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ORIGINAL ARTICLE

A case study of the planktonic communities in two hydrologically different oxbow lakes, Vistula River, Central Poland

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ABSTRACT

*Floodplain lakes are important elements of landscapes with large rivers. In this study we compared planktonic communities of two oxbow lakes of the Vistula River. We investigated how the inflow of the river's water affected their physicochemical and biological conditions including water temperature, water transparency, oxygen concentration, and macrophyte coverage of the bottom. These parameters in turn affected plankton community. The average phytoplankton abundance in the isolated lake was over two times lower than in the lake connected to the river. Cryptophyta dominated in the phytoplankton community in the isolated lake and diatoms – in the lake supplied with water from the river. The average abundance of zooplankton in the isolated lake was more than twice as high as that in the lake which was connected to the river. The first lake proved to be more attractive for zooplankton due to its stable living conditions (similar to the conditions observed in ponds), higher temperature in summer, and nutrient availability due to the high abundance of small phytoplankton. The results of our research indicate that species composition, plankton abundance, and Chl-*a *concentration depended on whether there was water exchange between the particular lake and the Vistula River. Hydrological conditions shaped the relationships between the components of the biota.*

Key words: Cryptophyta, diatoms, floodplain lakes, hydrology, Rotifera, wetlands.

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INTRODUCTION

Floodplain lakes are important elements of landscapes with large rivers. However, improper management of natural resources leads to degradation and extinction of these ecosystems, which are known for high biodiversity and ecological value (Hillbricht-Ilkowska, 1999; Redford and Richter, 1999; Tockner *et al.* 2009).

Floodplain lakes play a significant role in a river system:

- They constitute a geochemical barrier (reducing the inflow of nutrients and contaminants to the river) (Lake and Bond, 2007; Dembowska and Napiórkowski, 2012).
- They provide shelter for animals after river floods (Meschiatti *et al.*, 2000; Paira and Drago, 2007)
- They constitute a habitat for aquatic animals (Junk *et al.*, 1989; Shiel *et al.*, 1998).

Oxbow lakes can be seen as places for smooth transition from flowing to stagnant waters (Baranyi *et al.*, 2002; Starmach *et al.*, 1976). According to Jezierska-Madziar (2005), oxbow lakes are formed in two ways: naturally and artificially (regulation of a riverbed). Natural oxbow lake are cut off from the main stem of the river. Because of their small surface and depth they easily undergo succession. During the process they are overgrown with water plants, become shallower, and finally disappear. Artificial oxbow lakes are formed by human hydrological activity. Lakes of this type are often connected to the river on one side. With the right level of water in the river, the connection offers a water exchange.

The significance of plankton in the ecosystems of floodplain lakes was described by Salbrechter (1998), Keckeis *et al.* (2003), Gumiri *et al.* (2005), Napiórkowski (2009), Obolewski (2011), and Dembowska *et al.* (2012). Anderson and Bonecker (2004) as well as Schöll (2009) point out that plankton communities in floodplain lakes are determined primarily by two things: i) whether they are connected or not to the river; and ii) whether water inflow causes any disturbances.

We assume that irregular inflows of water from the river destabilise conditions in oxbow lakes including water transparency and temperature and inhibit macrophyte growth. All these changes affect plankton community. We put forward a hypothesis that phytoplankton should be more abundant and diverse in the oxbow lake connected as compared to one isolated from a river. The inflow of the river's water into this lake inhibits the development of submerged vegetation and increases phytoplankton biomass. It also provides nutrients and intensifies nutrients' release from the bottom sediments of the lake (Hein *et al*., 2004; Kasten, 2003; Grabowska *et al.*, 2014).

Macrophytes in the lake isolated from the river can suppress phytoplankton development through allelopathic influence, shading water and the bottom, and competing for food (Scheffer, 1998). Numerous studies confirm a relationship between vascular vegetation and planktonic algae (Gross, 2003; Gross *et al*., 2007; Lau and Lane, 2002; Mulderij *et al*., 2007).

On the other hand, we expected that zooplanktonic community in the lake connected with the river should be less abundant and less diverse than in the isolated lake. Thomaz *et al*. (2007) noted that zooplankton diversity decreases due to the *homogenizing effect* in floodplain lakes, flooded by water from rivers. When the water is stagnant macrophyte biomass in the lake increases. Macrophytes offer perfect conditions for zooplankton. They provide shelter for zooplankton against planktivorous fish and invertebrate predators (Lauridsen *et al*., 1996). Moreover, zooplankton inhabiting macrophyte stands can feed on algae found between plant stems, periphyton, protozoans, bacteria and detritus (Kuczyńska-Kippen and Nagengast, 2006). Basu *et al.* (2000) examining the fluvial lakes of St Lawrence River, observed a 9-fold higher zooplankton biomass within dense macrophyte stands than in open water or sparsely vegetated areas.

In view of the absence of information on plankton in floodplain lakes, we evaluated the taxonomic composition and abundance of planktonic communities (phytoplankton and zooplankton) in two oxbow lakes associated with the Vistula River. One of the lakes is periodically connected with the river, and the second is totally isolated from the riverbed. Our specific objective was to determine the influence of the water from the Vistula River on these two habitats.

METHODS

Study area

With the length of 1068 km The Vistula River is the longest river in Poland and has the second largest (after Neva) catchment area of the Baltic Sea (194,000 km^2). The Vistula has all the characteristics of a lowland river over most of its course. In the 19th century, the river was regulated between 718 km and the mouth (1068 km). Despite human interference (changing the river's flow) and advancing degradation, the river and the valley represent an extremely valuable natural environment (Kentzer *et al.*, 2010).

The first floodplain terrace has a number of oxbow lakes which are the remains of the backwaters of the river and are periodically flooded (during major floods only). There are also artificial oxbow lakes in the river valley. The study was conducted on two different floodplain lakes, natural and artificial, the latter created after the flood embankments had been constructed during river regulation at the beginning of the 19th century (Makowski, 1998).

The studied lakes (Fig. 1) are situated in the valley of the Lower Vistula, within the city of Toruń, between 734 and 738 km of the river's course. Site 1 (53°01'N; 18°39'E) includes the floodplain lake of the Vistula River located on the 734th km of the river's course. It is a meandering part of the river, which is being overgrown by vegetation and which developed, as many others, due to the Vistula River regulation. It is a small water body without direct surface contact with the water of the Vistula River. In the floodplain lake, the following species of macrophytes occur: yellow pond-lily (*Nuphar lutea* (L.) Sm.), rigid hornwort (*Ceratophyllum demersum* L.), and star duckweed (*Lemna trisulca* L.). The morphometric characteristics of the oxbow lake are: a surface area of 2.5 ha maximum length of 220 m, maximum width of 40 m, and a maximum depth of 2.0 m. Site 2 (53°00'N; 18°33'E) includes the floodplain lake of the Vistula River, situated at the 738th km of the river's course. This oxbow lake developed as a result of the Vistula River regulation. It is relatively shallow, young, and usually connected to the Vistula River (with the average water level in the river). In the oxbow lake, the following species of

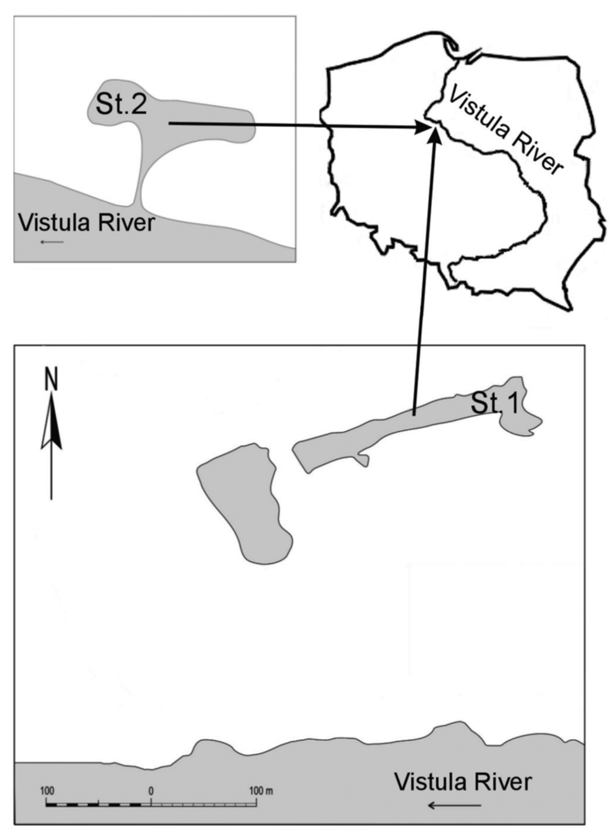

Fig. 1. Location of the sampling sites in floodplain lakes (Poland).

macrophytes occur: common hornwort (*Ceratophyllum demersum*), arrowhead (*Sagittaria sagittifolia* L.) which grows on the shores of the oxbow lake, but when the water level is very low it forms peculiar islands in the middle of the oxbow lake, Canadian waterweed (*Elodea canadiensis* Michx.), pondweed species (*Potamogeton* sp.), and water milfoil sp. (*Myriophyllum* sp.). The morphometric characteristics of the floodplain lake are: surface area 1.0 ha, maximum length 160 m, maximum width 100 m, degree of connection with the Vistula River from 0 to 30 m. The maximum depth depends on the water level in the river (from 60 to 160 cm).

The value of TP at summer in 2008 at the site 1 amounted 0.16 mg L^{-1} and 0.36 mg L^{-1} at site 2. The concentration of mineral forms of nitrogen and phosphorus amounted 0.134 mg L^{-1} ($N\text{-}NO_3$), 0.068 mg L^{-1} ($P\text{-}PO_4$) for site 1; and 0.208 mg L^{-1} ($N\text{-}NO_3$), 0.067 mg L^{-1} ($P\text{-}PO_4$) for site 2.

Sampling methodology

Water samples were collected twice a month between April and September, 2008. All phytoplankton and zooplankton samples were collected at a depth of ca. 0.5 m in the central part of every lake. Phytoplankton samples for species composition analyses were collected with a plankton net; 25 μm mesh size. Vertical and horizontal hauls were made. The samples were then preserved in 4% formaldehyde. For quantitative analyses, no concentrated water samples were collected and immediately fixed with 1% acidified Lugol's iodine (J in KJ). The abundance of algae was determined with the method of Utermöhl (1958) using an inverted microscope (MOD-2 PZO). The counting unit was the individual cell, filament or colony. The abundance is presented as the number of individuals per mililiter (N, ind. mL^{-1}). Zooplankton samples were collected with a 1 litre Patalas bucket. Water was filtered through a plankton net; mesh size 25 μm. In order to obtain one sample of zooplankton, 10 litres of water were filtered. All zooplankton samples were preserved in Lugol's solution (Nogrady *et al.*, 1993; Harris *et al.*, 2000). The identification of phyto- and zooplankton was performed with the use of a light microscope Nikon Alphaphot-2 as well as a Panasonic camera and MultiScan computer software for image analysis.

The taxonomical identification of algae was made according to Ettl, 1978, 1983; Hindák, 2008; Javornickỳ, 2003; Komárek and Anagnostidis, 2007, 2008; Komárek and Fott, 1983; Komárek and Komárkowa, 2006; Komárek and Zapomèlova, 2007, 2008; Krammer and Lange-Bertalot, 1986, 1988, 1991a, 1991b; Popovskỳ and Pfiester, 1990; Růžička, 1977; Starmach, 1968, 1974, 1983; Wołowski, 1998; and Wołowski and Hindák, 2005. For the identification of zooplankton the commonly available studies and keys were used (Einsle, 1996; Flössner, 1972; Kiefer, 1978; Nogrady *et al*., 1993; Radwan, 2004; Rybak and Błędzki, 2010; Smirnov, 1996).

The collection of samples was measured along with the physical and chemical parameters of water, such as: Secchi disk visibility (SD, m), temperature (WT, °C), oxygen concentration (DO, mg L^{-1}), saturation (DO sat., %), conductivity (EC, μS cm^{-1}), and pH. Measurements of physico-chemical parameters were performer by Multi 3430SET F WTW field probes. Every two weeks, the content of chlorophyll *a* (Chl-*a*, μg L^{-1}) was determined with the method of Nusch (1980). Data on the water level (WL, cm) and flow rate (Q, $m^3\ s^{-1}$) of the Vistula River in Toruń were obtained from the Meteorological and Hydrological Institute – the Regional Hydrological and Meteorological Station in Toruń, Poland.

Pearson's simple correlation (IBM, 2012) was applied to analyse the relationships between the total number of plankton and the environmental factors. A canonical correspondence analysis (CCA) was performed using MVSP 3.22 software to show the relations between plankton and physico-chemical parameters at investigated sites (Kovach, 2010).

RESULTS

Physical and chemical parameters

The average water level in the Vistula River at the time the samples were collected was 252 cm. The water level in the Vistula River remained at a rather average and low level (Fig. 2a). The highest WL in the Vistula River occurred in April (353 cm) and was almost 300 cm lower than the alarm status for Toruń (650 cm). When the Vistula WL dropped below 230 cm both stations were isolated. This was the situation from late June to late July and in late summer during the whole month of August. In the remaining period, Site 1 was isolated but Site 2 was connected to the main channel of the Vistula. The flow rate (Fig. 2a) of water in the Vistula River in Toruń during the study period, was lower than average and amounted to 750 $m^3\ s^{-1}$. The maximum Q (1208 $m^3\ s^{-1}$) was recorded in late April. The water level was strongly correlated with the flow rate in the Vistula River ($r=0.92$, $P<0.05$).

The average water temperature (Fig. 2b) during the six months, at Site 1, was 17.3°C and was lower by half a Celsius degree compared to the average temperature recorded at Site 2 (17.8°C). The highest temperature (22.9°C on June 10, 2008) and the lowest temperature (9.0°C on Apr 12, 2008) were recorded at Site 2. The average oxygen concentration in the waters of the Vistula oxbow lakes at Site 1 was 6.2 mg L^{-1}, (saturation, 62%), at Site 2 was 8.6 mg L^{-1} (saturation, 93%). The maximum value of this parameter, *i.e.* 14.6 mg L^{-1} (166% water saturation) was recorded at Site 2 (July 22). The minimum value, *i.e.* 1.6 mg L^{-1} (18% water saturation) was recorded at Site 1 on Aug 05

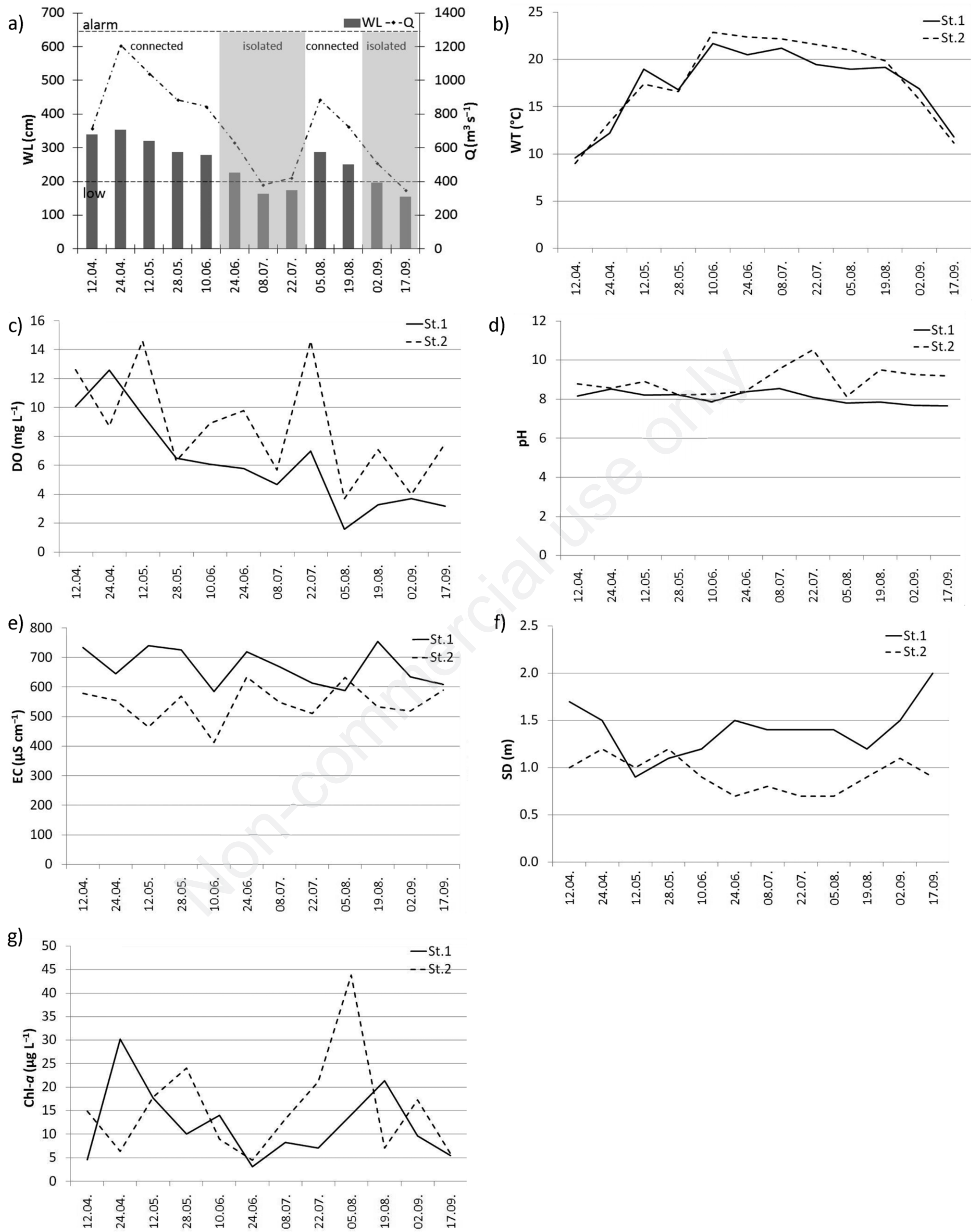

Fig. 2. Seasonal variation of the physic-chemical parameters: a) water level (WL, m) and flow rate (Q, $m^3 s^{-1}$), the shadowed background indicates the period of disconnection between st.2 and river; b) water temperature (WT, °C); c) oxygen concentration (DO, mg L^{-1}); d) pH; e) electrolytic conductivity (EC, µS cm^{-1}); f) Secchi disk visibility (SD, m); g) content of chlorophyll *a* (Chl-*a*, µg L^{-1}).

(Fig. 2c). Water reaction (Fig. 2d) in the oxbow lakes was alkaline (basic). The average pH value at Site 1 amounted to 8.0, whereas at Site 2 to 8.9. The highest value of this parameter, *i.e.* 10.53, was recorded at Site 2, whereas the lowest value of 7.65 was recorded at Site 1. The average value of EC (Fig. 2e) for Site 1 was 669 µS cm^{-1}, for Site 2 was 546 µS cm^{-1}. The maximum value of conductivity, *i.e.* 754 µS cm^{-1} was recorded at Site 1 (Sept 19), and the lowest value of 413 µS cm^{-1} was recorded at Site 2 (June 10). The mean Secchi depth (Fig. 2f) at Site 1 amounted to 1.4 m and ranged from 0.9 (May 11) to 1.7 (Apr 12). Whereas the average SD value at Site 2 came to 0.9 m and ranged from 0.7 m (June 24, July 22, Sept 05) to 1.2 m (Apr 24). The water transparency was significantly negatively correlated to the temperature at both sites ($r=-0.61$; $r=-0.62$). The average value of chlorophyll *a* (Fig. 2g) for Site 1 was 12.14 µg L^{-1}, for Site 2 – 15,42 µg L^{-1}. The maximum value of chlorophyll *a* 43.8 µg L^{-1} was recorded at Site 2 (Aug 5), and the lowest value of 3.1 µg L^{-1} was recorded at Site 1 (June 24). Tab. 1 summarizes the mean values and ranges of physico-chemical parameters in the two investigated sites.

Plankton

At Site 1, there were 109 taxa of phytoplankton recorded (Supplementary Tab. 1). The richest species groups were: diatoms, 39 taxa (36% of species composition); green algae 30 taxa (28%), Euglenophyta 12 taxa (11%), and Chrysophyceae 10 taxa (9%). Other algae phyla were represented by only a few species. At Site 1, sixty-nine forms and species of zooplankton were recorded: 54 taxa (78% of species composition) of Rotifera, 11 species (16%) of Cladocera, and 4 species (6%) of Copepoda.

At Site 2, 188 taxa of phytoplankton were recorded (Supplementary Tab. 1). The richest species groups were: diatoms, 100 (53% of species composition); green algae 59 taxa (31%), Euglenophyta 12 taxa (6%), and Cyanoprokaryota 10 taxa (5%). Other algae phyla were represented by only a few species. There were 58 forms and species of zooplankton: 49 taxa (85% of the species composition) of Rotifera, 7 species (12%) of Cladocera, and 2 species (3%) of Copepoda. At the studied sites, larval forms of copepodites and nauplii were recorded. All together, 41 species of zooplankton were recorded at both sites, 25 species were recorded only at Site 1, and 17 species were recorded only at Site 2 (Supplementary Tab. 2).

The average count of total phytoplankton (Fig. 3a) was over two times lower at Site 1 (1653 ind. mL^{-1}) compared to Site 2 (4168 ind. mL^{-1}). The mean abundance of total zooplankton (Fig. 3b) was nearly two times higher at Site 1 (3934 ind. L^{-1}) compared to Site 2 (1657 ind. L^{-1}). Cryptophyta dominated in phytoplankton at Site 1, constituting 60% of the total count (1081 ind. mL^{-1}), Chlorophyta made up 16% (292 ind. mL^{-1}), and Chrysophyceae 13% (240 ind. mL^{-1}). Rotifera dominated among zooplankton at Site 1 (Supplementary Tab. 2), constituting 81% of the total count (3178 ind. L^{-1}). Cladocera made up 3% (117 ind. L^{-1}), and Copepoda 16% (639 ind. L^{-1}).

Bacillariophyceae dominated in phytoplankton at Site 2, constituting 43% of the total count (1813 ind. mL^{-1}). Cryptophyta made up 27% (1132 ind. mL^{-1}), and Chlorophyta 24% (1014 ind. mL^{-1}). Rotifers also predominated at Site 2, constituting 78% of the total number (1294 ind. L^{-1}). Copepoda were dominant among crustaceans. The average count of copepods was 248 ind. L^{-1}, which made up 15% of the zooplankton abundance. Cladocera accounted for 7%, with the average count of 115 ind. L^{-1}. The dominant species among Rotifera were: *Keratella cochlearis* (Gosse, 1851), *Keratella quadrata* (Müller, 1786), and *Asplanchna priodonta* (Gosse, 1850), among Cladocera: *Bosmina longirostris* (Müller, 1785), while among Copepoda, larval forms of copepods: nauplii and copepodites dominated.

In the floodplain lake isolated from the Vistula River,

Tab. 1. Range and mean values of physicochemical parameters over the growing season (from April to September 2008) in two floodplain lakes.

Parameters	Site 1			Site 2		
	Mean	Range	Standard deviation	Mean	Range	Standard deviation
SD (m)	1.4	0.9-2.0	0.29	0.9	0.7-1.2	0.18
DO (mg L^{-1})	6.2	1.6-12.6	3.23	8.6	3.7-14.6	3.72
DO sat. (%)	62	18-113	28.81	93	1.3-166	41.06
WT (°C)	17.3	9.6-21.7	3.99	17.8	9.0-22.9	4.69
pH	8.0	7.7-8.5	0.31	8.9	8.1-10.5	0.7
EC (µS cm^{-1})	669	586-754	66.11	546	413-635	67.41
Chl-*a* (µg L^{-1})	12.14	3.12-30.18	7.87	15.42	4.48-43.78	11.0
TSI (SD, Chl-*a*)	54.3	48.0-60.2	4.23	58.4	53.1-66.4	3.69

SD, Secchi disk visibility; DO, dissolved oxygen; WT, water temperature; EC, electrolytic conductivity; TSI, trophic state indices.

temperature changes adversely affected the abundance of diatoms and chrysophyceae (r=−0.50, r=−0.52, P<0.05), but changes positively correlated (Tab. 2) with the abundance of crustacean zooplankton (r=0.72, P<0.05). The inverse correlation between the abundance of green algae (r=−0.63, P<0.05), and water transparency (SD) was also observed at Site 1. Water level (WL) and flow rate (Q) were positively correlated with the number of diatoms, Chrysphyceae, and green algae (Tab. 2) at isolated site.

The temperature was negatively correlated with the abundance of total phytoplankton (especially Cryptophyta, r=–0.60 and diatoms r=–0.63, P<0.05) and zooplankton at that floodplain lake which was periodically connected with the Vistula River (Tab. 2). The rotifer abundance was positively correlated with the level of water in the river and water oxygen saturation at Site 2. The water level was closely and positively associated with the total abundance of zooplankton (r=0.76, P<0.05) and phytoplankton (r=0.76, P<0.05); Cryptophyta, Bacillariophyceae, and Chlorophyta. The crustacean zooplankton (abundance) development was positively correlated with temperature (T) and negatively with transparency (r=–0.52, P<0.05). High water temperatures were associated with high abundance of dinoflagellates (r=0.58, P<0.05) and copepods (r=0.55, P<0.05). Copepods also negatively responded to an increase in the water level of the river and connected floodplain lake (Tab. 2).

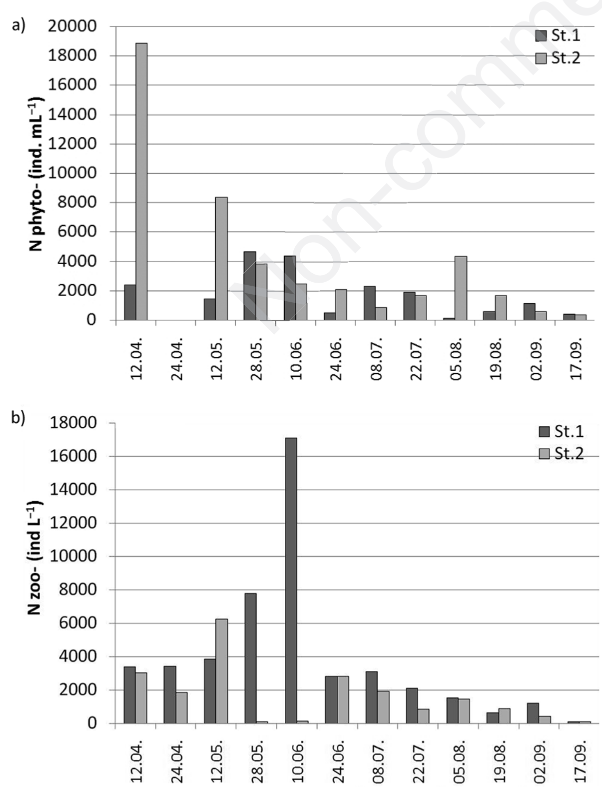

Fig. 3. Temporal variation on the total abundance of phyto- (a) and zooplankton (b).

The results of the CCA analysis, at Site 1 (Fig.4a), completely reflected the simple Pearson correlation between plankton and physico-chemical factors. The development of crustacean zooplankton had a strong positive correlation with the temperature and inversely with the water level and flow rate in the Vistula River. Phytoplankton growth reduced water transparency. The concentration of chlorophyll a was dependent on the abundance of large algae *i.e.* Dinophyta, Chlorophyta, Cyanoprokaryota and Euglenophyta. While at Site 2 (Fig.4b), environmental factors were very disturbed by irregular infusions of river water into the oxbow lake. The changes were so dynamic that it was difficult to find a clear relationship between the plankton and physico-chemical factors. The results of the CCA analysis confirmed only simple correlations between crustacean plankton, Dinophyta, and the water level and temperature.

DISCUSSION

After the regulation of the lower Vistula, the exchange of water between the river and many lakes is limited and is observed only during floods when water level in the Vistula is extremely high (Napiórkowski and Napiórkowska, 2014).

Our research indicates that the irregular inflows of water from the river destabilize environmental conditions in the investigated oxbow lakes. Water from the river reduced transparency, decreased the temperature, and inhibited macrophyte growth in the lakes. Replenished macrophytes were not able to provide refuge for zooplankton (*i.e.* did not offer protection against predators). Following the destruction of macrophyte community, planktonic algae became the main primary producers.

The investigated oxbow lakes had slightly different trophic state indices (TSI). With TSI=54, Site 1 (Carlson, 1977) can be classified as eutrophic. This lake is shallow, with clear, highly transparent water (the bottom can be seen) and has abundant submerged vegetation (Scheffer, 1998). The lake's stable conditions resulted from the fact that for several years the lake's water has not mixed with the river's water (limnophase). The second oxbow lake (Site 2), located just behind the flood embankments is connected with the river through a channel, and thus has continuous exchange of water with the river. The lake is regularly flooded (potamophase). Only extremely low level of water in the Vistula (below 230 cm) limit the water exchange. The lake has a slightly higher trophic level with an average TSI of 58.

Frequent water exchange caused resuspension of bottom sediment and reduced water transparency in the lake. This water body resembles a shallow lake in a turbid state.

Despite many negative consequences of the inflow of river's water, it also leads to the refreshing of water in the lake. The Vistula is characterized by a stable oxygen regime (Glińska-Lewczuk and Burandt, 2011). When its lakes suffer from oxygen depletion, the river's water improves their saturation. This could be observed in the studied oxbow lakes in August and September, 2008. During these months, at Site 1 (the lake isolated from the Vistula River), significant oxygen deficit was observed. At Site 2 (the lake connected to the river), though, oxygen depletion was not noted. Good oxygen conditions at Site 2 could, among other factors, could have promoted the development of zooplankton, the fact seems to be confirmed by the correlation between the oxygen content and the average zooplankton abundance. At Site 1 a relationship of this kind was not observed.

Temperature is one of the most important physical factors determining biological processes in aquatic environments (de Azevedo and Bonecker, 2003; Gyllström *et al*., 2008; Starmach *et al.*, 1976; Vadadi-Fülöp *et.al.*, 2009). The average water temperature in the oxbow lake isolated from the Vistula River was lower than in the lake connected with the river. During the summer the temperature at Site 2 was higher. When connection was observed, temperature was lower because a cooling effect of the river. Increased temperature had an ambiguous effect on phytoplankton growth: it could have inhibited the growth of diatoms and Chrysophyceae at Site 1, and diatoms and Cryptophyta at Site 2. A positive effect of the temperature on the development of dinoflagellates was quite remarkable, though only at Site 2. Raised temperature also increased the abundance of crustaceans at both stations (Tab. 2). Site 1 was a shallow landlocked oxbow lake, which heats up easily. As high temperature is favourable for the development of Cladocera (Forro *et al.*, 2008), more Cladocera species were recorded at this site.

The phytoplankton species composition in oxbow lakes is usually similar to the one typical of eutrophic lakes, with several extra species found only in these specific ecosystems (Krasznai *et al.*, 2010). Wojciechowska *et al.* (2007) reported that the number of species of planktonic algae in oxbow lakes ranges from 250 to 300. The number of species found in an ecosystem is often related to the number of analysed samples; in the oxbow lakes of the Tisza River (Krasznai *et al.*, 2010), 50 taxa of phytoplankton were recorded in 4 samples and 308 taxa in 19

Tab. 2. The relationship between planktonic organisms abundance and environmental variables.

	N phyto	CYAN	CRYPT	DINO	Chryso	Bacill	EUGL	CHLO	N zoo	Rot	Clad	Cop
Site 1												
N zoo	0.81	0.14	0.84	0.15	0.36	0.12	0.25	0.16				
Rot	0.82	0.18	0.79	0.19	0.42	0.20	0.28	0.21				
Clad	0.12	-0.21	0.41	-0.23	-0.21	-0.35	-0.10	-0.24				
Cop	0.24	-0.20	0.59	-0.21	-0.25	-0.41	-0.11	-0.26				
SD	-0.39	-0.44	-0.19	-0.32	-0.07	-0.18	-0.36	-0.63	-0.41	-0.41	-0.07	-0.14
DO	0.46	-0.10	0.15	0.06	0.59	0.51	0.16	0.37	0.20	0.25	-0.13	-0.22
DO sat.	0.51	-0.08	0.27	0.07	0.46	0.39	0.19	0.42	0.30	0.32	0.03	-0.07
T	0.09	0.03	0.40	-0.09	-0.52	-0.50	-0.07	0.03	0.32	0.20	0.62	0.72
pH	0.31	0.13	0.14	0.05	0.27	0.29	0.26	0.28	0.07	0.00	0.31	0.36
EC	0.03	0.28	-0.43	0.22	0.40	0.64	0.30	0.44	-0.20	-0.18	-0.09	-0.24
Chl-a	-0.02	0.26	-0.05	0.01	-0.21	-0.03	-0.01	0.25	0.08	0.16	-0.43	-0.42
WL	0.30	0.29	-0.10	0.14	0.62	0.60	0.23	0.34	0.30	0.39	-0.29	0.25
Q	0.27	0.49	-0.06	0.25	0.44	0.44	0.32	0.53	0.33	0.41	-0.24	-0.15
Site 2												
N zoo	0.53	-0.13	0.35	0.00	0.81	0.52	0.06	0.50				
Rot	0.63	-0.08	0.47	-0.15	0.86	0.60	-0.09	0.54				
Clad	-0.13	-0.21	-0.23	0.64	0.08	-0.16	0.28	0.21				
Cop	-0.37	-0.17	-0.51	0.37	-0.22	-0.28	0.74	-0.33				
SD	0.25	-0.12	0.48	-0.48	0.10	0.23	-0.29	-0.18	0.25	0.11	-0.44	-0.52
DO	0.48	0.49	0.38	-0.38	0.40	0.50	-0.33	0.20	0.48	0.61	0.13	-0.20
DO sat.	0.29	0.54	0.18	-0.24	0.38	0.32	-0.43	0.11	0.29	0.52	0.26	0.09
T	-0.57	0.17	-0.60	0.58	0.00	-0.63	0.31	0.05	-0.57	-0.22	0.42	0.55
pH	-0.24	0.57	-0.38	-0.54	-0.14	-0.06	0.16	-0.64	-0.24	-0.13	-0.14	0.41
EC	0.07	-0.18	-0.03	0.48	-0.31	0.05	0.59	0.33	0.07	-0.13	0.33	0.22
Chl-a	0.14	0.24	0.10	0.22	0.25	0.03	0.02	0.53	0.14	0.08	-0.30	-0.20
WL	0.76	-0.22	0.77	0.00	0.45	0.63	-0.37	0.77	0.76	0.56	-0.18	-0.53
Q	0.85	-0.16	0.78	0.14	0.62	0.58	-0.38	0.75	0.85	0.51	-0.14	-0.51

CYAN, Canoprokaryota; CRYPT, Cryptophyta; DINO, Dinophyta; Chryso, Chrysophyceae; Bacill, Bacillariophyceae; EUGL, Euglenophyta; CHLO, Chlorophyta; Rot, Rotifera; Clad, Cladocera; Cop,Copepoda; Pearson correlation coefficient P<0.05; statistical significances are underlined.

samples. The number of phytoplankton species identified in the Vistula River's oxbow lakes seems low but is in fact similar to the number of taxa identified in the Amazon floodplain lakes (Melo and Huszar, 2000).

Kuczyńska-Kippen and Nagengast (2006), who studied shallow lakes dominated by macrophytes, proved that these water bodies constitute a better habitat for zooplankton than oxbow lakes with sparse macrophytes. A well-developed macrophyte community in oxbow lakes ensures the diversity of zooplankton. The lake which was cut off from the Vistula River (Site 1) had a more abundant zooplankton community. The bottom of this lake was

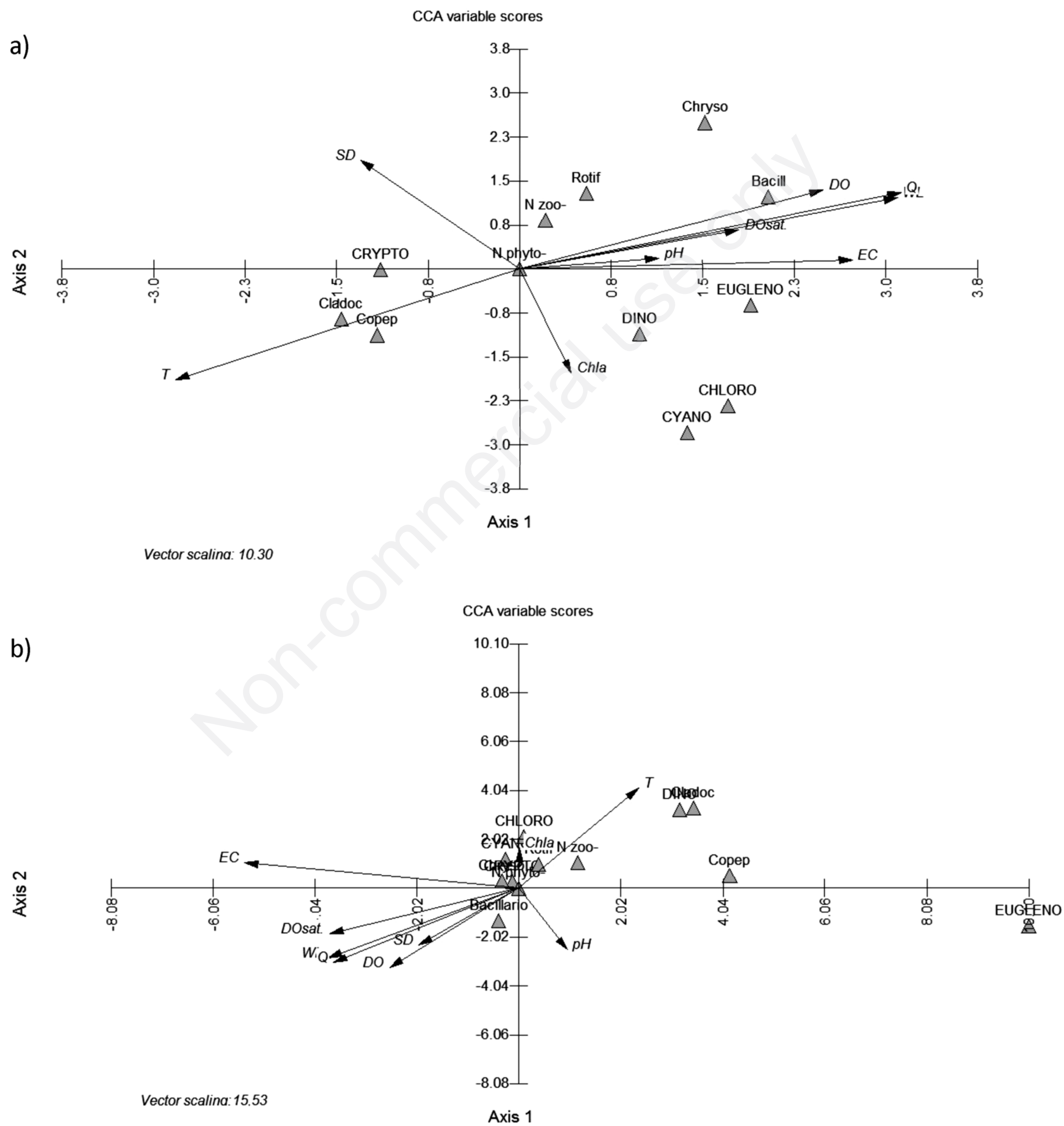

Fig. 4. Canonical correspondence analysis (CCA) biplot of plankton and physico-chemical parameters: a) at Site 1 (Axis 1, 48.2% of explanation; Axis 2, 22.3% of explanation); b) at Site 2 (Axis 1, 41.3% of explanation; Axis 2, 21.3% of explanation).

thickly covered with elodeids (*Ceratophyllum*, *Myriophyllum*). Sixty-six species of zooplankton were identified, 25 of which were only found only at this site. Rotifer species were predominant at both sites (79% at Site 1 and 85% at Site 2). According to many authors (Keckeis *et al.*, 2003; Pithart *et al.*, 2007; Schöll, 2009), rotifers are the dominant group in heleoplankton. Because of their high tolerance to adverse conditions (Radwan, 2004), they are commonly found in both stagnant and flowing waters.

Phytoplankton abundance at the two sites was different. In the lake isolated from the river it was two and a half times lower than in the lake connected with the river. Small nanoplankton forms, typical of unstable, mixed ecosystems (Wojciechowska *et al.*, 2007), dominated in both lakes. Common in oxbow lakes, Cryptophyta were also predominant in the investigated isolated lake. According to the classification by Reynolds *et al.* (2002) updated by Padisák *et al.* (2009), Cryptophyta represent the Y functional group adapted to poor light conditions. As mixotrophs, they are present in oxbow lakes with abundant organic matter, which comes mainly from macrophyte decomposition (Jones, 2000). These forms are active, and can migrate into the depths of lakes under sufficiently stable conditions. This ability allows them to compete with other algae, *e.g.* cyanobacteria. Moreover, Cryptophyta serve as food for zooplankton (Reynolds *et al.*, 2002). It seems that the relatively low abundance of these algae at Site 1 and the high correlation between the Cryptophyta abundance and the total zooplankton abundance and between the Cryptophyta abundance and the rotifer abundance resulted from zooplankton pressure (Tab.2).

Site 2 was under the substantial influence of the Vistula River. The water inflow was responsible for a greater total abundance of phytoplankton (Tab. 2). Small-sized diatoms, dominant in phytoplankton, were supplied with the river's water and belonged to the C, D, and P associations (Reynolds *et al.*, 2002; Padisák *et al.*, 2003). Mihaljević *et al.* (2009) recorded a significant contribution of diatoms to phytoplankton abundance in oxbow lakes during potamophase, as was the case in the studied oxbow lake (Site 2). Diatoms abundance was correlated with water level and flow rate in the Vistula (Tab. 2). Small organisms were also dominant in the zooplankton community. The most abundant rotifers constituted from 78% to 81% of the total zooplankton.

Demetraki-Palaeolog (2007) maintains that rotifers generally represent about 90% of total zooplankton abundance in rivers, Baranyi *et al.* (2002) reported that rotifers accounted for almost 85%, and Illyová *et al.* (2008) reported 67 to 78% zooplankton abundance in the backwater of the Danube River. It has been suggested that the apparent predominance of rotifers in rivers and floodplain lakes may be connected with their small size and relatively short generation time compared to the larger crustaceans (van Dijk and van Zanten, 1995; Lair, 2006; Radwan, 2004). In addition, rotifers appear to be better adapted to adverse conditions of lotic and semi-lotic habitats (Marneffe *et al.*, 1996).

The following species prevailed in the rotifers' community in the investigated oxbow lakes: *Keratella cochlearis, Keratella quadrata,* and *Asplanchna priodonta*. Among the Cladocera, the most frequently found was *Bosmina longirostris.* Baranyi *et al.* (2002) studying the oxbow lakes of the Danube River, also noted that *Bosmina longirostris* dominated among cladocerans. Similar results were also obtained by Vadadi-Fülöp *et al.* (2009). No dominant species among copepods were identified due to the small number of mature individuals. Copepod larval forms (nauplii and copepodites) were the most frequent, similarly to other oxbow lakes (Spaink *et al.*, 1998; Hein *et al.*, 1999; Keckeis *et al.*, 2003; Schöll, 2009). Copepods dominated over cladocerans among the crustaceans in the oxbow lakes of the lower Vistula. Cladocerans prefer stable conditions because they are more sensitive to periodic inflows of river's water (Vadadi-Fülöp, 2009). For this reason, the number of cladoceran species was greater at Site 1 (12 species) than at Site 2 (7 species) since Site 2 is periodically connected with the river.

The average zooplankton abundance at Site 1 was more than twice as high as that at Site 2. This indicates that this lake constitutes a better habitat for zooplankton due to its ecological stability (conditions similar to those found in ponds), higher temperature in summer (de Azevedo and Bonecker, 2003), and nutrient availability (high abundance of small phytoplankton). The macrophyte abundance in the studied oxbow lakes was also important. Site 1, with its stability (no inflow of water from the river), offered better conditions for the development of macrophytes than Site 2 which was periodically flooded by the water from the Vistula River. It seems obvious that better developed macrophyte community provides better cover and substrate for zooplankton. In addition, both submerged and emerged plants improve oxygen saturation (Kuczyńska-Kippen and Nagengast, 2006).

The phytoplankton abundance at Site 1 was several times lower than at Site 2. This difference may have been caused by zooplankton grazing. In oxbow lakes connected with rivers the impact of zooplankton grazing is less significant (Keckeis *et al.*, 2003), which explains why zooplankton pressure of on phytoplankton was much higher at Site 1.

CONCLUSIONS

The comparison of two oxbow lakes, *i.e.* the lake isolated from the main stem of the river and the lake periodically connected with the river, shows that the lakes have different environmental conditions, different plankton abundances and species compositions. Due to its lower trophic status, the isolated lake had lower temperature, pH, chlorophyll *a* concentration and dissolved oxygen content. In this water body phytoplankton was less abundant and contained a smaller number of species, but zooplankton was better developed. These conditions ensured species richness and Cladocera abundance. The contribution of Cryptophyta and Rotifera was high in both lakes. Diatoms were more frequent in the lake periodically flooded by the river. On the other hand, the conditions for zooplankton development were worse in the absence of macrophytes and nutrients.

The results of the research indicate that species composition, plankton abundance, and Chl-*a* concentration depended primarily on whether there was an exchange of water between the river and the lake. Hydrological conditions affected the relationships between biota components.

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