POLISH JOURNAL OF NATURAL SCIENCES
Abbrev.: Pol. J. Natur. Sc., Vol 29(2): 137–152, Y. 2014

THE EFFECT OF ENVIRONMENTAL FACTORS ON THE STRUCTURE OF PHYTOPLANKTON IN THE LOWER ODRA RIVER

Łukasz Sługocki, Iwona Goździk, Małgorzata Pilecka-Rapacz, Robert Czerniawski, Józef Domagała

Department of General Zoology
University of Szczecin in Szczecin

K e y w o r d s: phytoplankton, large river, cooling water, power plant.

A b s t r a c t

Comparison of phytoplankton composition from selected sites in the lower Odra River was done to determine whether the effects of heated water are strongest, from the considered environmental factors. Samples of phytoplankton were collected in April, July and October 2009–2011 at five sites along the lower section of the Odra River. The most pronounced differences between the phytoplankton at the sites were revealed in the phytoplankton abundance and they were related to the time of water retention, the washing out of plankters from slack waters, and the predation by molluscs and zooplankton. The strongest correlations were found between the phytoplankton abundance, the content of inorganic nutrients and temperature. Taxonomic composition of phytoplankton at all sites in the same months was similar. Cooling water from the power plant seems to accelerate eutrophication in the discharge but has no significant impact on the phytoplankton composition downstream in the Odra River.

WPŁYW CZYNNIKÓW ŚRODOWISKOWYCH NA STRUKTURY FITOPLANKTONU W DOLNEJ ODRZE

Łukasz Sługocki, Iwona Goździk, Małgorzata Pilecka-Rapacz, Robert Czerniawski, Józef Domagała

Katedra Zoologii Ogólnej
Uniwersytet Szczeciński w Szczecinie

S ł o w a k l u c z o w e: fitoplankton, duże rzeki, wody pochłodnicze, elektrownia.

Address: Łukasz Sługocki, University of Szczecin, ul. Felczaka 3c, 71-412 Szczecin, Poland, phone: +48 91 444 15 79, e-mail: lukasz.slugocki@univ.szczecin.pl

Abstrakt

Porównano skład fitoplanktonu z wybranych stanowisk dolnej Odry w celu określenia, który spośród badanych czynników środowiskowych ma najsilniejszy wpływ na kształtowanie owych struktur. Próby fitoplanktonu pobrano w kwietniu, lipcu i październiku w latach 2009–2011 na pięciu stanowiskach w dolnym odcinku Odry. Kompozycja taksonomiczna fitoplanktonu na wszystkich stanowiskach była podobna. Największe różnice w strukturach fitoplanktonu na poszczególnych stanowiskach dotyczyły jego liczebności. Było to związane z czasem retencji wody, wymywaniem fitoplanktonu z zastoisk oraz wyjadaniem tych organizmów przez mięczaki i zooplankton. Najsilniejsze korelacje zaobserwowano między liczebnością fitoplanktonu a zawartością nieorganicznych składników odżywczych i temperatury. Wody podgrzane z elektrowni wydają się przyspieszać proces eutrofizacji w kanale zrzutowym. Nie zaobserwowano jednakże istotnego wpływu podwyższonej temperatury wody na skład fitoplanktonu na stanowiskach zlokalizowanych poniżej ujścia kanału niosącego wody podgrzane.

Introduction

In lower sections of large rivers, the retention time can be long enough for plankton colonisation and reproduction (ALLAN 1998). Besides the hydrological conditions such as, time of retention and discharge, chemical (inorganic nutrients), physical (temperature, conductivity) and biotic (grazing, competition) are also important conditions for the growth of plankton structures (BASU and PICK 1997, MOSS et al. 1989, REYNOLDS 1988). With regards to plankton supply, of great significance is the presence of ponds, oxbow lakes or dam reservoirs permanently or periodically connected with the rivers (DEMBOWSKA 2009). The phytoplankton washed out from these water reservoirs into the rivers is often essential for development of the river phytoplankton (ALLAN 1998). The changes in phytoplankton composition also depends on the season and environmental conditions in a given different sections of that river (TAVERNINI et al. 2011), which offers specific conditions for the development of phytoplankton.

Because of the above described significant diversity in the sites, the lower section of the Odra River has been found suitable for study. It is characterised by many interconnected sections, offering different morphological and biological conditions, despite being in relatively close distance. We expect that phytoplankton assemblages at various sites would be different enough to form different communities. Moreover, exploring the forces responsible for those differences would be valuable in understanding the ecological dynamics in rivers.

A diversity of environmental conditions of the lower Odra sections, could relate to the anthropogenic activity, including the discharge of cooling water from a power plant. The effect of cooling water discharge on phytoplankton has been studied by many authors (JORDAN et al. 1983, ŁABĘCKA et al. 2005, POORNIMA et al. 2006, RAYMOND and RAYMOND 1969, TYSZKA-MACKIEWICZ

1983, ZARGAR and GHOSH 2006). The factors identified by most of them, as being responsible for changes in the phytoplankton composition include: mechanical stress, the lethal effect of temperature, the influence of chemical agents (used for conservation of cooling systems in a power plant) and predation by filter feeders. Although the effect of the temperature on phytoplankton has often been studied, the results are rather ambiguous. Reduced levels of phytoplankton production have been observed at the cooling water temperatures of 25°C [Lewis Creek Reservoir, Texas, (WELCH and WARD 1978)], 30°C [York River, Virginia, (WARINNER and BREHMER 1966); Lake Erie and Ontario, (CRIPPEN et al. 1978); mid-Atlantic power plants, (SMITH et al. 1974)], 37.5°C [Nanticoke Estuary, Maryland, (FLEMER and SHERK 1977)]. In Poland, the influence of cooling water on phytoplankton has been best recognised for the Power Plant Pątnów-Adamów-Konin (SOCHA and HUTOROWICZ 2009). However, these authors' studies concerned mainly limnic reservoirs. In general, there is not much literature from the central Europe region that pertains to the power plant effluent discharge and its effects. It would be practical for the specific remedial action.

According to DODDS (2006), phosphorus and nitrogen are the most important nutrients regulating the autotrophic state in running waters and their presence is positively correlated to gross primary production in the streams. The insufficient information on the influence of inorganic nutrients in the lower sections of rivers, such as the Odra River, has prompted this attempt to identify the factors influencing the phytoplankton growth.

Comparison of phytoplankton composition from selected sites in the lower Odra River was done to determine whether the effects of heated water are strongest, from the considered environmental factors. Realisation of the study required the following steps:

a) determination of abundance, similarity in qualitative and taxonomic composition of phytoplankton in the interconnected sections of the river;

b) determination of the influence of physico-chemical factors on the communities of river phytoplankton;

c) determination of the effect of cooling water on the phytoplankton composition in the main bed of the Odra River.

Methods

The Odra River is one of the major Central European lowland rivers (854 kilometres) and the second longest river in Poland. The lower Odra River is still classified as eutrophic although the status of its water has been improving (*Raport o stanie środowiska*... 2004). The samples were collected at five different sites along the lower section of Odra River (Figure 1). The sites were selected taking into account conditions such as depth, width and the coverage of macrophytes. Site 1: the Odra River is 200 m wide, 10 m depth, before division, its bed is regular with bays overgrown by rushes; site 2: the West Odra River is 100 m wide, 7 m depth, upstream to this site, there is a weir regulating the water levels that form a reservoir; site 3: the point of discharge of the cooling water, from the power plant channel is 35 m wide, 4 m depth; site 4: the East Odra River, downstream of site 3, the river is about 175 m wide, 12 m depth, with a regular bed, and near the banks there is a narrow band of rushes; site 5: the Odyniec Channel joining the West and East sections of the Odra River, the banks have wide bands grown with rushes, the bottom is grown with macrophytes, the width of the channel at this site is close to 150 m and depth to 5 m, in which the rate of water flow is the lowest.

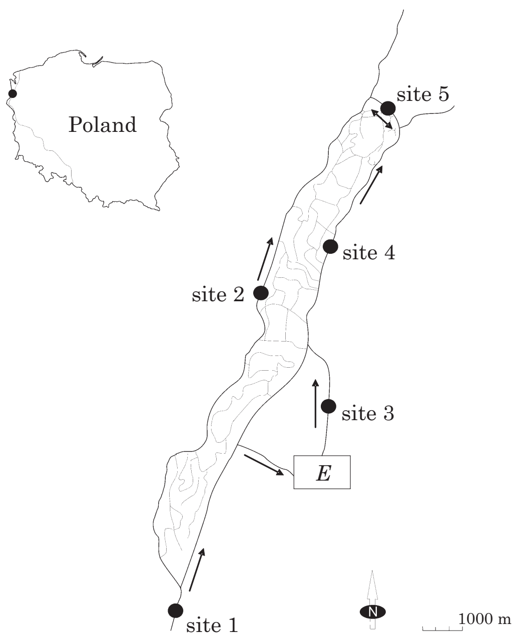


Fig. 1. The Odra River (study area) with sites. Site 1 – The Odra River before division, site 2 – The West Odra River, site 3 – The point of discharge of the cooling water, site 4 – The East Odra River, site 5 – The Odyniec Channel (joining the West and East sections of the Odra River), *E* – power plant, arrows – river flow

Samples of phytoplankton were collected in the months of April, July and October in the years 2009–2011. Each sample was taken just below the surface to fill the 1L containers. The samples were preserved in a 4% solution of formaldehyde. Phytoplankton subsample counting was made in 2 mL

Sedgewick-Rafter chambers. Identification was performed under a Nikon Eclipse 50i microscope. Identification of phytoplankton was made using taxonomic keys by STARMACH (1989), BUCKA and WILK-WOŹNIAK (2007), BURCHARD et al. (2010) to the lowest possible taxonomic unit. Enumerate algal forms were counted as one for each colony, filament, diatom cell (regardless if colonial or filamentous).

Temperature, pH, conductivity and dissolved oxygen content were measured by a CX-401 meter made by Elmetron. The contents of nitrites, nitrates, ammonium nitrogen, total nitrogen, total phosphorus and orthophosphates were measured by a Hach Lange DR-850 photometer. The mean values of the environmental variables of the seasons in 2009–2011 are given in Table 1.

Table 1

Mean values of physico-chemical variables at sites examined of the lower Odra in 2009–2011

	Temp. [°C]	pH	O_2 [mg dm^{-3}]	Cond. [µS cm^{-1}]	N-NH_3 [mg dm^{-3}]	N-NO_3 [mg dm^{-3}]	N-NO_2 [mg dm^{-3}]	P-PO_4 [mg dm^{-3}]	TN [mg dm^{-3}]	TP [mg dm^{-3}]
Site 1	16.0	8.35	8.03	629.1	0.12	0.7	0.011	0.20	1.9	0.46
Site 2	16.5	8.17	7.44	669.5	0.18	0.9	0.013	0.20	2.1	0.48
Site 3	22.3	8.27	7.33	744.6	0.15	0.9	0.012	0.21	2.0	0.50
Site 4	16.8	8.30	7.50	660.9	0.14	0.8	0.010	0.18	2.1	0.42
Site 5	16.7	8,46	8.68	651.4	0.18	0.8	0.019	0.18	2.0	0.46

Temp. – temperature, cond. – conductivity, N-NH_3 – ammoniacal nitrogen, N-NO_3 – nitrate nitrogen, N-NO_2 – nitrite nitrogen, P-PO_4 – orthophosphate, TN – total nitrogen, TP – total phosphorus

The Sørensen similarity index was applied to compare phytoplankton at all sites, using MVSP 3.21 software. The statistical analysis was used to evaluate the coefficients differences in phytoplankton at the sites, simple correlations and multiple regressions were tested with Statistica 10 software. The significance of differences in the number of taxa and abundance of phytoplankton was tested by the U Mann Whitney test. Relationships between the environmental variables and phytoplankton abundance were tested by the Pearson correlation test. Identification of the best predictors of phytoplankton abundance was performed by employing multiple stepwise regressions. The percentage of variation explained by the pattern was based on R^2. Interpretation of the influence of environmental variables on phytoplankton abundance was made on the basis of canonical correspondence analysis (CCA) and was performed using Vegan 1.15.1 (OKSANEN 2009).

Results

The total number of taxa identified at all sites throughout the whole period of study was 61, including 29 Chlorophyta, 17 Bacillariophyceae, 7 Cyanoprokaryota, 4 Euglenophyta and 2 Chrysophyceae. A general tendency was that with increasing distance between the sites the taxonomic similarity decreased, but the differences were minor. Five Bacilliariophyceae taxa: *Aulacoseira* sp., Centrales non-det, *Fragilaria* sp., *Melosira sp.*, *Synedra* sp. were characterised by high frequency (80–100%) at all sites (Table 2). Among

Table 2

Taxonomic composition of phytoplankton at sites examined of the lower Odra River in 2009–2011

Specification	Site 1	Site 2	Site 3	Site 4	Site 5	Specification	Site 1	Site 2	Site 3	Site 4	Site 5
Cyanoprokaryota						**Chlorophyta**					
Chroococcus sp.	+	+	+	+	+	*Actinastrum* sp.	+	MF	+	MF	+
Gomphosphaeria sp.	+	+	+		+	*Ankistrodesmus* sp.	+				
Merismopedia sp.	+	MF	+	+	+	*Ankyra* sp.	+	+	+	+	+
Microcystis sp.	MF	MF	MF	MF	MF	*Closterium* sp.	MF	MF	HF	+	+
Oscillatoria sp.	+	+	+	+	+	*Coelastrum* sp.	+	MF	+	+	+
Snowella sp.	+	+	+	+		*Crucigenia* sp.	+	+	+	+	+
Woronichinia sp.		+				*Desmodesmus* sp.	+	MF	MF	HF	MF
Euglenophyta						*Dictyosphaerium* sp.	+	MF	MF	MF	MF
Astasia sp.				+		*Eutetramorus* sp.	+	+	+	+	+
Euglena sp.		+	+	+		*Golenkinia* sp.					+
Phacus sp.	+	+		+	+	*Gonatozygon* sp.	+	+	+		
Trachelomonas sp.	+	+	+	+	+	*Kirchneriella* sp.	+	+			+
Dinophyceae						*Lagerheimia* sp.	+	+		+	+
Ceratium sp.	+	+	+		+	*Micractinium* sp.	+	+	+	+	+
Peridinium sp.	+			+	+	*Monoraphidium* sp.	+	+	+	+	+
Bacillariophyceae						*Oocystis* sp.	MF	MF	MF	MF	MF
Amphora sp.	+	+	+	+	+	*Pandorina* sp.	MF	+	+	MF	MF
Asterionella sp.	+	MF	MF	MF	+	*Pediastrum* sp.	MF	HF	HF	HF	HF
Aulacoseira sp.	HF	HF	HF	HF	HF	*Planktosphaeria* sp.				+	
Caloneis sp.	+	+	+	+	+	*Pteromonas* sp.	+				
Centrales non-det	HF	HF	HF	HF	HF	*Scenedesmus* sp.	HF	HF	HF	HF	HF
Cymatopleura sp.	MF	MF	MF	+	+	*Schroederia* sp.					
Cymbella sp.	+	+	+	+	+	*Selenastrum* sp.	+		+	+	+
Fragilaria sp.	HF	HF	HF	HF	HF	*Spirogyra* sp.			+		
Gomphonema sp.	+	+	+	+	+	*Staurastrum* sp.	+	+	MF	MF	MF
Melosira sp.	HF	HF	HF	HF	HF	*Stichococcus* sp.				+	
Navicula sp.	+	MF	+	MF	+	*Tetraedron* sp.	+				
Nitzschia sp.	+	+	+	+	+	*Tetrastrum* sp.		+		+	+
Pennales-non-det	+	+	+	+	+	*Ulothrix* sp.	+	+		+	+
Pinnularia sp.	+	+	+	+		**Chrysophyceae**					
Pleurosigma sp.	+	+	+	+	+	*Dinobryon* sp.	+			+	+
Surirella sp.	+	+	+	+	+	*Uroglena* sp.				+	
Synedra sp.	HF	HF	HF	HF	MF						

HF – highest frequency (80–100%), MF – intermediate frequency (60–80%). Frequency is the number of occurrences of taxa at sites according to all study periods.

Chlorophyta, one taxon (*Scenedesmus* sp.) showed high frequency and two others (Oocystis sp., Pediastrum sp.) showed intermediate frequency (60–80%). One taxon from Cyanoprokaryota (*Microcystis* sp.) showed intermediate frequency at all sites. The taxonomic similarity between all sites varied from 0.71 to 0.79 (Table 3).

Table 3

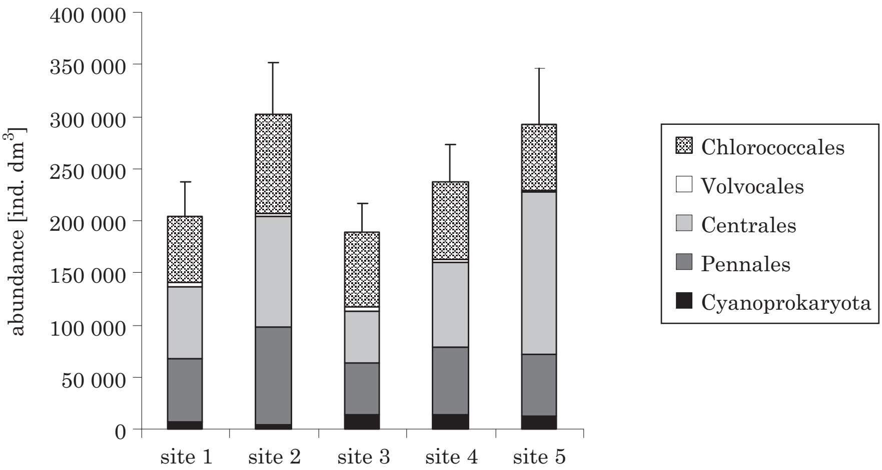
Variation of mean taxonomic Sørensen's similarity Index of phytoplankton, between examined sites of the lower Odra River in 2009–2011

Site	1	2	3	4
2	0.76	–	–	–
3	0.74	0.79	–	–
4	0.73	0.75	0.73	–
5	0.72	0.72	0.71	0.78

The taxonomic composition of phytoplankton was similar and no significant differences in the number of taxa at all sites were noted ($P > 0.05$) – Table 2. The highest numbers of taxa were found in the samples from the West Odra River, while the lowest – from the cooling channel. The highest number of taxa represented Chlorophyta and Bacillariophyceae. Chlorophytes were represented on average by 46% of all taxa at all sites, 42% of this number belonged to Chlorococcales, and only 4% to Volvocales. Bacillariophyceae were represented on average by 41% of all taxa noted at all sites, of which 28% belonged to Pennales and 13% to Centrales. Cyanoprokaryota were represented on average by 8% of all taxa at all sites, while the other groups of phytoplankton made about 1% of all taxa.

Similarly as for the number of taxa, no statistically significant differences in abundance of particular groups of phytoplankton were found between the sites ($P > 0.05$); although in the water of the cooling channel (site 3), its abundance was lower than at the other sites (Figure 2). The highest average abundance of phytoplankton was noted at the West Odra River (site 2) and the Odyniec Channel (site 5), while the lowest at the cooling channel (site 1). Relatively low phytoplankton abundance was also noted above the fork of the river (site 1) and in the East Odra River (site 4).

Among all groups of phytoplankton the most abundantly represented were Bacillariophyceae, consisting of Centrales and Pennales. Centrales on average were found in the highest number at site 5 (52.7%) and in the lowest number at site 3 (26.7%). Pennales on average were the most abundant at site 2 (30.6%), while the least at site 5 (20.6%). Abundant were also Chlorophyta, from which Chlorococcales on average were the most abundant at site 3 (37.7%), while the least at site 5 (21.5%), and Volvocales were the most at site 3 (2.1%) and the



Groups which have an abundance of less than 1500 ind. dm^{-3} were not included
Fig. 2. Mean + SD abundance ind. dm^{-3} of Chlorococcales, Volvocales, Centrales, Pennales, and Cyanoprokaryota at sites examined of the lower Odra River

least at site 5 (0.5%). In the phytoplankton the contribution of Cyanoprokaryota varied from 1.5% at site 2 to 7.6% at site 3 of phytoplankton abundance. The contribution of the other groups was less than 1%.
Pearson coefficient calculations indicated many correlations between abiotic factors (Table 1) and phytoplankton groups. Particularly significant were the correlations between temperature and the abundance of Centrales, Volvocales, Chlorococcales ($P < 0.05$) – Table 4.

A significant negative correlation was found between the abundance of Cyanoprokaryota and the dissolved oxygen content ($P < 0.05$). Moreover, a correlation between the conductivity and the abundance of Bacillariophyceae

Table 4
Significant Pearson's correlations between environmental variables and abundance of phytoplankton

Variable	Temp.	O_2	Cond.	N-NH_3	N-NO_3	N-NO_2	P-PO_4	NTOT	PTOT
Cyanoprokaryota	–	-0.415**	–	–	–	–	–	–	0.678***
Euglenophyta	–	–	–	–	–	–	–	-0.309*	–
Dinophyceae	–	0.327*	–	–	–	–	–	–	–
Pennales	–	–	-0.304*	-0.311*	0.530***	–	–	0.447**	-0.323*
Centrales	0.453**	–	0.338*	–	-0.297*	0.328*	–	–	–
Volvocales	0.651***	–	–	–	–	–	0.538***	–	–
Chlorococcales	0.692***	–	0.593***	0.309*	-0.350*	–	0.351*	–	-0.382*

Temp. – temperature, cond. – conductivity, N-NH_3 – ammoniacal nitrogen, N-NO_3 – nitrate nitrogen, N-NO_2 – nitrite nitrogen, P-PO_4 – orthophosphate, NTOT – total nitrogen, PTOT – total phosphorus; Significance *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

(Pennales and Centrales) and Chlorococcales (P < 0.05) was noted. The correlation (P < 0.05) was also found among the abundance of green algae and total phosphorus, the abundance of Volvocales and orthophosphates, abundance of Pennales and nitrates.

The multiple stepwise regression showed that temperature, ammonium nitrogen contents, nitrates, nitrites, orthophosphates, total nitrogen and total phosphorus were statistically correlated with the abundance of individual taxonomic groups of phytoplankton (P < 0.05) – Table 5. From 24% to 68% of variation in abundance of particular taxonomic groups were explained by the analysis. The most significant predictors were: temperature correlated with abundance of Pennales and Volvocales (P < 0.05) and the content of total phosphorus correlated with the abundance of Cyanoprokaryota, Dinophyceae, Pennales and Chlorococcales (all P < 0.05).

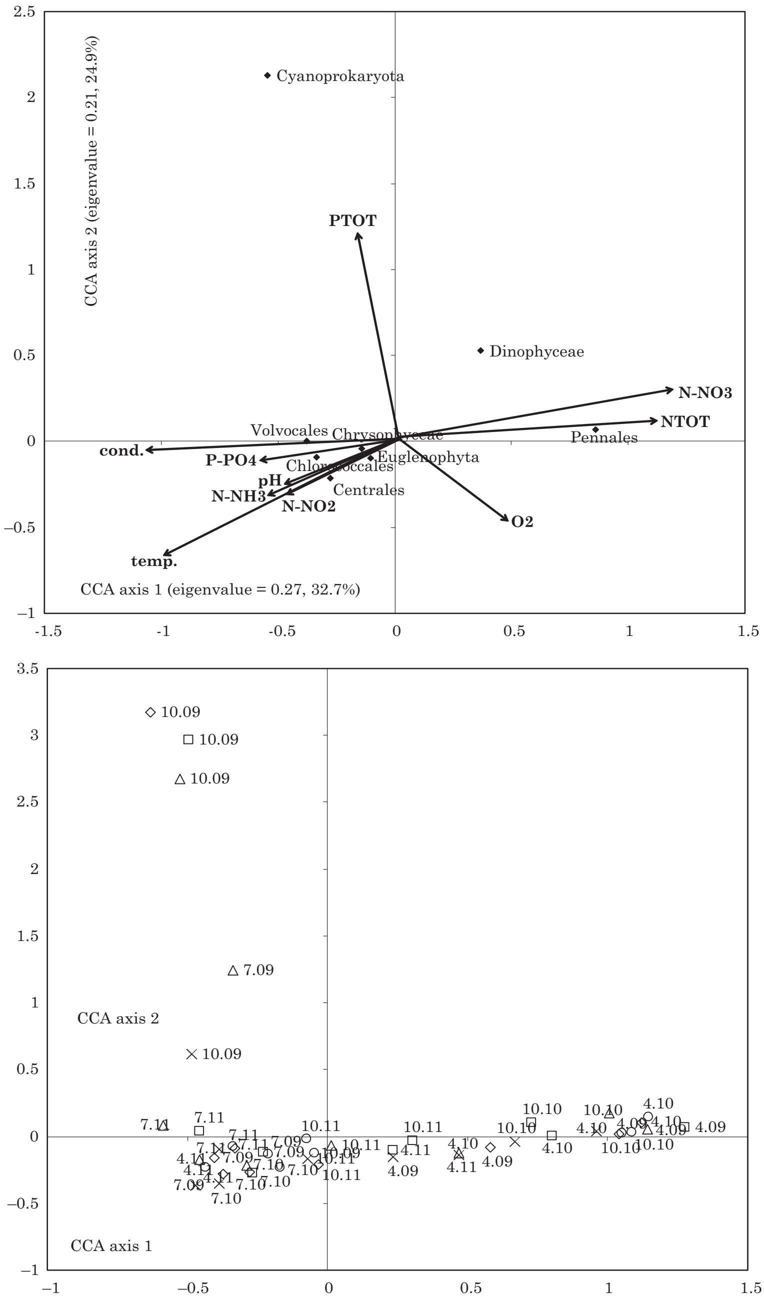
Table 5

Significances of the effects of environmental variables on the abundances of phytoplankton based on multiple regressions (stepwise procedure), with the following dependent variables: abundance of Cyanoprokaryota, Dinophyceae, Pennales, Centrales, Volvocales, and Chlorococcales

Variable	Temp.	$N\text{-}NH_3$	$N\text{-}NO_3$	$N\text{-}NO_2$	$P\text{-}PO_4$	NTOT	PTOT	R^2
Cyanoprokaryota	–	–	–	–	–	–	**	0.61
Dinophyceae	–	–	–	–	–	–	*	0.24
Pennales	**	*	*	–	–	–	***	0.65
Centrales	–	–	–	**	–	–	–	0.44
Volvocales	**	–	*	–	**	*	–	0.68
Chlorococcales	–	–	–	–	–	*	*	0.65

Independent variables taken for analysis were: Temp. – temperature, $N\text{-}NH_3$ – ammoniacal nitrogen, $N\text{-}NO_3$ – nitrate nitrogen, $N\text{-}NO_2$ – nitrite nitrogen, $P\text{-}PO_4$ – orthophosphate, NTOT – total nitrogen, PTOT – total phosphorus; significance *P < 0.05, **P < 0.01, ***P < 0.001

Canonical correspondence analysis CCA proved a pronounced effect of 10 environmental variables on the abundance of particular taxonomic groups, which explain 57.6% variation in the phytoplankton. The first axis was best correlated with conductivity, the content of total nitrogen, nitrates and temperature (Figure 3). While the second one was best correlated with the content of phosphorus and dissolved oxygen. The separation of results on the CCA axis into two groups according to the seasons indicated a significant influence of the season on the phytoplankton structure and abundance. The first group included the results obtained from April and October, while the second included the results collected from July.



Environmental variables: temp. – temperature, O_2 – dissolved oxygen, pH, Cond – conductivity, $N–NH_3$ – ammonium nitrogen, $N–NO_3$ – nitrate nitrogen, $N–NO_2$ – nitrite nitrogen, $P–PO_4$ – orthophosphate, NTOT – total nitrogen, PTOT – total phosphorus. Sites: 1 – square, 2 – circle, 3 – triangle, 4 – rhombus, 5 – cross. Values indicated as [month, year].

Fig. 3. CCA constrained ordination of taxa and samples from sites in the lower Odra River

Discussion

Taxonomical and quantitative diversity of phytoplankton

The highest number of taxa represented Bacillariophyceae and Chlorophyta, which has also been observed in other large rivers: in the Minho River in Portugal; the Po River in Italy; the Vistula River in Poland, the Moselle River in France (DESCY 1993, DODDS 2006, TAVERNINI at al. 2011, VASCONCELOS and CERQUEIRA 2001).

As follows from the similarity index values, phytoplankton at none of the sites was statistically significantly different in respect of taxonomical compositions. A tendency of decreasing taxonomic similarity with increasing distances between the sites was noted. This is particularly well pronounced with comparison of Site 1 to the other sites. WETZEL (2012) has reported the similarity indices declined with increasing distance between sampling sites. In our study, the actual distances between sites were smaller than those in the study of the above author, but also on a smaller scale this rule was found to hold true. Moreover, in our opinion, the similarity was related to the specific conditions at the sites. The lowest similarity in taxonomic composition was observed between the Odyniec Channel (site 5) and the other sites, which additionally can be attributed to the specific conditions in this channel where the retention time is much longer.

Specific environmental conditions in these channels could stimulate formation of many kinds of niches favoured by plankton species. The highest number of taxa and their relatively high abundance in the West Odra River (site 2) can be explained as a consequence of phytoplankton supply from the channels that join the main bed of the West Odra River and by their development in upstream-reservoirs. Such dam reservoirs change the hydrological and ecological conditions in flowing water and are valuable sources of plankton in rivers (LAIR 2006).

Relatively low phytoplankton abundance at site 1 and site 4 can be explained by the high rate of water flow as described by ALLAN (1998), as increased retention time is known to be favourable for phytoplankton growth.

Interesting results were obtained for the Odyniec Channel (site 5). Thus one expects that higher number of phytoplankton should be observed because as the water flow decreases, the number of euplankton species increases (DEMBOWSKA 2009). However, as our results indicate, the number of phytoplankton in this channel is similar, which can be explained by certain limiting factors such as bivalves filtration and the predatory activity of zooplankton. Furthermore, in this channel, high abundances of *Dreissena polymorpha* (DOMAGAŁA et al., 2004) and *Sinanodonta woodiana* (DOMAGAŁA et al. 2007) were observed. As CARACO et al. (1997) report, bivalves can significantly restrict the phytoplankton biomass by selective filtration. Moreover, according to GOŁDYN and KOWALCZEWSKA-MADURA (2008), grazing by zooplankton is also an important factor affecting the structure of phytoplankton communities. CZERNIAWSKI et al. (2013) observed in the same time and in the same sites as we sampled the phytoplankton, a high number of zooplankters, in particular crustacean filter feeders reported in the Odyniec Channel (site 5). It seems that although the hydrological conditions were favourable, the phytoplankton composition and abundance in the Odyniec Channel (site 5) were probably determined by the biological conditions.

Impact of physico-chemical variables on phytoplankton abundance

Eutrophic rivers carry a high concentration of nutrients needed for phytoplankton growth (TAVERNINI et al. 2011). However, as found by REYNOLDS (1994) and as indicated by the results of present study, there is a positive correlation between the content of inorganic nutrients and the abundance of phytoplankton. This indicates that the content of nutrients has proved to be a limiting factor for phytoplankton growth. The correlations between groups of phytoplankton and inorganic nutrients seem to be caused by two factors: seasonal changes in the content of phosphorus and nitrogen (related to run-off from the fields) and different hydrological conditions at the studied sites. Hitherto hydrological variables were not measured by us, but according to literature these variables are the main factors that affect the plankton development in rivers (ALLAN 1998).

The content of both N and P (in organic and inorganic forms) can be important determinants of autotrophic and heterotrophic activity in rivers and streams as established by DODDS (2006). A positive correlation was found between the total phosphorus content and the abundance of Cyanoprokaryota, which was the most significant in the cooling channel (site 3), where elevated temperature accelerated eutrophication which was unambiguous in the decreasing of dissolved oxygen concentration and favoured the growth of Cyanoprokaryota. Correlations can be also found among the abundance of each Cyanoprokaryota, Dinophyceae, Pennales, Centrales, Volvocales, Chlorococcales and nutrients, which supports the thesis (TAVERNINI 2011) about the positive influence of nitrogen and phosphorus on the phytoplankton composition.

Water discharge itself produces changes in the physical and chemical condition, thus affecting phytoplankton assemblages (DESCY 1993). This can be seen in low-gradient rivers with long retention times. As indicated in

(Reynolds 1994), the micro-algal abundance is inversely correlated with the discharge rate and turbidity, and positively correlated with the content of nutrients. We have also observed such relationships; however, the effect of discharge rate and turbidity must be further investigated. The results of CCA showed that the factors which explain the differences in the phytoplankton abundance and composition at the sites studied with a rather high probability. The most important of these factors are the temperature and the content of nutrients, which is in full agreement with the results of correlation test and multiple stepwise regressions. Furthermore, the seasons also influence the content of nutrients, e.g. P and N. The separation of results obtained in April, July and October in CCA pattern indicates the most important impact on the phytoplankton composition and the abundance in the lower Odra River due to seasonal changes. Other authors have also reported more abundant structures of phytoplankton in summer months (Descy 1993, Gołdyn and Kowalczewska-Madura 2008).

Impact of cooling water

Many authors have been interested in the effect of cooling water from power plants on phytoplankton (Jordan et al. 1983, Martinez-Arroyo et al. 2000, Poornima 2006, Raymond and Raymond 1969, Tyszka-Mackiewicz 1983, Zargar and Ghosh 2006). It seems that such ecosystems are not homogenous and host many factors limiting phytoplankton development. Low phytoplankton abundance in cooling channels has been observed by many authors: Mulford (1974) Patuxent Estuary, Maryland; Goldman and Quinby (1979) Cape Cod and Montaup; Briand (1975) San Gabriel River, California. Although no statistically significant differences were noted in the mean abundances of phytoplankton between the studied sites, the lowest number of taxa and the lowest average phytoplankton abundance were noted in the cooling channel (site 3). It could be expected that probably slow water current in the cooling channel had a positive effect on phytoplankton growth, but there could be many factors restricting it, such as:

1) Mechanical stress (Langford 1990).

2) Predation by bivalve molluscs, (e.g. *Dreissena polymorpha, Corbicula fluminea* (Łabęcka et al. 2005) feeding on phytoplankton as discussed earlier (Caraco et al. 1997, Cohen et al. 1984).

3) And the lethal effect of elevated temperatures (Crippen et al. 1978, Flemer and Sherk 1977, Warinner and Brehmer 1966, Welch and Ward 1978). However, the effect of an elevated temperature seems difficult to explain as water temperatures reaching 30°C are observed in the cooling channel only

periodically in the summer. According to MARTINEZ-ARROYO et al. (2000) water temperatures above 30°C can lead to a decrease in the photosynthetic abilities in phytoplankton. On the basis of our results and those of other authors, it seems that the power plant cooling system restricts the abundance of phytoplankton, but has no significant effect on its taxonomic composition. Seasonal changes were crucial to the production of phytoplankton composition and the effects of heated water were minor.

Conclusion

The most pronounced differences were revealed in the phytoplankton abundance, which, according to the statements of cited authors, is probably related to the time of water retention, the washing out of plankters from slack water, predation by mollusks and zooplankton. Among the factors subjected to statistical analysis, the strongest correlation was between the phytoplankton abundance and inorganic nutrients, the next most important factor was the temperature. The effect of temperature seems to be related to seasonality temperature rather than to heated water from power plant. The phytoplankton in the cooling channel had a taxonomic structure similar to those at the other sites, but it was less abundant. The cooling water from the power plant seems to accelerate eutrophication in discharge but have no significant impact on phytoplankton composition downstream in the Odra River.

Translated by MARIA SPYCHALSKA

Accepted for print 1.07.2014

References

ALLAN D.J. 1998. *Ekologia wód płynacych.* PWN, Warszawa.

BASU B.K., PICK F.R. 1997. *Phytoplankton and zooplankton development in a lowland, temperate river.* J. Plankton Res., 19: 237–253.

BRIAND F.J.P. 1975. *Effects of power-plant cooling system on marine phytoplankton.* Mar. Biol., 33: 135–146.

BUCKA H., WILK-WOŹNIAK E. 2007. *Glony pro- i eukariotyczne zbiorowisk fitoplanktonu w zbiornikach wodnych Polski Południowej*. Instytut Ochrony Przyrody – PAN, Kraków, pp. 1–352.

BURCHARDT L. 2010. *Klucz do oznaczania gatunków fitoplanktonu jezior i rzek*. Biblioteka Pomocy Dydaktycznych. Bogucki Wydawnictwo Naukowe, Poznań.

CARACO N.F., COLE J.J., RAYMOND P.A., STRAYER D.L., PACE M.L., FINDLAY S.G., FISCHER D.T. 1997. *Zebra mussel invasion in a large, turbid river: phytoplankton response to increased grazing.* Ecology, 78(2): 588–602.

COHEN R.R.H., DRESLER P.V., PHILLIPS E.J.P., CORY R.L. 1984. *The effect of the Asiatic clam, Corbicula fluminea, on phytoplankton of the Potomac River.* Maryland, Limnol. Oceanogr., 29(1): 170–180.

CRIPPEN R.W., FANMY F.K., SEEPERSAD B., HAYTON A.M. 1978. *Impacts of tree types of power generating discharge system on entrained plankton.* Fourth National Workshop on Entrainment and Impingement, Ecologycal Analysts, Melville, N. Y., pp. 191–202.

CZERNIAWSKI R., PILECKA-RAPACZ M., DOMAGAŁA J. 2013. *Zooplankton communities of inter-connected sections of lower River Oder* (NW Poland). Cent. Europ. J. Biol., 8(1): 18–29.

DEMBOWSKA E. 2009. *Phytoplankton species diversity of the Lower Vistula from Wyszogród to Toruń.* Oceanological and Hydrobiological Studies, 38(4): 63–74.

DESCY J.P. 1993. *Ecology of the phytoplankton of the River Moselle: effects of disturbances on community structure and diversity.* Hydrobiologia, 249: 111–116.

DODDS W.K. 2006. *Eutrophication and trophic state in rivers and streams.* Limnol. Oceanogr., 51: 671–680.

DOMAGAŁA J., ŁABĘCKA A.M., MIGDALSKA B., PILECKA-RAPACZ M. 2007. *Colonisation of the channels of Międzyodrze (northwestern Poland) by Sinanodonta woodiana (Lea, 1834).* Pol. J. Natur. Sc., 22(4): 679–690.

DOMAGAŁA J., MIGDALSKA B., ŁABĘCKA A.M., PILECKA-RAPACZ M. 2004. *Anadonta woodiana (Lea, 1834) na Pomorzu Zachodnim*. Zeszyty Naukowe Uniwersytetu Szczecińskiego. Acta Biol., 10: 199–202.

FLEMER D., SHERK J. 1977. *Thermal effects of steam electric station operation on entrained phytoplankton.* Hydrobiologia, 55: 33–44.

GOLDMAN J.C., QUINBY H.L. 1979. *Phytoplankton recovery after power plant entrainment*. J. Wat. Pollut. Cont. Fed., 51: 1816–1823.

GOŁDYN R., KOWALCZEWSKA-MADURA K. 2008. *Interactions between phytoplankton and zooplankton in the hypertrophic Swarzędzkie Lake in western Poland*, J. Plankton Res., 30: 33–42.

JORDAN R. A., MARTIN P.G., SUTTON C.E. 1983. *Selective effects of phytoplankton entrainment at the Surry Power Plant, James River, Virginia.* Hydrobiologia, 106: 253–261.

LAIR N. 2006. *A review of regulation mechanisms of metazoan plankton in riverine ecosystem: aquatic habitat versus biota.* River Res. Appl., 22: 567–593.

LANGFORD T.E.L. 1990. *Ecological effects of thermal discharges.* Elsevier Applied Sciences Publishers Ltd, England.

ŁABĘCKA A.M., DOMAGAŁA J., PILECKA-RAPACZ M. 2005. *First record of Corbicula fluminalis (O.F. Müller, 1774) in Poland*. Folia Malacologica, 13(1): 25–27.

MARTINEZ-ARROYO A., ABUNDES S., GONZALEZ M.E., ROSAS I. 2000. *On the influence of hot-water discharges on phytoplankton communities from a costal zone of the gulf of Mexico.* Water Air Soil Poll., 119: 209–230.

MOSS B., BOOKER I., BALLS H., MANSON K. 1989. *Phytoplankton distribution in a temperate floodplain lake and river system. Hydrology, nutrient sources and phytoplankton biomass*. J. Plankton Res., 11: 813–838.

MULFORD R.A. 1974. *Morgantown entrainment*. IV.: *Phytoplankton taxonomic studies*. [In:] L.D. *Jensen Second workshop on entrainment and intake screening*. Report 15. The Johns Hopkins University Department of Oceanography and Environmental Engineering, Baltimore, PP. 169–175.

OKSANEN J. 2009. *Multivariate analysis of ecological communities in R: vegan tutorial*. http://cc.oulu.fi/~jarioksa/opetus/metodi/vegantutor.pdf, pp. 42, access: 30.11.2012.

POORNIMA E.H., RAJADURAI M., RAO V.N.R., NARASIMHAN S.V., VENUGOPALAN V.P. 2006. *Use of coastal waters as condenser coolant in electric power plants. Impact on phytoplankton and primary productivity*, J. Therm. Biol., 31: 556–564.

Raport o stanie środowiska w województwie zachodniopomorskim w latach 2002–2003. Monitoring rzek. 2004, WIOŚ, pp. 157–169.

RAYMOND M.P., RAYMOND S.G. 1969. *Destruction of Phytoplankton in the Cooling Water Supply of a Steam Electric Station.* Chesapeake Science, 10: 165–171.

REYNOLDS C.S. 1994. *The long, the short and the stalled: on the attributes of phytoplankton selected by physical mixing in lakes and rivers*. Hydrobiologia, 289: 9–21.

REYNOLDS C.S. 1988. *Potamoplankton: paradigms, paradoxes and prognoses*. *Algae and the Aquatic Environment*. Biopress, Bristol, pp. 285–331.

SMITH R.A., BROOKS A.S., JENSEN L.D. 1974. *Effects of condenser entrainment on algal photosynthesis at Mid Atlantic power plants, Second Workshop on Entrainment and Intake Screening*, The Johns Hopkins University Department of Oceanography and Environmental Engineering, Baltimore, pp. 113–122.

SOCHA D., HUTOROWICZ A. 2009. *Changes in the quantitative relations of the phytoplankton in heated lakes.* Arch. Pol. Fish., 17: 239–251.

STARMACH K. 1989. *Plankton roślinny wód słodkich*. PWN, Warszawa-Kraków.
TAVERNINI S., PIEROBON E., VIAROLI P. 2011. *Physical factors and dissolved reactive silica affect phytoplankton community structure and dynamics in lowland eutrophic river (Po river, Italy).* Hydrobiologia, 669: 213–225.
TYSZKA-MACKIEWICZ J. 1983. *Bioseston i peryfiton rzeki Wisły na odcinku od Puław do Warszawy*. Prace Komisji Biologicznej PTPN, Warszawa-Poznań, 63: 114.
VASCONCELOS V.I., CERQUEIRA M. 2001. *Phytoplankton community of river Minho (international section).* Limnetica, 20(1): 135–141,
WARINNER J.E., BREHMER M.L. 1966. *The effects of thermal effluents on marine organisms*. Air Wat. Pollut, 10: 277–284.
WELCH M.O., WARD C.H. 1978. *Primary productivity: analysis of variance in a thermally enriched aquatic system. Energy and Environmental Stress in Aquatic Systems*. DOE Symp. Ser. 48. U.S. Dept. Energy Tech. Inf. Center., pp. 381–391.
WETZEL C.E., BICUDO D.C., ECTOR L., LOBO E.A., SOININEN J., LANDEIRO V.L., BINI L.M. 2012. *Distance Decay of Similarity in Neotropical Diatom Communities.* National Institute of Water & Atmospheric Research, New Zealand, 7: 9.
ZARGAR S., GHOSH T.K. 2006. *Influence of cooling water discharges from Kaiga nuclear power plant on selected indices applied to plankton population of Kadra reservoir.* J. Environ. Biol., 27(2): 191–198.