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RESEARCH ARTICLE

Dynamics of algae communities in an oxbow lake (Vistula River, Poland)

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Abstract. This paper presents the results of research on phytoplankton in an oxbow lake on the Vistula River. Originally, the reservoir was natural; however, at the beginning of the twentieth century, the basin of the oxbow lake was dredged and broadened. In 1934, the harbor basin became a protected spawning ground for pikeperch, and as such is a unique site in Poland. The research presented herein was conducted during the growing season of 2008, when 249 taxa of algae were identified in the phytoplankton, mainly Chlorophyta and Bacillariophyceae. The average biomass of the oxbow lake during the entire research period was 33 mg dm^{-3}. The largest biomass was recorded in August at more than 90 mg dm^{-3}. During the entire growing season, the dinoflagellates *Peridinium willei* (Huitfeld-Kaas) played a significant role in the phytoplankton. In the summer, a mass bloom of blue-green algae occurred in the phytoplankton, with the following dominant species: *Aphanizomenon flos-aquae* (L.) Ralfs ex Born. et Flah.; *Dolichospermum planctonicum* (Brunnthaler) comb.n.; *Synechocystis aquatilis* (Sauvageau). Port Drewny was classified as hypertrophic based on the results of the phytoplankton research and the physicochemical conditions. The dominance of blue-green algae, including potentially toxic species, could be dangerous for Port Drzewny as a protected spawning ground for pikeperch.

Keywords: algal blooms, biomass, chlorophyll, oxbow lake, phytoplankton, pikeperch

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Introduction

Biological studies in watercourses are usually performed in the main stream, and changes in biocoenoses are analyzed with the River Continuum Concept (Vannote et al. 1980). Riparian habitats that are periodically flooded or temporarily disturbed by river inundations belong to the common area of the river-floodplain system (Junk et al. 1989, Bayley 1995). Ecological processes occurring in this great ecosystem are very dynamic, and the area influenced by the processes is highly variable. The river-floodplain system comprises the main stream (lotic habitats), flooded ponds and lakes (lentic habitats), and periodically flooded terrestrial areas. Oxbow lakes are characteristic elements of floodplain systems, are situated in river valleys, and are either permanently or periodically connected or completely separated from riverbeds. They develop as a result of disconnection and isolation from meander necks, or as a result of separation from rivers by riverside embankments during freshets (Żmudziński et al. 2002). Fragments of former riverbeds that are periodically or permanently connected with functioning riverbeds are also recognized as oxbow lakes. Oxbow lakes can develop naturally or because of river engineering. Young oxbow lakes, which develop as a result of hydrotechnical treatments during the straightening of river channels, are usually connected with river waters from one side. This connection plays a significant role in the continuous water exchange between such reservoirs and rivers (Jezierska-Madziar 2005), and significantly affects the structure and functioning of communities of living organisms.

Oxbow lakes are a type of water biotope that differs considerably from the river beds that they are connected to. According to Starmach et al. (1976), oxbow lakes are islands of lentic waters next to the continuously moving waters of river beds, and their biocoenoses represent a transitional zone between these two environments. Different types of phytoplankton communities develop under specific environmental conditions, and the short life cycles of algae enable scientists to follow changes occurring in ecosystems. Changes in phytoplankton species composition, abundance, and biomass occur simultaneously with changes in the trophic status of reservoirs. On the other hand, phytoplankton modifies the environment in which it lives, thus affecting the other biocoenosis components of the ecosystem.

The aim of the research presented in this paper was to investigate phytoplankton species composition and biomass in Port Drzewny, an oxbow lake on the Vistula River, prior to its planned restoration. An attempt was made to asses the trophic status of the reservoir and the potential influence exerted by phytoplankton on this ecosystem by determining phytoplankton biomass and selected physicochemical parameters. Port Drewny plays an important natural function as a spawning ground for Vistula River pikeperch. The development of specific types of phytoplankton communities is a significant factor affecting the abiotic properties of waters, as is the extent of trophic pressure exerted by zooplankton through predation, which consequently affects fish communities.

Material and methods

Study area

Port Drzewny is situated in the western part of Toruń (53°01'02"N; 18°30'44"E). It constitutes an element of the waterway of the Vistula River, with which it is connected by the entrance channel at 744.5 km of the river course. The wet dock there is 1800 m long and 350-390 m wide, whereas the entrance channel is 1500 m long and 60-70 m wide. The water surface area at the average water level is 59.39 ha at the wet dock, and 11.37 ha at the entrance channel for a total surface area of 70.76 ha. In terms of surface area, Port Drzewny in Toruń is the largest basin of this type on the Vistula River.

In the nineteenth century, the development of the timber trade led the municipal authorities of Toruń to undertake the construction of a port that would provide suitable conditions for storing wood during the winter and for sawmill processing. Construction began in 1906 in a natural oxbow lake, which had already developed from an arm of the Vistula River in the seventeenth century. The western and eastern parts of the oxbow lake were dredged and the ground level around the lake was increased to 41 m above sea level. Port Drzewny was an inland navigation port on the Vistula River, but it did not have any riversides or cargo handling facilities. At present, it is not exploited as part of the Vistula water transport system. In 1934, the harbor basin became a protected pikeperch spawning ground by virtue of the declaration no. 18/34 of January 10, 1934 issued by Provincial Governor of Pomerania. In this respect, the port is a unique site in Poland.

Sampling and methods

Phytoplankton was collected twice a month between April and September, 2008. The sample collection site was located on a platform on the northern shore of the reservoir (Fig. 1). Qualitative samples for species composition analyses were collected with a no. 25 plankton net using vertical and horizontal hauls. The samples were preserved in formaldehyde. For quantitative analyses, unthickened samples were collected from beneath the surface, i.e., at a depth of approximately 0.5 m. Materials for quantitative analyses were preserved with Lugol's solution (J in KJ).

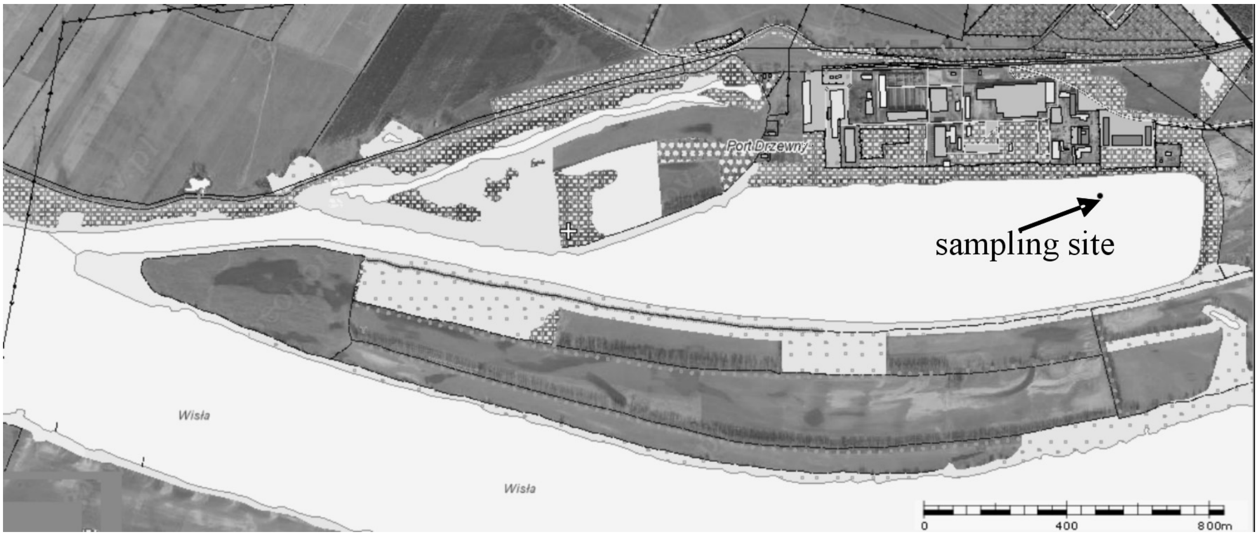

Figure 1. Map of the reservoir Port Drzewny (http://maps.geoportal.gov.pl).

The algae count was determined using the Utermöhl method (1958) and biomass with the volumetric method (Kawecka and Eloranta 1994) assuming that 1 mm^3 of algae is equal to 1 mg. The following water physicochemical parameters were also determined: temperature (T), pH, electrolytic conductivity (EC), and oxygen content (O_2, % O_2).

Water for chemical analyses was collected once a month. The content of orthophosphates, nitrates, nitrites, and ammonium ions were determined in the water. Standard methods of analysis were applied for the determinations (Hermanowicz et al. 1999). Every two weeks the content of chlorophyll a was determined with the method by Nusch (1980).

The trophic state index (TSI) was calculated based on Secchi disc visibility and chlorophyll a concentration (Carlson 1977, Carlson and Simpson 1996). The dominant species described in this paper, with biomass exceeding 10%, were classified into functional groups based on studies by Kruk et al. (2002), Reynolds et al. (2002), Reynolds (2006), and Padisák et al. (2009).

Pearson's simple correlation (MS Excel) was applied to analyze relationships between total biomass and environmental factors. A multivariate statistical package was applied (MVSP 3.2, Kovach Computing Services) to assess the similarity between phytoplankton communities (Jaccard's coefficient), species diversity (Shannon-Wiener evenness), and relationships between dominant species and environmental variables (CCA).

Results

The species richness in the studied reservoir was high; 249 taxa of algae was confirmed, as follows: green algae – 100 taxa (40% of species composition); diatoms – 96 (39%); cyanobacteria – 41 taxa (16%). Other algae phyla were represented by a few species (Fig. 2). The phytoplankton count fluctuated between 0.4 10^6 ind. dm^{-3} in April and 771 10^6 ind. dm^{-3} in August. The average density during the entire research period was 93 10^6 ind. dm^{-3}. The total biomass of phytoplankton (Fig. 3) fluctuated between 5.6 and 91.5 mg dm^{-3}, at an average value of almost 33 mg dm^{-3}. Cyanobacteria made the highest contribution (43%) to the biomass. The total biomass was characterized by two peaks during the summer season in July and August. The increase in the total biomass was related to increased water temperature (Fig. 4). The Pearson's correlation coefficient for these parameters was $r^2 = 0.485$.

The lowest phytoplankton biomass value was noted at the beginning of the research period when

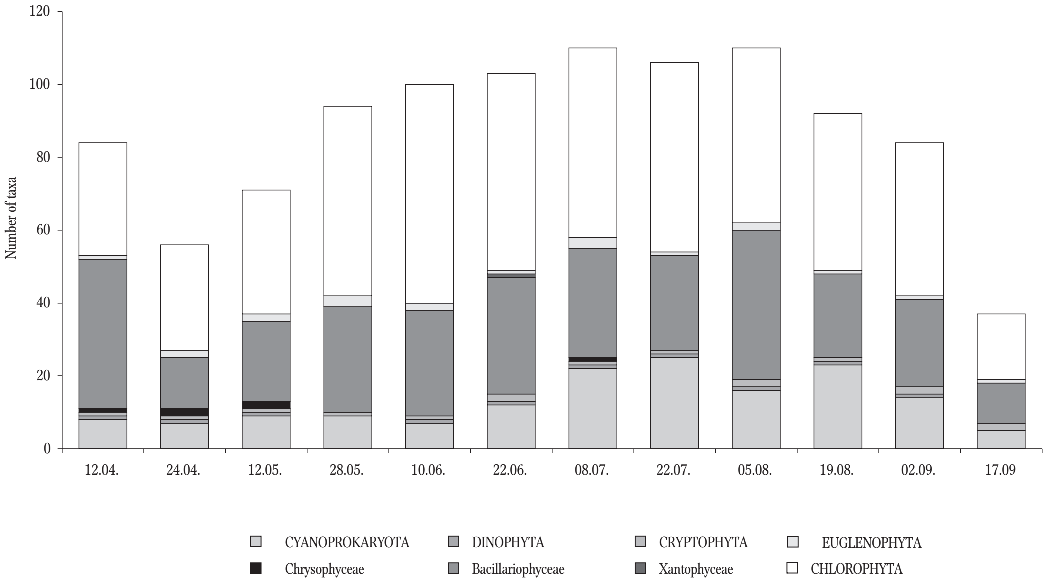

Figure 2. Number of algae species occurring in phytoplankton of Port Drzewny in 2008.

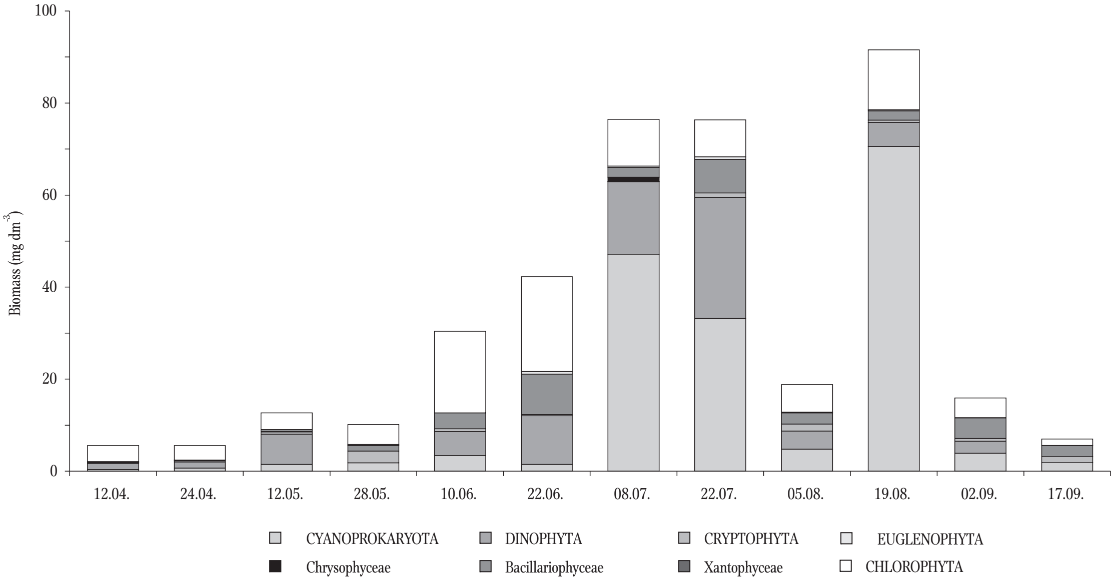

Figure 3. Dynamics of phytoplankton biomass in Port Drzewny in 2008.

species representing functional groups T, Lo, and J (Table 1) were of major significance. The highest contribution of *Peridinium willei* (Huitfeld-Kaas) (Lo) coincided with the lowest concentration of P-PO_4, whereas low biomass was reflected in the lowest concentration of chlorophyll a (Fig. 4). Biomass increased consistently from April to July. The period of dinoflagellate dominance was followed immediately by a relatively significant increase in the contribution of *Cryptomonas erosa* Ehr. Initially, the highest biomass was noted for species from functional groups G, Lo, B, K, and Y (Table 1). The phytoplankton species composition changed significantly between the spring and summer seasons. The Jaccard's coefficient classification revealed a group of spring species with a degree of similarity of more than 0.45 and a separate group of summer species (Fig. 5). In July, biomass reached a value of 76 mg dm^{-3} because of

Table 1
Dominant algae species and values of total biomass (mg dm^{-3}) in phytoplankton of Port Drzewny (algae occurring constantly, i.e., in more than 75% samples, are underlined)

Date	Biomass (mg dm^{-3})	Dominant species	% B	Adaptive strategy*	Functional groups**
12.04	5.6	*Planktonema lauterbornii*	29	S	T
		Peridinium willei	24	S	Lo
		Pediastrum boryanum	19	CR	J
24.04	5.6	*Planktonema lauterbornii*	31	S	T
		Peridinium willei	24	S	Lo
12.05	12.7	*Peridinium willei*	52	S	Lo
28.05	10.1	*Cryptomonas erosa*	25	CRS	Y
		Synechococystis aquatilis	18	C	K
10.06	30.4	*Pandorina morum*	17	CS	G
		Peridinium willei	17	S	Lo
22.06	42.3	*Peridinium willei*	25	S	Lo
		Actinocyclus normanii	16	CR	B
08.07	76.4	*Aphanizomenon flos-aquae*	39	S	H
		Peridinium willei	21	S	Lo
22.07	76.3	*Peridinium willei*	35	S	Lo
		Dolichospermum planctonicum	21	CS	H
05.08	18.8	*Peridinium willei*	21	S	Lo
		Synechocystis aquatilis	16	C	K
19.08	91.5	*Synechocystis aquatilis*	54	C	K
		Dolichospermum planctonicum	16	CS	H
02.09	15.9	*Actinocyclus normanii*	19	CR	B
		Peridinium willei	17	S	Lo
		Synechocystis aquatilis	17	C	Z
17.09	7.0	*Actinocyclus normanii*	34	CR	B
		Synechocystis aquatilis	26	C	K
		Cryptomonas erosa	19	CRS	Y
		Scenedesmus communis	13		J

*after Kruk et al. (2002), Bucka and Wilk-Woźniak (2007) and Wilk-Woźniak (2009)
**after Kruk et al. (2002), Reynolds et al. (2002), Reynolds (2006), Padisák et al. (2009)

the intense development of Nostocales (*Dolichospermum planctonicum* (Brunnthaler) comb.n., *Aphanizomenon flos-aquae* (L.) Ralfs ex Born. et Flah.) representing group H_1, and the dinoflagellate species *P. willei* from group Lo. Intense phytoplankton development resulted in low water transparency and high concentrations of chlorophyll a (Fig. 4). Pearson's correlation coefficient for biomass and water transparency was $r^2 = 0.646$, and for biomass and chlorophyll a concentration it was $r^2 = 0.871$. At the end of August, the biomass increased to the maximum value of 91.5 mg dm^{-3}. The contribution of cyanobacteria to the biomass was also the highest during the most intense phytoplankton development and was 77%. The species *D. planctonicum* and *Synechocystis aquatilis* (Sauvageau), which are representatives of functional groups H_1 and K, developed most intensely at this time. The lowest evenness value of 0.412 was noted when algal blooms occurred (Table 2). CCA analysis of direct ordination (Fig. 6) confirmed a strong relationship between the biomass of dominant species and increased temperature. At the same time, intense phytoplankton development modified the environment by increasing pH and chlorophyll a concentrations (184 µg dm^{-3}), as well as by reducing water transparency to a value of 0.3 m. The biomass dropped in September, when phytoplankton development was limited mainly by decreasing water temperature. The similarity between the phytoplankton

Table 2
Values of species diversity indexes in Port Drzewny

Sample	Shannon-Wiener Index	Evenness	Number of species
12.04	0.964	0.501	84
24.04	1.012	0.579	56
12.05	0.948	0.512	71
28.05	1.207	0.612	94
10.06	1.284	0.642	100
22.06	1.308	0.65	103
08.07	1.019	0.499	110
22.07	1.031	0.509	106
05.08	1.21	0.593	110
19.08	0.809	0.412	92
02.09	1.168	0.607	84
17.09	0.707	0.451	37

community in September and that from previous months (Jaccard's coefficient 0.23) was at the lowest, which resulted from the small number of species occurring at that time (Fig. 5). The reservoir was classified as highly eutrophic based on SD visibility (TSI 70), chlorophyll a concentration (TSI 68), and phytoplankton biomass (32.7 mg dm^{-3}).

Discussion

As in many oxbow lakes, the species richness in Port Drewny is dominated by diatoms and green algae sometimes accompanied by cyanobacteria and euglenoids (O'Farell et al. 2003, Paidere et al. 2007, Pithart et al. 2007, Bovo-Scomparin and Train 2008). Pasztaleniec et al. (2006) report that oxbow lake phytoplankton is rich in species, with the number of taxa in these ecosystems ranging from 250 to 300. Most of the taxa identified in Port Drzewny are cosmopolitan species that occur in eutrophic waters (Bucka and Wilk-Woźniak 2002, 2007). The comparison of the taxonomic composition of Port Drzewny with plankton in the lower Vistula (Dembowska 2002a, 2002b, 2005) revealed 130 common phytoplankton species. Since the reservoir

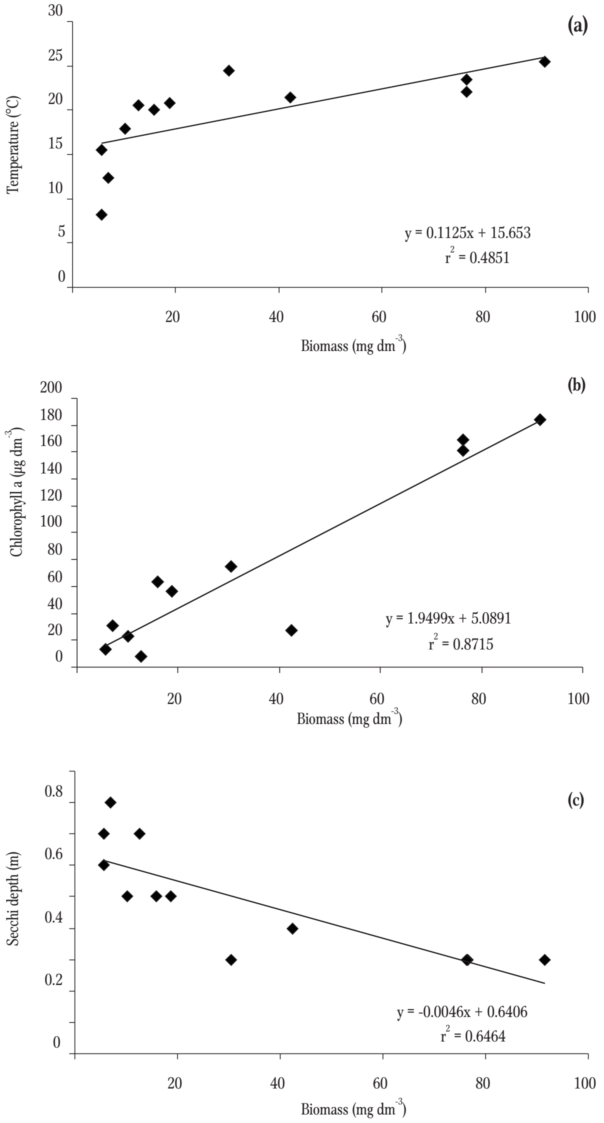

Figure 4. Relationships between phytoplankton biomass and environmental factors in Port Drzewny in 2008. a. biomass vs. temperature; b. biomass vs. chlorophyll *a;* c. biomass vs. SD visibility.

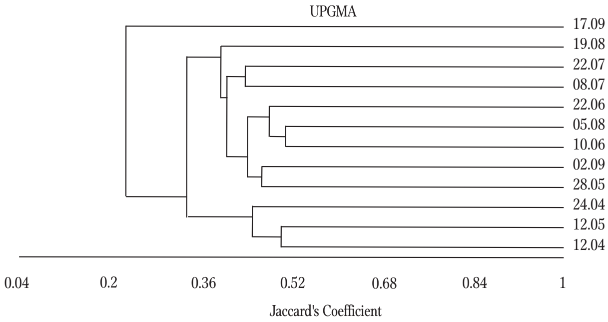

Figure 5. Similarity of phytoplankton species composition in Port Drzewny in 2008.

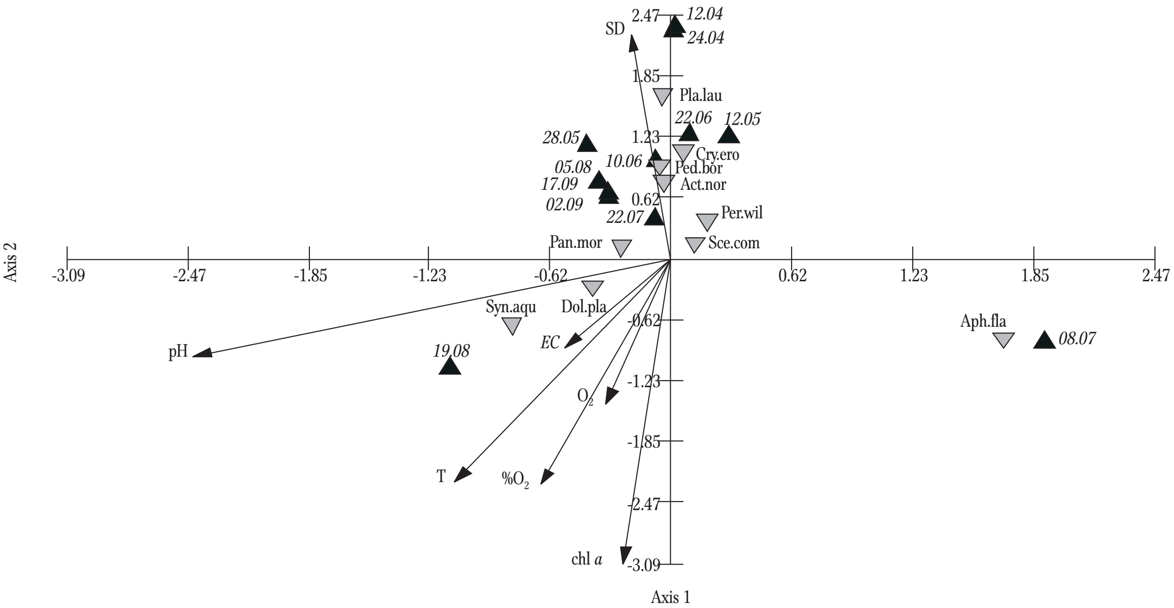

Figure 6. CCA analysis of biomass of dominant species and environmental variables.

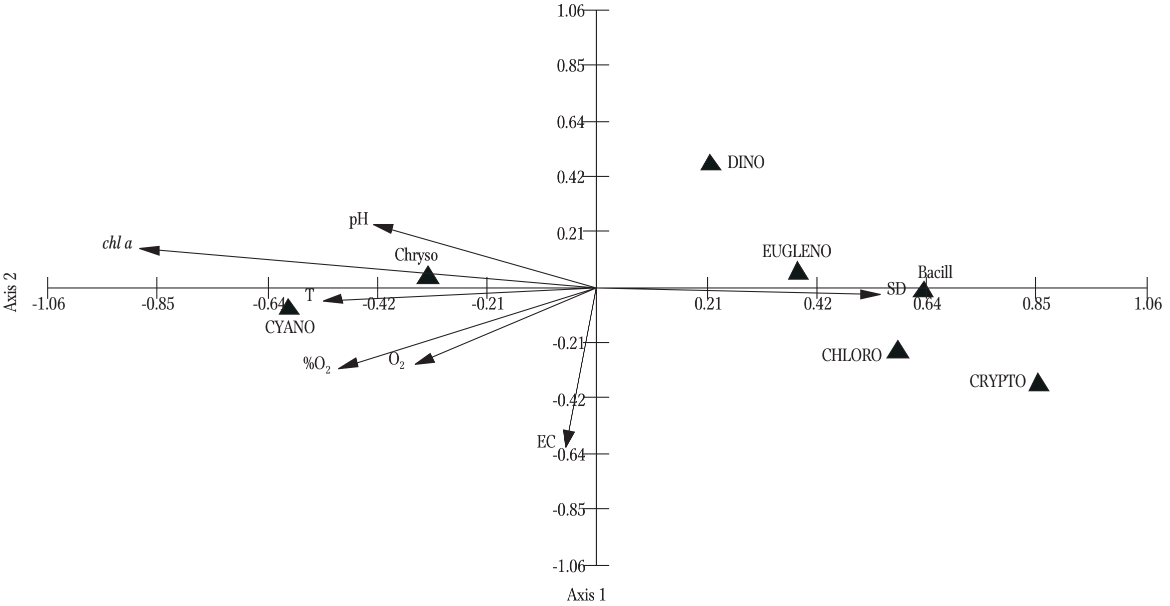

Figure 7. CCA analysis of phytoplankton-group biomass and environmental variables.

has a permanent connection with the river, this conclusion is not surprising. Larger, periodic inflows of Vistula waters to the reservoir might have been caused by the power plant on the dam in Włocławek, which is almost 80 km upstream from above the inlet channel into Port Drzewny. The cyclic operation of the power plant and regular water discharge from Włocławek Reservoir cause short-term, but conspicuous, increases in water level in the Vistula River downstream from the dam.

The very high values of phytoplankton density and biomass indicate that the reservoir is hypertrophic, which, according to the criteria developed by Bucka (1987) and Smayda (1997), indicate a constantly occurring water bloom. Similarly high values of phytoplankton abundance and biomass were recorded in small ponds in the Parana River valley (O'Farell et al. 2003). Much higher phytoplankton biomass values were recorded by Padisák et al. (2003) in a few oxbow lakes in Hungary where cyanobacteria Nostocales and Oscillatoriales dominated, as well as in oxbow lakes dominated by Chlorococcales, Cryptomonadales, and Bacillariophyceae. Nonetheless, many riparian water bodies are characterized by much lower phytoplankton abundance and biomass values (O'Farell et al. 2003, Padisák et al. 2003, Pithart et al. 2007).

Throughout the research period, the dinoflagellate species *P. willei* was a constant species that always occurred at a high biomass. Different species from the genus *Peridinium* often dominate in small water bodies, including oxbow lakes (Padisák et al. 2003). In early May, the biomass of this dinoflagellate species increased more than fivefold, which indicates significant environmental changes. Unfavorable abiotic conditions can induce the mass development of species capable of active movement. *Peridinium* is a mixotroph, which means it can develop in conditions that are unfavorable for obligatory autotrophs. The dominant species in spring and at the beginning of summer in the Port Drzewny oxbow lake represent mainly the S life strategy (Reynolds 2006), including the following: *P. willei, Planktonema lauterbornii* Schmidle*, A. flos-aquae* (Table 1). The dominance of this type of strategist results from high environmental stability with possible short-term disturbances induced by wind mixing or small river water inflows. The occurrence of these species is connected with high water temperatures as well as deficiencies of nutrient substances, especially orthophosphates, which are characteristic of this reservoir.

Flagellate algae, capable of active migration, like dinoflagellates, include cryptophytes representing the CSR strategy. They are also characterized by mixotrophy as a survival strategy. The dominance of representatives of this group is observed when water blooms of other algae end (Wilk-Woźniak 2009) or at the beginning of summer when the amount of light and bacteria biomass are great (Jones 2000). Although Pithart et al. (2007) and Bovo-Scomparin and Train (2008) report the strongest association of Cryptophyta with light deficiency, their development in Port Drzewny was correlated with good light conditions in the water (Fig. 7), whereas negative correlations were noted in relation to temperature and pH. Vertical migrations of *Cryptomonas* and their capacity for rapid cell division (growth) could compensate for losses caused by predation by cladocerans (Bucka and Wilk-Woźniak 2002), whose greatest development usually occurs at the end of May and the beginning of June.

In the summer (starting from July), the phytoplankton was completely restructured, and Cyanoprokaryota began to dominate. The similar dominance of cyanobacteria was observed in the Parana River during the dry season when cyanobacteria constituted 65% of the total phytoplankton biomass (Bovo-Scomparin and Train 2008). As in Port Drzewny, the development of blue-green algae in other water bodies tends to be preceded with the spring dominance of green algae, cryptophytes, and diatoms (Burchardt et al. 2007). Blue-green algae are characterized by high resistance to conditions that are unfavorable for eukaryotic algae, and many species also prefer water temperatures above 20°C (Konopka and Brock 1978, Bucka and Wilk-Woźniak 2005) and high pH 8.4-9.2 (Fig. 7). Planktonic cyanobacteria are well adapted to conditions of low light intensity (Shapiro 1990, Mischke and Nixdorf 2003, Pitchart 2007), which favors their mass development. The development of cyanobacteria was strongly positively correlated with temperature, high pH, and oxygen content. The strongest correlation also occurred with chlorophyll a concentration. A negative correlation was recorded with water transparency. In July, *A. flos-aquae* and the genus *Dolichospermum* formed a water bloom, and the total number of recorded filaments of both types was 19.5 million dm^{-3}. Algal blooms of *A. flos-aquae* were also observed in July in other Polish water reservoirs (Bucka and Wilk-Woźniak 2005, Burchardt et al. 2007, Kozak 2010). One consequence of phytoplankton blooms are conditions that are unfavorable for the development of other organisms. Oxygen deficits can occur in a considerable water volume along with hypersaturation at the water surface. Mass cyanobacterial blooms, during which cyanotoxins can be released into the water, are particularly dangerous. Pliński (2009) reported that the thermal optimum for the production of toxins by *Aphanizomenon* is 26°C, and for *Anabaena* it is 22.5°C. Representatives of both genera of blue-green algae formed algal blooms in the studied oxbow lake in July and August. Thus, it appears to be necessary in the future to determine the content of cyanotoxins. Cronberg and Annadotter (2006) and Landsberg (2002) report numerous cases of harmful, and even lethal, effects of these toxins on aquatic organisms, with larval stages of fish being the most susceptible. *Aphanizomenon* is a potential producer of anatoxin-a, which can inhibit the reproduction of many rotifer species. *Aphanizomenon* can also produce lupenyl acetate and C18 lipid mueggelone, which, in high concentrations, can inhibit the development of the cardiovascular system and lead to the death of fish larval forms, whereas studies on adult forms of *Cyprinus carpio* L. revealed mucus on the gills and skin. Research by Bownik et al. (2008) confirmed cyanotoxins have a negative influence on the immune system of fish, and particularly on the viability of lymphocytes T and B.

The maximum phytoplankton biomass of 91.5 mg dm^{-3} was recorded at the end of August. At this time *S. aquatilis* dominated decidedly. *S. aquatilis* is characterized by small cell diameter of the order of 5 μm, because of which it is classified as nanoplankton. These algae represent the K group occurring in shallow waters that are rich in nutrients (Kruk et al. 2002, Reynolds et al. 2002, Reynolds 2006).

Representatives of S strategy occurred at the same frequency as those of C strategy (*S. aquatilis*) in late summer and fall. The presence of these species indicates the presence of stress-related factors and increased incidences of disturbing phenomena, mainly water mixing. During this period, nutritional conditions improved (higher concentrations of orthophosphates) although light deficiencies occurred frequently.

Dynamic changes in phytoplankton biomass were also reflected in chlorophyll a concentration, and the two parameters are characterized by a strong linear correlation (Pearson $r^2 = 0.871$). Much lower values of chlorophyll a concentration were obtained by Lelková et al. (2004), who investigated oxbow lakes of the Morava River, where maxima ranged from 39 to 60 μg dm^{-3}. Much higher fluctuations in chlorophyll a concentration were recorded in the oxbow lakes of the Bug River (Pasztaleniec et al. 2006), where average values ranged from less than 10 to 146 μg dm^{-3}.

In conclusion, Port Drzewny is a highly eutrophic, over-fertilized water reservoir. The strong development of phytoplankton with intense blooms dramatically affects the environmental conditions of this ecosystem by reducing water transparency and increasing chlorophyll a concentration. Intense primary production is periodically responsible for the hypersaturation of the surface water layer. Cyanobacteria species forming algal blooms in this reservoir could potentially produce toxic substances, and this, combined with the large quantity of organic matter, could pose a serious threat to the ecosystem. This is particularly unfavorable for this reservoir since it serves as a spawning ground.

This water body could serve in an important recreational role in future thanks to its location within the administrative boundaries of Toruń, and its large surface area (approximately 70 ha). However, the water quality must be improved. This is usually achieved through restoration measures designed to reduce or eliminate algal blooms. However, it is difficult to predict whether restoration will produce the anticipated long-term effects since the reservoir is located in flood areas. Previous observations in other restored reservoirs indicate that after emptying and refilling the reservoir, *Aphanizomenon* still created water blooms (Kozak 2010). This means that this species of blue-green algae is difficult to remove. Thus, the question remains regarding the future of Port Drzewny as a protected spawning ground for pikeperch.

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