(2) MRT = 100,000 cyanobacterial cells per mL ≈

10 mg L^{-1} biomass ≈ 50 μg L^{-1} Chl-*a* ≈ 20 μg L^{-1} microcystins (up to 50 μg L^{-1})

The significance of changes in environmental variables between the lakes was tested with the non-parametric Kruskal-Wallis test to compare more than two independent samples. The adopted significance level was 0.05. Furthermore, in determining the dependence between cyanobacteria features (their total biomass, biomass of particular orders) and chosen physicochemical parameters, the Spearman rank correlation coefficient was used. Taking into account these cyanobacteria–environment relations, the classification of samples was done using principal component analysis (PCA) with a correlation matrix (StatSoft, Inc. v.10).

3. RESULTS

3.1. Environmental conditions

The high concentrations of total nitrogen and total phosphorus were recorded in the majority of surveyed lakes (Fig. 2). This was accompanied by high total organic carbon and chlorophyll *a*, as well as by very low Secchi disk visibility. The

exceptionally large nutrient content was noted in Lake Karczemne, whereas the lowest concentrations in Lake Święte. Nevertheless, the physicochemical parameters contributed to a certain differentiation between them. Statistically significant differences were found mainly in the concentrations of chlorophyll *a* and total phosphorus (Table 2).

The TN:TP ratios and Secchi disk visibility also revealed significant differentiation between all lakes. Low TN:TP ratios (< 10) were frequently noted in four lakes: Święte, Klasztorne Duże, Klasztorne Małe and Karczemne, whereas in the other lakes they reached up to 22. A Secchi disk visibility below 1 m was also frequently noted. Only in Lake Święte, the Secchi disk was visible almost at the lake bottom.

The temperature and the concentrations of dissolved oxygen, phosphates, total nitrogen, nitrates, ammonium nitrogen and total organic carbon in the surface water layers were more or less similar and slight differences were statistically non-significant. Among all lakes Lake Karczemne (situated within a town with 4-fold more inhabitants) was characterized by the highest concentrations of chlorophyll *a*, nitrogen and phosphorus in parallel with the lowest Secchi disk visibility, thus, it was the most eutrophied lake. The values of trophic state index (TSI based on SDV, Chl-*a*, TP, TN) ranged from 58 to 86 and were significantly differentiated (Table 2).
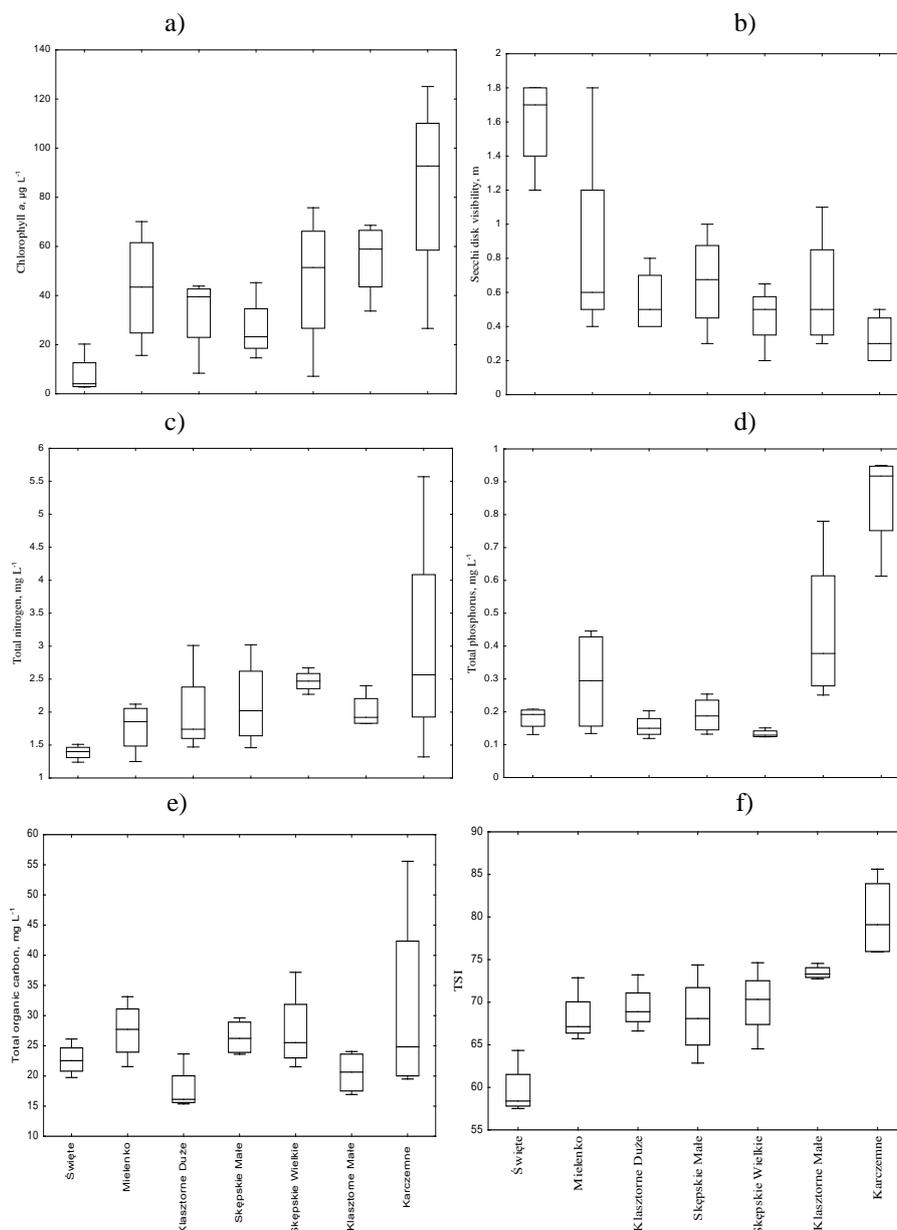

Figure 2. The selected physicochemical parameters and trophic state index (TSI) (min-max, median, quartiles) in urban lakes during the growing season (April-November).

Table 2. The significance of physicochemical parameters' changes and trophic state between the urban lakes.

Parameter, code	Kruskal-Wallis test, H	p*
Secchi disk visibility, SDV	13.191	*0.040*
Temperature, T	0.659	0.999
Dissolved oxygen, DO	5.593	0.470
Chlorophyll *a*, Chl-*a*	14.401	*0.026*
Total organic carbon, TOC	11.246	0.081
Total nitrogen, TN	11.575	0.072
Total phosphorus, TP	19.215	*0.004*
Phosphates	19.984	*0.003*
TN:TP ratio	22.352	*0.001*
Trophic state index, TSI	20.001	*0.003*

statistically significant, p<0.05.

The TSI below 60 was recorded only in Lake Święte, whereas TSI>60 in Lakes Mielenko, Skępskie Małe and TSI>70 in Lakes Klasztorne Duże, Klasztorne Małe and Karczemne. The values of TSI$_{TOC}$ based on total organic carbon content were usually above 70 and consequently they enhanced the general TSI values.

3.2. Cyanobacteria development pattern

During the growing season (April-November) the cyanobacterial biomass varied within a broad range, reaching up to ca. 166.0 mg L^{-1}. The lowest average and maximum (1.4 and 4.6 mg L^{-1}) biomasses were found in small, polymictic Lake Święte. In two lakes (Mielenko and Klasztorne Duże), cyanobacteria on average formed 5.0 mg L^{-1} of biomass, whereas in the other lakes they formed from 18.0 to 45.0 mg L^{-1}. In summer, the average biomass of cyanobacteria in all lakes ranged from 2.5 to 88.8 mg L^{-1} (Fig. 3a). Thus, all average values exceeded the WHO low risk threshold (2.0 mg L^{-1}) of cyanobacterial blooms designated for recreational waters. Although in five lakes cyanobacterial biomass exceeded the moderate risk threshold. This level was exceeded by up to 9-fold (summer average) and 17-fold (summer maximum) in shallow Lake Karczemne, where occurred the most intensive bloom. On the other hand, very high average biomass (up to 60 mg L^{-1} in epilimnion) was also observed in deep Lake Klasztorne Małe. In other lakes, the cyanobacteria growth was less intensive than in Lake Karczemne and Lake Klasztorne Małe, but it was greater than the WHO thresholds. Except for shallow Lake Święte, cyanobacterial biomass did not reach the moderate risk threshold, but it slightly exceeded the low risk threshold of 2 mg L^{-1}. Furthermore, the new thresholds for high and very high risks in top 0-4m of water layer were proposed. Applying the rule of doubling effect against the previous limit value, the summer average biomass of 20 mg L^{-1} (as twice WHO moderate risk threshold) was designed as high risk threshold and successively 40 mg L^{-1} as very high risk threshold. The last threshold was even exceeded in three lakes.

The cyanobacteria assemblages of the surveyed lakes were composed of taxa belonging to three orders Chroococcales, Nostocales and Oscillatoriales. Chroococcaleans formed approximately 90% of the summer cyanobacterial biomass in four lakes (Mielenko, Skępskie Małe, Klasztorne Małe and Karczemne) (Fig. 3b), and they reached up to 160 mg L^{-1} in Lake Karczemne. They were mainly *Microcystis aeruginosa* Kütz. and *Microcystis wesenbergii* (Kom.) Kom. The potential toxin risk (PTR), concerning the WHO toxin possibility in top 0-4 m of water layer, showed high theoretical microcystins content in these *Microcystis*-dominated lakes (Table 3). The lowest PTR value (up to 43-45 µg L^{-1} in highly toxic bloom) could be expected in Lake Mielenko, where cyanobacterial biomass exceeded four-fold the WHO low risk threshold. Subsequently PTR was greater in the lakes with higher exceedances of risk thresholds. Maximally up to ca. 445 µg L^{-1} of microcystins could be theoretically expected in highly toxic blooms potentially occurred in Lake Karczemne (the most acute scenario).

Oscillatoriales taxa dominated in two lakes Skępskie Wielkie and Święte, and their contribution reached up to 92% of cyanobacterial biomass (Fig. 3b). The filamentous *Limnothrix redekei* (Van Goor) Meff. developed abundantly only in Lake Skępskie Wielkie. Whereas an intensive development of *Oscillatoria tenuis* Ag. ex Gom. (88% of cyanobacterial biomass) was only noted in Lake Święte. In Lake Klasztorne Duże, the cyanobacteria assemblages were co-dominated by *Aphanocapsa incerta* (Lemm.) Cronb. & Kom., *Cuspidothrix issatschenkoi* (Usač) Rajan, *Dolichospermum flos-aquae* (Bréb. ex Born. et Flah.) Wack., Hoff. et Kom., *Limnothrix redekei* and *Planktothrix agardhii* (Gom.) Anagn. & Kom. These species represent all three orders, whose percentage shares in cyanobacterial biomass were similar, approximately each 33%.
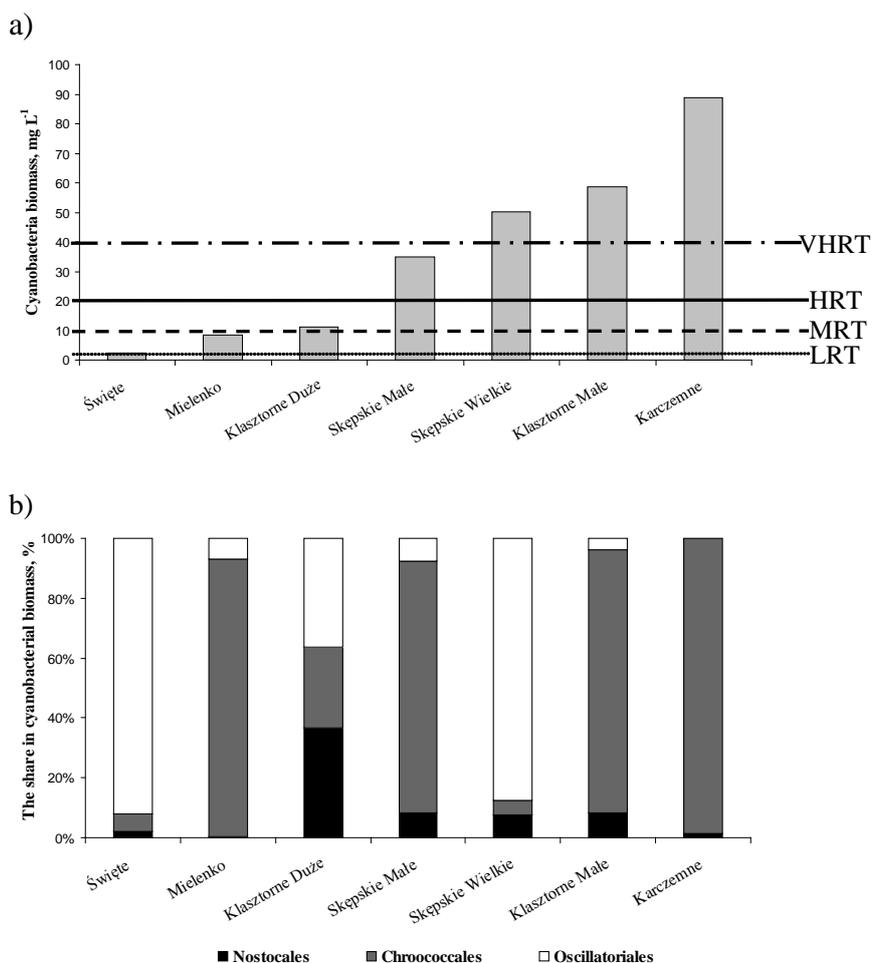
a)

b)

■ Nostocales   ■ Chroococcales   □ Oscillatoriales

Figure 3. The summer average cyanobacterial biomass (a) and percentage share of the orders Nostocales, Chrooocccales and Oscillatoriales (b) in surveyed lakes, the horizontal lines represent risk thresholds of cyanobacterial blooms: low (LRT) and moderate (MRT) from WHO guidelines (Chorus & Bartram 1999), and high (HRT) and very high (VHRT) as newly-proposed.

3.3. Cyanobacteria versus environmental variables

Significant correlations between selected cyanobacteria features and environmental variables confirmed PCA analysis (Fig. 4a). A very close positive correlation was found between biomass(cyanobacteria and their particular orders) and the concentrations of chlorophyll *a* and total nitrogen, although a strong negative relation was found for Secchi disk visibility. The samples were then classified (Fig. 4b). Based on the first component (PC1, with explanation above 39% of total variability), it was possible to separate the samples into three groups. The first group included samples taken mainly from the lakes: Święte, Mielenko and Skępskie Małe with the lowest, or/and relatively lower, cyanobacterial biomass and nutrient concentrations than in other lakes. The most comparable to this group were single samples taken from Lake Klasztorne Duże and Lake Skępskie Wielkie. The second group was comprised of other samples taken mainly from Lake Klasztorne Małe and Lake Skępskie Wielkie. However, the high-level of cyanobacteria development in very nutrient-rich conditions of Lake Karczemne contributed to distinguishing a separate, but rather inconsistent group. PC2 (with 20% explanation of total variability), confirmed the distinction of Lake Karczemne from the other lakes. This classification allowed groups of lakes to be distinguished which are potentially at risk of cyanobacterial blooms.

4. DISCUSSION

4.1. Environmental conditions

The temperate lakes situated within the borders of two towns with different numbers of inhabitants were classified as urban-type lakes. The long-term anthropogenic pressure on these lakes (Mazur-Marzec et al., 2008) led to heavy eutrophication.
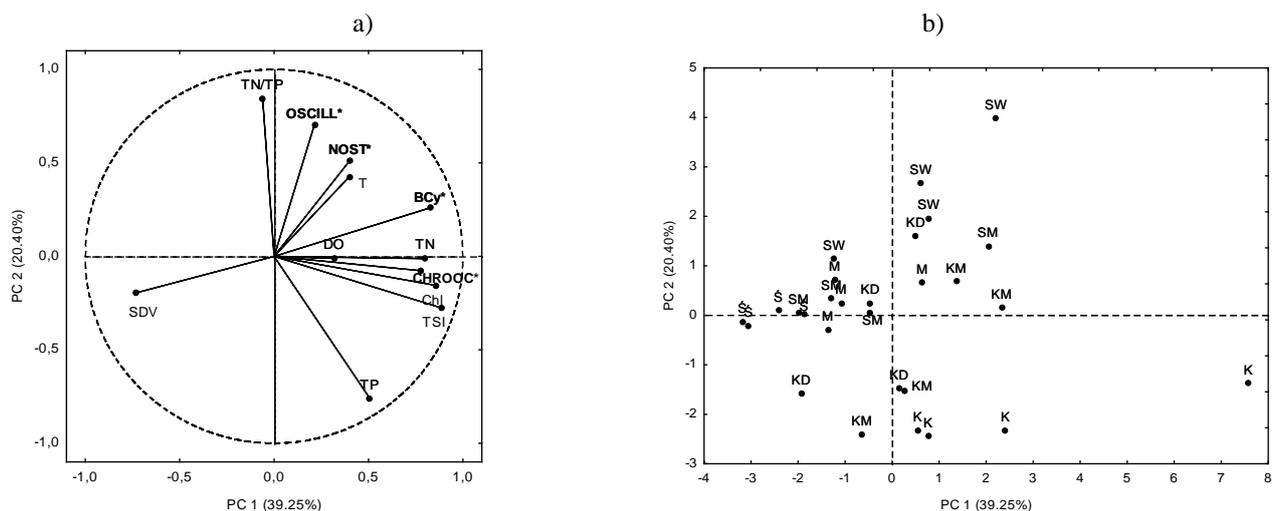
Figure 4. Principal Components Analysis (PCA) of the cyanobacteria features* in relation to environmental variables: ordination diagram (a) and classification of samples (b), the explanation of the physicochemical parameters' abbreviations was given in Table 2, BCy – cyanobacterial biomass, OSCILL – Oscillatoriales biomass, NOST – Nostocales biomass, CHROOC – Chroococcales biomass, the codes of lakes (K, KD, KM, M, SM, SW) were given in Table 1.

Table 3. The potential toxin risk – PTR in the *Microcystis*-dominated urban lakes.

Lake	Low risk threshold		Moderate risk threshold	
	exceedance*	PTR**	exceedance*	PTR**
Mielenko	4.3	8.6-17.2 (43)	0.9	18.0 (45)
Skępskie Małe	17.4	34.8-69.6 (174)	3.5	70.0 (175)
Klasztorne Małe	29.4	58.8-117.6 (294)	5.9	118.0 (295)
Karczemne	44.4	88.8-177.6 (444)	8.9	178.0 (445)

*multiple exceedance of risk threshold by summer average cyanobacterial biomass
**PTR expressed as potential microcystin content (μg L^{-1}), the calculations concerning two ways: for LRT – ca. 2-4 (10) μg L^{-1}, for MRT – ca. 20 (50) μg L^{-1} of microcystins are possible in top 0-4 m of water layer (Chorus & Bartram 1999).

The high concentrations of total nitrogen, total phosphorus and chlorophyll *a*, as well as very low Secchi disk visibility allowed all water bodies to be classified as being at worse than good ecological status (Regulation of the Minister of the Environment, Official Journal of Laws 2011, No. 257, Item 1545). Nevertheless, the physicochemical conditions influenced their certain trophic differentiation. According to Carlson (1977) and Carlson & Simpson (1996), a meso-eutrophic (TSI >50) state in Lake Święte and eutrophic states (TSI >60) in Lakes Mielenko, Skępskie Małe and even a hyper-eutrophic state (TSI >70) in Lakes Klasztorne Duże, Klasztorne Małe and Karczemne were indicated. Furthermore, in such lakes cyanobacteria might become a very serious problem for a properly functioning aquatic ecosystem and thus, for e.g. water supply, fisheries or recreation.

4.2. Cyanobacteria development pattern

A similar character of huge human impact and potential good environmental conditions for cyanobacteria were throughout the growing season and especially in summer. The summer average cyanobacterial biomass recorded in all lakes usually significantly exceeded the WHO-defined low risk threshold of cyanobacterial blooms designated for recreational waters (Chorus & Bartram 1999). The WHO-defined moderate risk threshold (10 mg L^{-1}) was exceeded in five lakes. Furthermore, comparing the phytoplankton bloom thresholds of 3 mg L^{-1}, 8 mg L^{-1} or 10 mg L^{-1} given by the other authors (e.g. Heinonen 1980; Nebaeus 1984; Oliver & Ganf 2000), the cyanobacterial biomass in the majority of lakes was also considerably higher. In Lakes Karczemne and Klasztorne Małe the cyanobacterial biomass (in the whole water column or epilimnion) was close to or even significantly exceeded the high risk threshold (10,000,000 cells L^{-1} or ca. 100.0 mg L^{-1}) specified for scum forming in the top 4 cm of surface layer (Chorus & Bartram 1999). Regarding the new designed thresholds of summer average cyanobacterial biomass for high (20 mg L^{-1}) and very high (40 mg L^{-1}) risks, the significant excedances were also recorded. These thresholds can be also common for other temperate dimictic and polymictic lakes concerning cyanobacterial bloom risks in

pelagic top 0-4 m of water layer.

Moreover, such study fits quite well in the implementation of the WFD targets. From a lake's ecological status point of view, the value of 2 mg L^{-1} was also proposed as the cyanobacterial bloom intensity threshold of good/moderate ecological status of the lakes. Whereas ca. 10 mg L^{-1} and above 20 mg L^{-1} were typical summer averages in the lakes with poor and bad ecological status. Important phenomenon for urban lakes was from several- to many-times exceedances of both WHO risk thresholds. Maximally up to 44-times of LRT or 9-time of MRT exceedances were in shallow Lake Karczemne. In this *Microcystis*-dominated lake up to ca. 450 μg L^{-1} of microcystins could be theoretically expected as potential toxin risk – PTR. A study by Mazur-Marzec et al., (2008) indicated that *Microcystis* created intensive bloom events with total concentration of hepatotoxic microcystins up to 305.4 μg L^{-1} (analysed with HPLC-DAD) in Lake Karczemne in 2005. They also reported that in Lake Klasztorne Małe, Lake Klasztorne Duże, when hepatotoxic cyanobacteria *Planktothrix agardhii* (Gom.) Anagn. & Kom. and *Microcystis* species co-dominated in phytoplankton, the microcystin concentrations were detected, but in significantly lower amounts. These could suggest that the potential harm of *Microcystis* taxa could occur also in 2013 in the lakes within the town of Kartuzy. Furthermore, these taxa could be primarily responsible for the potential harmful blooms also in the lakes within the town of Skępe: Lake Skępskie Małe and Lake Mielenko, but toxin analyses were not done yet. The PTR calculated indicated that, theoretically, there was possible expected microcystin concentration maximally up to 175 μg L^{-1} and 295 μg L^{-1} in highly toxic blooms of these lakes, respectively. A serious harmfulness might be also connected with other species. The filamentous *Limnothrix redekei*, abundant in Lake Skępskie Wielkie, has not yet been recognized as the main bloom contributor or potential toxin producer in Polish lakes (Kobos et al., 2013), although it may sporadically be (Jakubowska et al., 2013). The other main Oscillatoriales representative *Oscillatoria tenuis*, noted only in Lake Święte, is well-known as a neurotoxin (including anatoxin) producer which is also harmful for humans and animals, causing cardiac and respiratory failure (Mutawie 2012). The genera *Aphanizomenon*, *Cuspidothrix* (previously *Aphanizomenon*), *Dolichospermum* (previously *Anabaena*) and *Planktothrix*, were also recognized as responsible for bloom forming and toxin production in Poland as well as all over the entire world (Grabowska & Mazur-Marzec 2011; Kobos et

al., 2013). Thus, these main cyanobacteria (Oscillatoriales and Nostocales) contributors dominated or co-dominated could also present a potential risk for toxin occurrence in urban lakes.

4.3. Cyanobacteria versus environmental variables

A suitable temperature and nutrient enrichment can encourage the massive cyanobacteria growth (Paerl & Huisman 2008), what was recorded in some surveyed urban lakes. A similar finding of cyanobacteria response to TN and temperature was also reported by Rolland et al., (2013), Zębek (2015) for a shallow urban lake and by Napiórkowska-Krzebietke et al., (2012) and Messyasz et al., (2015) for other shallow lakes as in the case of phytoplankton-nitrogen relations (Török & Teodorof 2013). An increased nitrogen concentration in phosphorus-enriched waters can primarily accelerate cyanobacterial biomass (Dolman et al., 2012). On the other hand, the water temperature affects the organic matter transformations in waters (Dunalska et al., 2012).

At low TN:TP ratio (< 10) very different species were as dominants and formed differentiated biomass. For example, the chroococcalean *Microcystis* species (negative correlated with TN:TP) dominated during the persistent bloom (> 100 mg L^{-1}) or filamentous *Oscillatoria tenuis* dominated in the relatively small cyanobacteria biomass (< 8 mg L^{-1}). Chroococcaleans *Microcystis* and *Aphanocapsa* also co-dominated in cyanobacteria assemblages when the TN:TP ratio ranged from 10 to 17, indicating a possible co-limitation by N and P (Napiórkowska-Krzebietke et al., 2013). The massive development of filamentous *Limnothrix redekei* and *Pseudanabaena* sp. was connected with a TN:TP ratio of c.a. 19, what has also became common for cyanobacteria dominance at high ratio (Carvalho et al., 2013; Baptista & Nixdorf 2014). The N_2-fixing species often coincide with rather low ratio (Teubner et al., 1999; Havens et al., 2003), and the biomass of *Aphanizomenon* and *Cuspidothrix* can show a positive significant correlation to TN:TP ratio. This all confirms the theory of Dolman et al., (2012) that cyanobacteria species can show very differentiated reactions to various N and P enrichment-level, and *Aphanizomenon*, for example, can reach the highest biomass in lakes with high TN:TP ratios whereas other species required low TN:TP ratios.

Generally, the global nutrient enrichment can accelerate the massive development of cyanobacteria (Chorus & Bartram 1999) as well the whole phytoplankton (Li et al., 2014). A statistically-

significantly positive TSI-cyanobacteria relations obtained confirmed this theory for the eutrophied waters. However, such a close correlation between cyanobacterial biomass and TSI was also found in nutrient-poor lakes (Napiórkowska-Krzebietke et al., 2013). In consequence, higher turbidity-altering light conditions influenced the negative relations of cyanobacteria and Secchi disk visibility. Furthermore, this phenomenon can also be consistent with the self-shading theory (Kolokolnikov et al., 2009), giving cyanobacteria an advantage in competition with other species.

In summary, such massive development of cyanobacteria related to nutrient-rich conditions, causing a restriction of recreational use, constitutes a partly recognition of recovery potential of almost all surveyed urban lakes. Therefore, the most of them needs to be restored, along with other shallow urban lakes (Łopata et al., 2013; Grochowska et al., 2014) to considerably improve the water quality in Poland. The properly recognized of both biotic-abiotic relations in such aquatic conditions can help in prediction of lake recovery potential (Norton et al., 2009).

5. CONCLUSIONS

Strong long-term anthropogenic pressure has constituted a serious threat to the lakes situated within the borders of two towns: Kartuzy and Skępe. Cyanobacteria usually associated with nutrient-rich conditions were found to be a very frequent, important component of the phytoplankton in these lakes, especially in summer assemblages. Cyanobacteria growth significantly increased accordingly with increasing water temperature and total nitrogen concentrations. Thus, they positively affected the concentration of chlorophyll *a* in water and negatively impacted water clarity. In comparison to the risk thresholds designated by the World Health Organization for cyanobacterial blooms in recreational waters, the summer average biomass exceeded the low risk threshold in all lakes, although the majority of lakes exceeded (up to 9-fold) a moderate risk threshold. Regarding top 0-4m of water layer, the new cyanobacterial-biomass thresholds for high and very high risks were proposed: 20 mg L^{-1} and 40 mg L^{-1} (summer average) respectively. These thresholds can be common for pelagic waters (both polymictic and dimictic) in temperate zone. It was assumed that the maximal cyanobacterial biomass in Lake Karczemne (170 mg L^{-1}) and in Lake Klasztorne Małe (100 mg L^{-1}) exceeded even the high risk threshold defined for surface scum with a high probability cyanotoxin risk. The cyanobacterial blooms were formed by potentially toxic species,

especially by the genera *Microcystis*, *Cuspidothrix* (*Aphanizomenon*), *Dolichospermum* (*Anabaena*), *Limnothrix* and *Planktothrix*. Undoubtedly, cyanobacteria contributed strongly to unfavorable changes in water ecosystems with a potentially high cyanotoxic risk and seriously restrict the recreational use of urban lakes. Thus, this study indicated that the majority of urban lakes should be restore to improve their water quality. Therefore, cyanobacteria-environment relations (especially those positive to N- and P-enrichment) and the assessment of bloom intensity including the WHO potential toxin risk should be very useful for determining the main water management targets for urban lakes.

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