Mass development of phytoplankton in the River Warta in Poznań (Poland) in the 21st century

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Abstract: The first studies of phytoplankton of the River Warta in Poznań (Poland) were carried out in the 20th century (in 1922–23 and 1950–57). In the growing seasons the dominant groups were diatoms and green algae. Cyanobacteria were noted, but they did not have high abundance. The aim of this work is to present the phytoplankton research conducted on the River Warta in Poznań in the 21st century (in 2003, 2009, 2010 and 2016). In all years the dominance of diatoms and green algae in terms of biomass was noted. However, in late summer cyanobacteria biomass was high and this group became dominant or co-dominant. Spring blooms were created by unicellular centric diatoms, e.g. *Stephanodiscus minutulus* and colonial green algae: *Coelastrum microporum* or *Micractinium pusillum*. In summer, bloom-forming taxa were unicellular centric diatoms, colonial diatoms: *Aulacoseira granulata* or *Fragilaria crotonensis* and cyanobacteria: *Aphanizomenon flos-aquae* and *Woronichinia naegeliana*. The occurrence of taxa typical of dam reservoirs and lakes suggests the influence of the Jeziorsko Reservoir on the phytoplankton of the River Warta, but it does not exclude the impact of tributaries and oxbow lakes. The research conducted in the 20th and 21st century show important changes in the taxonomical structure and abundance of phytoplankton.

Key words: eutrophic river, water bloom, cyanobacteria, *Aphanizomenon flos-aquae*

Introduction

Intensive development of phytoplankton, including cyanobacteria, often occurs in different kinds of water bodies as a result of the water eutrophication and the global climate change of recent decades (O’Neil 2012). Cyanobacteria blooms have been observed in numerous lakes and reservoirs in Poland (Zagajewski et al. 2007; Grabowska and Mazur-Marzec 2011; Mankiewicz-Boczek et al. 2011; Kobos et al. 2013; Gągała et al. 2014) and many other countries around the world (Carmichael 2008; Merel et al. 2013). They have also been noted in eutrophic rivers, e.g. in the River Nakdong in South Korea (Ha et al. 1998) in the River Murrey in Australia (Al-Tebrineh et al. 2012) and in the River Nile in Egypt (Mohamed et al. 2015). In Poland they have been observed in e.g. the River Narew (Grabowska and Mazur-Marzec 2011) and in the River Obrzyca (Piontek et al. 2017).

Growth of phytoplankton in rivers is intensified by nutrients flowing from the catchment area, the presence of nutrient and phytoplankton rich tributaries

(Istvánovics et al. 2010), oxbow lakes (Grabowska et al. 2014), and dam reservoirs (Prygiel and Leitaó 1994; Kasza 2009; Grabowska 2012; Mądrecka 2015).

Rivers are very unstable environments for phytoplankton development because of constant water flow and water turbulence. Another important factor affecting phytoplankton is light availability, which can be significantly limited by high water turbidity (Allan and Castillo 2009). Moreover, the environment of the riverbed is inhomogeneous. There are areas characterized by reduced water discharge and increased concentration of different nutrients, in which phytoplankton can develop more intensively, called “dead-zones” or “storage-zones”. These areas also include backwaters and river branches (Reynolds and Descy 1996; Reynolds 2000).

Instability and heterogeneity of river water lead to frequent structural changes in taxonomy and phytoplankton concentration. This shows the importance of continuous and long-lasting monitoring research which can extend our knowledge of the ecology of bloom-forming taxa in rivers. It is also necessary and helpful from the point of view of water quality assess-

ment and limitation of harmful effects of water bloom e.g. high concentration of cyanotoxins in river water.

The aim of this work is to present a taxonomical and quantitative analysis of phytoplankton of the River Warta in Poznań at the beginning of the 21st century against the background of previous research. Particular attention is focused on dominant phytoplankton groups and bloom-forming taxa.

Methods

Water samples for physical, chemical, chlorophyll-*a* and phytoplankton analyses were taken from the current of the River Warta in the city center of Poznań near Queen Jadwiga Bridge in 2003 or near Saint Roch Bridge in 2009, 2010 and 2016 (244.5 km of river flow) (Fig. 1). In 2003 a monitoring study was conducted and the samples were collected only between the end of May to October – once a month (in May and October) or twice a month (from June to September). In this year total phytoplankton biomass and chemical parameters were not analyzed. In 2009, 2010 and 2016 the frequency of sampling was once a month (in March and April) or twice a month (from May to October).

Water samples for phytoplankton studies were collected in polyethylene bottles and preserved with Lugol's solution. Samples for autotrophic picoplankton (APP) study were conserved with buffered glutaraldehyde to obtain the final concentration of 1–2% (Hawley

and Whitton 1991a). Water temperature and pH were measured directly at the sampling site.

Phytoplankton taxonomy and the amount of cells was studied with a light microscope (Olympus BX-60) and an inverted microscope (MOD-2, Motic AE31) after sedimentation in settling chambers according to the method by Utermöhl (Wetzel and Likens 1991). Autotrophic picoplankton subsamples (of 1 cm³ volume) were filtered through nucleopore black filters with a diameter of 25 mm and a pore size of 0.2 µm at low vacuum pressure. Then, APP cells were dyed with the use of fluorochrome DAPI (4',6-diamidino-2-fenylindol) (Porter and Feig 1980) and analyzed using an epifluorescence microscope (Olympus BX-60). Biovolume of phytoplankton taxa was calculated on the basis of cell volume and their abundance. Biomass was expressed as wet weight, assuming that the volume of 10⁶ µm³ is equivalent to 1 µg (wet weight) (Amblard et al. 1995). The threshold value of water bloom was 10 mg dm⁻³ of phytoplankton biomass according to the criterion of Pavoni (1963).

Chlorophyll-*a* concentrations were determined spectrophotometrically after filtration through Whatman GF/F glass fiber filters and extraction in 90% acetone. Standard methods were used for analyses of concentrations of phosphates, mineral forms of nitrogen, total phosphorus and total nitrogen (Hermanowicz et al. 1999).

Hydrological data – water level and water discharge of the River Warta near Saint Roch Bridge were obtained from the database of the Institute of Meteorology and Water Management available on the website (<https://dane.imgw.pl>).

Study area

The River Warta is the third longest river in Poland (808.2 km). The sampling station was located in the center of the city of Poznań in the Greater Poland Voivodeship. In this area the Warta flows in a northerly direction within the geographical mesoregion known as the Poznań Ravine of the Warta River, which is part of the Greater Poland Lakeland. Through almost all the area of the Greater Poland Voivodeship it is classified as abiotic type 21 (large lowland rivers). According to data of the Central Statistical Office of Poland (GUS 2016) mean annual discharge calculated for the years 1951–2010 at the stream gauge near Saint Roch Bridge is 102 m³ s⁻¹.

The River Warta is highly eutrophic and is subject to strong anthropogenic influence. The catchment area of the Greater Poland Voivodeship is 26.7×10³ km. About 65% of it is used as farmland – mainly arable land. The Warta also has many tributaries rich in nutrients and

Fig. 1. Locality of the city of Poznań and the sampling site (black circle)

is a receiver of wastewater from many municipal and industrial wastewater plants. At 484.3 km of river flow there is also the dam of the Jeziorsko Reservoir whose max. volume is $202.8 \times 10^6 \text{ m}^3$ and max. area is 42.3 km^2 . This reservoir has been operating since 1986, but its first maximal impoundment was achieved in 1992 (RZGW 2007).

The River Warta is used for industry – particularly for the energy industry, for agricultural irrigation and fishery management. It is also the source of drinking water for the inhabitants of Poznań (Pułyk 2010). In Poznań the river and its adjacent area are increasingly used for recreational purposes.

Results

In the studied years values of the water level were similar and were in the range of low or middle water level zone (Table 1). The exception was the level noted in 2010, whose values were in the middle or high water level zone. In this year in May and June the values exceeded the warning state and were higher than 400 cm, as a result of flood wave propagation. The ranges and mean values of water discharge were also similar in 2003, 2009 and 2016. They did not usually exceed diurnal mean annual water discharge calculated for this river. Higher values were observed only in March and April of 2009 and 2016 during the melt. In the case of 2010, the mean value of water discharge was approximately 3-fold higher than in the other years. Mean values of water temperature were similar in 2009, 2010 and 2016 and amounted to $16.0\text{--}16.5^\circ\text{C}$. The mean value in 2003 was higher because of the smaller number of samples. The pH value was usually slightly alkaline ($8.20\text{--}8.89$).

Concentration of total nitrogen and total phosphorus was high and indicative of the high trophic state of the river. In 2016 the mean value of mineral forms of nitrogen was approx. 2–3 times lower than in 2009 and 2010 (Table 1). Mean values of phosphates were similar in the 3 investigated years and amounted to $0.114\text{--}0.140 \text{ mg P dm}^{-3}$. In 2003, 2009 and 2016 concentration of chlorophyll-*a* exceeded $30 \text{ } \mu\text{g dm}^{-3}$ in the majority of samples, which confirmed the high trophy of the Warta according to the criterion proposed by Dodds et al. (1998). Lower values of this parameter were noted in 2010 (only in 3 samples was concentration $>30 \text{ } \mu\text{g dm}^{-3}$).

The total amount of phytoplankton was variable in each growing season, but usually exceeded 10^4 cells per cubic centimeter. The mean value of autotrophic picoplankton ranged from 17.5 to $35.4 \times 10^3 \text{ cells cm}^{-3}$ (Table 1). The most important taxa from this size group were cyanobacteria: *Synechocystis*, *Synechococcus*, *Aphanocapsa*, *Cyanogranis ferruginea*, *Mersmopedia tenuissima* and green algae: *Chlorella*, *Choricystis*, *Pseudodictyosphaerium jurisii*.

The high value of phytoplankton biomass exceeding 10 mg dm^{-3} indicated the occurrence of spring and summer water blooms in the River Warta (Fig. 2). In the spring of 2003 the water bloom was caused by unicellular centric diatoms and colonial green algae, whereas in 2016 it was mainly caused by the unicellular centric diatoms. In all the studied years, at the beginning of summer, the water blooms were formed by unicellular centric diatoms (in 2003, 2009, 2016) and/or colonial diatoms (in 2009, 2016), but in the late summer water blooms were formed by cyanobacteria (in 2009, 2003, 2016), diatoms (in 2003, 2010) and green algae (in 2016) (Tables 2 and 3). Taxonomical groups of phytoplankton noted in the Warta in low biomass were:

Table 1. Hydrological, physical, chemical and biological parameters of water during the growing season (March–October) in 4 investigated years (mean values were put in brackets)

Parameter	Unit	2003*	2009	2010	2016
Water level	[cm]	141–244 (171)	160–270 (200)	219–484 (320)	137.5–267.5 (176.5)
Water discharge	[$\text{m}^3 \text{ s}^{-1}$]	38.5–88.0 (52.1)	46.1–113.0 (69.6)	80.4–302.0 (156)	34.0–109.0 (55.4)
Water temperature	[$^\circ\text{C}$]	6.8–25.5 (19.5)	4.2–23.7 (16.2)	7.3–26.0 (16.0)	5.5–22.9 (16.5)
pH		7.78–9.52 (8.89)	7.94–9.11 (8.33)	7.55–8.60 (8.20)	8.00–8.80 (8.36)
Mineral nitrogen	[mg N dm^{-3}]	NA	0.725–2.545* (1.363)*	1.387–3.036 (2.103)	0.147–0.958 (0.620)
Total nitrogen	[mg N dm^{-3}]	NA	2.754–4.399* (3.870)*	3.536–6.521 (4.296)	1.774–3.149 (2.551)
Phosphates	[mg P dm^{-3}]	NA	0.051–0.179* (0.124)*	0.048–0.203 (0.114)	0.076–0.206 (0.140)
Total phosphorus	[mg P dm^{-3}]	NA	0.071–0.850* (0.240)*	0.116–0.750 (0.243)	0.202–0.368 (0.273)
Chlorophyll- <i>a</i>	[$\mu\text{g dm}^{-3}$]	2.5–155.3 (78.0)	5.6–133.0 (44.3)	1.6–75.4 (26.5)	19.6–150.8 (82.0)
Total phytoplankton abundance	[$10^3 \text{ cells cm}^{-3}$]	NA	5.5–267.4 (76.0)	4.4–203.4 (62.8)	NA
Phytoplankton abundance without APP	[$10^3 \text{ cells cm}^{-3}$]	NA	4.3–263.1 (58.5)	1.5–170.2 (39.3)	14.3–374.9 (139.9)
APP abundance	[$10^3 \text{ cells cm}^{-3}$]	1.3–105.0 (35.4)	1.2–55.6 (17.5)	0.8–81.2 (23.5)	NA

* – analyzed since May to October only; NA – not analyzed.

Fig. 2. Biomass of dominant phytoplankton groups and concentration of chlorophyll-*a* in the River Warta in 2009, 2010 and 2016

Chrysophyceae, *Cryptophyceae*, *Euglenophyta*, *Dinophyta*, *Xanthophyceae*.

Unicellular centric diatoms with the highest biomass were taxa of the genera: *Stephanodiscus*, *Cyclotella*, *Thalassiosira*, *Actinocyclus*. Their mass occurrence was observed in May of 2003 and 2016, when their biomass exceeded 40 mg dm⁻³ (Table 2). In 2016 the water bloom was the effect of the intensive growth of *Stephanodiscus minutulus*. Colonial diatoms in turn form water blooms in the summer – *Aulacosei-*

ra granulata in 2009 and *Fragilaria crotonensis* in 2010 and 2016. In July of 2016 *F. crotonensis* had the highest biomass – over 75 mg dm⁻³ (Table 3).

As regards green algae, in June of 2003, the taxon with the highest biomass was *Coelastrum microporum* (10.3 mg dm⁻³) (Table 2). Other taxa with high biomass were: *Micractinium pusillum* (in 2016), *Pediastrum* (in 2016) and *Scenedesmus/Desmodesmus* (in all investigated years). High cell abundance but small biomass was observed in the case of taxa characterized by small cell

Table 2. Taxa with the highest biomass (>10% of total phytoplankton biomass – TPB) noted in 2003 and 2009

Date	Taxa	Biomass [mg dm ⁻³]	% of TPB
2003			
25 May	unicellular centric diatoms*	66.33	NA
6 June	unicellular centric diatoms*	16.80	NA
	<i>Coelastrum microporum</i>	8.69	NA
25 June	unicellular centric diatoms*	15.30	NA
	<i>Coelastrum microporum</i>	10.33	NA
5 July	unicellular centric diatoms*	4.51	NA
23 July	unicellular centric diatoms*	21.90	NA
7 Aug.	unicellular centric diatoms*	14.25	NA
22 Aug.	<i>Aphanizomenon flos-aquae</i>	11.17	NA
	unicellular centric diatoms*	11.10	NA
6 Sep.	unicellular centric diatoms*	5.10	NA
26 Sep.	unicellular centric diatoms*	2.85	NA
22 Oct.	unicellular centric diatoms*	0.63	NA
2009			
13 Mar.	unicellular centric diatoms*	0.46	45.9
	<i>Gyrosigma acuminatum</i>	0.13	13.2
15 Apr.	unicellular centric diatoms*	1.86	57.0
15 May	unicellular centric diatoms*	1.32	25.5
	<i>Nitzschia acicularis</i>	1.24	23.9
25 May	<i>Fragilaria crotonensis</i>	1.47	22.9
	unicellular centric diatoms*	1.17	18.3
	<i>Nitzschia acicularis</i>	0.85	13.2
8 June	unicellular centric diatoms*	0.45	30.6
22 June	unicellular centric diatoms*	1.15	16.4
6 July	unicellular centric diatoms*	10.57	50.3
20 July	<i>Aphanizomenon flos-aquae</i>	5.47	36.4
	<i>Aulacoseira granulata</i>	5.33	35.4
11 Aug.	unicellular centric diatoms*	1.78	36.6
24 Aug.	<i>Microcystis flos-aquae</i>	1.64	28.0
	<i>Aphanizomenon flos-aquae</i>	1.37	23.3
7 Sep.	<i>Aphanizomenon flos-aquae</i>	6.70	57.2
	<i>Microcystis flos-aquae</i>	2.93	25.0
21 Sep.	<i>Microcystis aeruginosa</i>	3.61	74.6
5 Oct.	<i>Aphanizomenon flos-aquae</i>	0.25	27.1
	unicellular centric diatoms*	0.10	11.2
19 Oct.	<i>Pseudanabaena mucicola</i>	0.20	25.8

Explanation: * – small unicellular centric diatoms from genera: *Stephanodiscus*, *Cyclostephanos*, *Cyclotella*, *Actinocyclus*, *Thalassiosira*; NA – not analyzed.

size e.g. *Actinastrum*, *Dictyosphaerium*, *Monoraphidium*, *Tetrastrum*, *Oocystis*.

In each investigated year, in the second half of summer, the cyanobacteria developed more intensively (Fig. 2). At the end of August 2003, *Aphanizomenon flos-aquae* formed a water bloom in which it occurred in fascicle visible to the naked eye. Its biomass amounted to 11.17 mg dm⁻³ (water temperature was 22.0°C and pH = 9.14). A similar phenomenon took place on the 7th September 2009, although its biomass was lower (6.7 mg dm⁻³; 16.1°C; pH = 8.3). On this date *A. flos-*

Table 3. Taxa with the highest biomass (>10% of total phytoplankton biomass – TPB) noted in 2010 and 2016

Date	Taxa	Biomass [mg dm ⁻³]	% of TPB
2010			
22 Mar.	unicellular centric diatoms*	0.04	44.8
19 Apr.	unicellular centric diatoms*	5.21	59.4
17 May	Ulotrichales	2.19	39.2
	unicellular centric diatoms*	2.00	35.9
26 May	unicellular centric diatoms*	2.25	40.7
	<i>Pseudanabaena limnetica</i>	0.80	14.5
14 June	<i>Closterium</i> spp.	0.09	21.7
	unicellular centric diatoms*	0.07	17.9
28 June	<i>Chlorella</i> spp.	2.31	38.6
	unicellular centric diatoms*	2.23	37.3
13 July	unicellular centric diatoms*	1.53	54.2
27 July	<i>Fragilaria crotonensis</i>	3.37	27.1
	<i>Microcystis aeruginosa</i>	2.49	20.1
3 Aug.	<i>Fragilaria crotonensis</i>	16.34	81.0
16 Aug.	<i>Fragilaria crotonensis</i>	19.38	52.3
	<i>Aphanizomenon flos-aquae</i>	14.51	39.2
2 Sep.	<i>Fragilaria crotonensis</i>	12.75	84.7
22 Sep.	unicellular centric diatoms*	1.06	35.9
	<i>Fragilaria crotonensis</i>	0.85	28.5
11 Oct.	unicellular centric diatoms*	1.92	68.5
25 Oct.	unicellular centric diatoms*	4.77	66.8
	<i>Fragilaria crotonensis</i>	1.37	19.2
2016			
17 Mar.	unicellular centric diatoms*	3.16	48.6
	<i>Asterionella formosa</i>	1.89	29.0
21 Apr.	<i>Asterionella formosa</i>	4.35	32.7
	unicellular centric diatoms*	2.63	19.8
17 May	unicellular centric diatoms*	34.05	82.7
31 May	unicellular centric diatoms*	16.80	67.3
16 June	unicellular centric diatoms*	2.17	20.2
	<i>Pediastrum duplex</i>	1.28	11.9
30 June	unicellular centric diatoms*	9.84	26.6
	<i>Micractinium pusillum</i>	3.89	10.5
12 July	<i>Fragilaria crotonensis</i>	75.31	71.3
	unicellular centric diatoms*	14.21	13.5
27 July	unicellular centric diatoms*	7.75	18.7
	<i>Pediastrum duplex</i>	5.12	12.3
16 Aug.	<i>Woronichinia naegeliana</i>	11.48	34.0
	<i>Fragilaria crotonensis</i>	5.41	16.0
	unicellular centric diatoms*	3.96	11.7
31 Aug.	<i>Woronichinia naegeliana</i>	8.76	26.9
	unicellular centric diatoms*	4.83	14.8
	<i>Micractinium pusillum</i>	3.85	11.8
13 Sep.	unicellular centric diatoms*	4.52	20.0
	<i>Micractinium pusillum</i>	2.28	10.0
28 Sep.	unicellular centric diatoms*	4.40	21.5
	<i>Micractinium pusillum</i>	2.97	14.5
14 Oct.	unicellular centric diatoms*	1.48	23.7
28 Oct.	<i>Fragilaria crotonensis</i>	5.48	39.2
	unicellular centric diatoms*	5.09	36.4

Explanation: * – small unicellular centric diatoms from genera: *Stephanodiscus*, *Cyclostephanos*, *Cyclotella*, *Actinocyclus*, *Thalassiosira*.

aquae dominated with *Microcystis flos-aquae* and their biomass together exceeded 82% of total phytoplankton biomass. A bloom of *A. flos-aquae* occurred again in August 2010 and achieved the highest biomass of 14.5 mg dm^{-3} (23.8°C ; $\text{pH} = 7.5$). This species was also noted in summer 2016 but its biomass was low. In August 2016, a mass occurrence of another cyanobacteria was observed – *Woronichinia naegeliana*. Its maximum value of biomass amounted to 11.5 mg dm^{-3} (19.3°C ; $\text{pH} = 8.5$).

Other cyanobacteria taxa with a high biomass which occurred in the investigated growing seasons were: *Microcystis aeruginosa*, *Pseudanabaena limnetica*, *Planktothrix aghardii*, *P. mucicola*, *Phormidium granulatum*, *M. wesenbergii*, *Dolichospermum flos-aquae*, *Planktolyngbya limnetica*, *Aphanizomenon gracile*, *D. spiroides*. Some rare species of cyanobacteria were also noted, but their biomass was low. These were: *Cuspidothrix issatschenkoi*, *Sphaerospermopsis aphanizomenoides*, *Anabaenopsis elenkinii*, *A. milleri*.

Discussion

In the River Warta the abundance of phytoplankton (without APP) was quite high but not similar in all the studied years. The mean cell number was the lowest in 2010, which was the effect of the high water discharge due to flooding at the end of May and beginning of June. High water discharge and water level of the river during the flood period led to an increase in the concentration of suspended matter, decrease of water transparency and diminishing of light conditions. These environmental factors limit phytoplankton growth and proliferation (Mihaljević et al. 2010). Decrease of phytoplankton biomass during flood was also observed in the River Danube (Mihaljević et al. 2010) and in Croatian floodplain rivers (Stanković et al. 2012). In the smaller, but also lowland river Narew below the Siemianówka Reservoir Grabowska (2012) noted a cell amount several times higher – from 6 to $1026.4 \times 10^6 \text{ cells cm}^{-3}$. In the River Wisła between Wyszogród and Toruń, characterized by a higher discharge than the Warta, the mean abundance of the phytoplankton amounted to $7.4 \times 10^6 \text{ ind. dm}^{-3}$ (Kentzer et al. 2010). In another Polish river – in the lower section of the Oder, Sługocki et al. (2014) noted approx. $200 \times 10^3 \text{ ind. dm}^{-3}$. Phytoplankton abundance in the River Morava (in the Czech Republic) ranged from 6.4 to $124.6 \text{ cells} \times 10^3 \text{ cm}^{-3}$ (Hašler et al. 2007).

Abundance of autotrophic picoplankton (APP) in the Warta was not high. In the Cybina – the tributary of the Warta, at sampling stations within the city of Poznań the total amount of picophytoplankton was several times higher and amounted to $0.35\text{--}2.9 \times 10^5 \text{ cells cm}^{-3}$ (Szeląg-Wasielewska et al. 2005). Strzeszyńskie Lake located in

Poznań was also characterized by higher abundance of APP and amounted to $0.1\text{--}8.1 \times 10^5 \text{ cells cm}^{-3}$ (Szeląg-Wasielewska 2004). The participation of APP as a component of the total phytoplankton biomass in the Warta was not significant. This confirms the observation of Hawley and Whitton (1991b), that relative contribution of APP to total phytoplankton biomass is the lowest when the trophic state is high. Autotrophic picoplankton is observed in waters of different trophic state, but studies show the sensitivity of APP to eutrophication, and also to water contamination, especially with heavy metals (Severn et al. 1989; Weisse 1991; Weisse and Mindl 2002). The environment of the eutrophic and polluted River Warta does not favor APP development.

Analysis of phytoplankton groups revealed the dominance of diatoms, green algae and cyanobacteria in the growing seasons of the 21st century, while studies conducted in the 20th century indicated the significance of diatoms and green algae. The first comprehensive research of the phytoplankton of the River Warta near Poznań was conducted by Hoppówna (1925) in 1922–1923. The results of this study showed the dominance of diatoms and green algae in abundance. Cyanobacteria was rarely or occasionally found in phytoplankton. Studies carried out in 1950–52 (Kniat and Kołaczowski 1963) and in 1953–60 (Kołaczowski and Preis 1962) confirmed high diversity of diatoms and green algae in the growing season.

Both diatoms and green algae are specific phytoplankton groups for large, slow-flowing, lowland rivers. Unicellular centric diatoms (e.g. *Stephanodiscus minutulus*), *Asterionella formosa*, *Aulacoseira granulata* and *Nitzschia acicularis* that occurred in high biomass in the Warta are common for large rivers (Reynolds and Descy 1996).

A high abundance of *Aulacoseira granulata* and *Nitzschia acicularis* was found in the River Warta many years before the present study – in 1953–1960 (Kołaczowski and Prais 1962). In the current century, besides the previously mentioned taxa, very high biomass of *Fragilaria crotonensis* has also been recorded. In summer of 2010 and 2016 this species formed water blooms. Its mass occurrence in the Warta confirmed its ability to grow intensively in eutrophic, turbulent waters and its tolerance to light limitation. A water bloom of this species was observed in the Rożnów Reservoir (Bucka and Wilk-Woźniak 2007). Its high biomass was also noted in the summer of 2010 in the section of the River Warta from the Jeziorsko Reservoir to the city of Poznań, in contrast to the station located above the reservoir. This suggested that the main reason for the mass occurrence *F. crotonensis* in the river was its mass development in the reservoir and good adaptation to the eutrophic river environment (Małdrecka 2015).

In the case of green algae, many taxa common for rivers were also noted in the River Warta, for instance from the genera: *Actinastrum*, *Coelastrum*, *Dictyosphaerium*, *Micractinium*, *Monoraphidium*, *Pediastrum*, *Desmodesmus/Scenedesmus* (Reynolds and Descy 1996). For comparison, Hoppówna (1925) in research conducted using net samples almost 100 years ago found a high abundance of the following taxa: *Scenedesmus quadricauda*, *Ankistrodesmus falcatus*, *A. hantzschii* var. *fluviatile*, *Schroederia setigera*. Kniat and Kołaczkowski (1963) recorded: *Scenedesmus*, *Pediastrum*, *Closterium*, *Chlorella*, *Zygnema*, whereas Kołaczkowski and Preis (1962) found: *Scenedesmus quadricauda*, *Pediastrum boryanum*, *Dictyosphaerium ehrenbergii*, *A. hantzschii*, *S. acuminatus*, *P. duplex*. The results of the research mentioned above show the similarity of the dominant green alga taxa over the period of approximately one century.

In 2003, 2009 and 2010, a cyanobacterial water bloom was created by *Aphanizomenon flos-aquae* – a species typical of eutrophic waters. Its occurrence has been described in many Polish dam reservoirs: the Goczałkowice Reservoir (Bucka 1989; Bucka and Wilk-Woźniak 2007), the Rożnów Reservoir (Bucka 1986; Bucka and Wilk-Woźniak 2007), the Sulejów Reservoir (Palus et al. 2007), the Zemborzyce Reservoir (Sierosławska et al. 2010), and other Polish lakes and reservoirs (Kobos et al. 2013).

In the River Warta the bloom of *A. flos-aquae* (its biomass $>10 \text{ mg dm}^{-3}$) was observed in the second half of summer, when the water temperature was $>22^\circ\text{C}$ and $\text{pH} = 7.5\text{--}9.14$, which corresponded with its optimal value of these parameters given by Bucka and Wilk-Woźniak (2007) ($18\text{--}25^\circ\text{C}$ and $\text{pH} = 7.5\text{--}10$). This taxon is able to develop intensively under different environmental stress conditions e.g. nutrient limitation, but requires high insolation and good transparency of water (Burchardt 1998; Bucka and Wilk-Woźniak 2007). In the River Warta it was observed in fascicles flowing near the water surface.

Aphanizomenon flos-aquae was not mentioned in Hoppówna's research (1925). The algologist gave the following list of cyanobacteria: *Microcystis aeruginosa*, *Oscillatoria limnetica*, *O. tenuis*, *O. sancta*, *O. chalybea*, *Anabaena* spp. *Anabaena spiroides*, *Gomphosphaeria neageliana*, *Merismopedia tenuissima*, *Lyngbya limnetica*. It was not recorded by Kołaczkowski and Preis (1962). In the growing season near Saint Roch bridge they found only the following taxa: *Oscillatoria* spp., *O. limosa*, *O. chlorina*, *O. princeps*, *Gleocapsa* sp., *O. tenera*, *O. formosa*, *Merismopedia glauca*, *Anabaena affinis*, *M. flos-aquae*, *Phormidium* sp., *Spirulina* sp., *Chroococcaceae*. This species was also unrecorded by Kołaczkowski and Preis (1962). They identified the fol-

lowing taxa: *Oscillatoria* spp., *Gleocapsa* sp., *M. glauca*, *Phormidium* sp., *M. flos-aquae*, *Chroococcaceae*. These data indicate the very rare occurrence or even absence of this taxon in the River Warta in the past century.

A high biomass of *Aphanizomenon flos-aquae* was observed in the River Warta in Poznań in the end of July 2005 (Szelaż-Wasielewska et al. 2009). A water bloom of this species was noted in the Warta-Gopło channel in late summer 2005 (Napiórkowska-Krzebietke 2014). It was also recorded in the section of the Warta from the Jeziorsko Reservoir to the city of Poznań in the late summer in 2009 and 2010 (Mądrecka 2015). This was a result of its mass development in the reservoir and it could indicate the very distinct influence of the Jeziorsko on the taxonomical structure and biomass of phytoplankton in the river below the dam. The impact of the Jeziorsko Reservoir on phytoplankton of the River Warta was studied at the end of the 20th century. It was expressed as an increase of taxonomical diversity and abundance of phytoplankton in the river and as changes in the phytoplankton biomass dynamic. The first water bloom of *A. flos-aquae* in the Jeziorsko Reservoir was observed in 1994. Its amount was approximately $124 \times 10^3 \text{ ind. cm}^{-3}$ (approx. 99% of the total phytoplankton abundance) (Galicka and Lesiak 1996a, 1996b; Galicka and Kruk 1999).

In 2016 *Woronichinia naegeliana* developed intensively in the river and was the major dominant species. This taxon is known to be specific for a wide range of water trophic, but its mass occurrence has been recorded in meso- and eutrophic waters – like those of the Warta. It is found in blooms with other cyanobacteria e.g. *A. flos-aquae* and *Microcystis aeruginosa*. Its monoculture is not frequently observed (Wilk-Woźniak et al. 2003). This cyanobacteria is not a very common component of the phytoplankton of Polish lakes and dam reservoirs. It has been observed in 41 out of 238 examined water bodies in Poland e.g. in lakes: Jarosławieckie, Bnińskie, Karczemne (Kobos et al. 2013). It is regularly noted in the Dobczyce Reservoir (Bucka and Wilk-Woźniak 2007). It was also observed in the Siemianówka Reservoir (Grabowska and Pawlik-Skowrońska 2008). In the River Warta it was found about one hundred years ago by Hoppówna (1925).

Conclusion

The results presented in this work conducted in 2003, 2009, 2010 and 2016 and data obtained from published and unpublished research of the phytoplankton of the River Warta indicate significant changes in its taxonomical structure and biomass during the last one hundred years and show the high likelihood of further modification in the future. Although some difficulties

were encountered in comparing the results of studies undertaken over a long period, it is possible to draw some general conclusions.

Phytoplankton in the past century was characterized by high taxonomical diversity of diatoms and green algae and its domination in phytoplankton abundance. On the other hand, in the present century, besides these two groups, the mass occurrence of cyanobacteria has been observed. Some of the bloom-forming taxa recorded in the River Warta are specific to rivers. They are colonial green algae: *Coelastrum microporum*, *Microcystis pusillum* and unicellular centric diatoms: *Stephanodiscus*, *Cyclotella*, *Thalassiosira*, *Actinocyclus* and the colonial diatom – *Aulacoseira granulata*. Additionally, some species more characteristic of dam reservoirs and lakes occurred in high biomass and created water blooms: *Fragilaria crotonensis*, *Aphanizomenon flos-aquae* and *Woronichinia naegelianiana*. This phenomenon suggests the influence of the Jeziorsko Reservoir (located approx. 239 km of river flow above the city of Poznań) on phytoplankton of the River Warta in Poznań, although it obviously does not exclude the impact of tributaries and oxbow lakes located in the catchment area and connected to the river.

It is highly recommended to continue the monitoring research of phytoplankton in Poznań and widen the range of studies within the catchment area of the River Warta to obtain more complex data concerning the origin of bloom-forming species and information about the environmental conditions that they prefer. This is the one of the aims of future research.

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