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Research article

Restoration of a shady urban pond – The pros and cons

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A B S T R A C T

The Bzura-7 pond (Łódź, Poland) is a typical shallow and shady urban reservoir situated on the Bzura River that is exposed to pollutants introduced mainly by internal loads and the supply from the catchment. In 2010–2012, the following characteristics were observed in the pond: a high allochthonous input of organic matter, high concentration of ammonium, low concentration of dissolved oxygen and low diversity of zooplankton, dominated mainly by *Daphnia* spp. From January to June 2013, restoration measures were performed, including sediment removal, increasing light access to the pond and construction of a sequential sedimentation-biofiltration system (SSBS). The aim of the present study was to investigate how the water quality in the Bzura-7 pond was affected by the restoration process, which included reducing pollutant inflows and enhancing habitat potential, thus increasing the diversity of this ecosystem. Restoration efforts improved the chemical and physical parameters of the water. The oxygen concentration increased, and the concentrations of TN and ammonium significantly decreased. Despite the increase in pond lighting, the growth of cyanobacteria was limited. However, we observed increased abundance of green algae and diatoms but less than adequate changes in the zooplankton community structures. Although we observed a significant increase in the zooplankton species richness after restoration, this increase was related to the small-bodied groups of zooplankton, rotifers and bosminiids, characteristic of eutrophic ecosystems. In addition, a planktivorous fish – sunbleak (*Leucaspius delineatus*) – was identified as an unintended side effect of the restoration effort. Further conservation efforts in the Bzura-7 pond and monitoring of results are still needed.

1. Introduction

One of the main functions of urban ponds is landscape water retention. The ponds receive stormwater and snow melt and are used for mitigation of stormwater flows into rivers (Mitsch and Gosselink, 2000). They are usually shallow, unstratified reservoirs with short retention times and high seasonal fluctuations in water levels (De Meester et al., 2005). However, even small impoundments perform multiple ecological functions, creating habitats for many organisms and thus enriching the diversity of an urban biocenosis (Céréghino et al., 2008; Hassall, 2014). Urban ponds influence the microclimate by increasing the humidity and reducing the variability of the temperature; thus, locally, they mitigate the effect of urban heat islands (Kupryś-Lipińska et al., 2009; Wibig, 2016). Urban reservoirs are valued in cities as one of the most attractive "natural" places for recreation (Lee and Maheswaran, 2011). However, due to their rapid sedimentation, plant overgrowth or other effects of eutrophication, they are often unable to perform their recreational functions. Additionally, various human pressures on these waters, e.g., bathing, fishing, and duck feeding, cause further degradation and impairment (Faulkner, 2004). In addition, the high nutrient content of the water is enhanced by its internal load. For these reasons, restoration of the pond is necessary (Collins et al., 2010).

Typical, effective restoration efforts are the mechanical removal of sediments, inactivation of phosphorus by introducing chemicals into the water, aeration and biomanipulation (e.g., Peretyatko et al., 2012; Rosińska et al., 2017). However, due to the high costs and the temporary and limited effectiveness of these methods, it is necessary to apply solutions that will reduce nutrient inflow from the catchment (Zalewski et al., 2012; Zalewski, 2015), such as the construction of buffer zones or the construction of pre-reservoirs

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for the sedimentation process. There are also innovative systems that limit the inflow of pollutants to the reservoirs (Jurczak et al., 2018). A few of these systems were demonstrated as ecohydrological approaches within the LIFE project "Ecohydrologic rehabilitation of recreational reservoirs "Arturówek" (Łódź) as a model approach to rehabilitation of urban reservoirs" (EH-REK) (LIFE08 ENV/PL/000517, 2008; Jurczak et al., 2012). This ecohydrological approach has resulted in significant improvements in the water quality of the restored urban reservoirs in the city of Łódź (Szulc et al., 2015; Jurczak et al., 2018).

One of the ecohydrological approaches in the framework of the LIFE project was the adaptation of the Bzura-7 pond to intensify its water self-purification process. Constructing the sequential sedimentation-biofiltration system (SSBS) to reduce the pollutants flowing into the reservoir along with additional activities, such as the removal of the bottom sediments and increasing access to sunlight, were used to achieve water quality improvement. This pond is small in size and has relatively high internal homogeneity due to substantial shading. The low availability of sunlight has resulted in low productivity and the heterotrophic nature of this ecosystem (Verhofstad et al., 2017). In these types of water bodies, production is based on microbial loop components, especially heterotrophic bacteria, for a large part of the vegetation season (Del Georgio et al., 1999; Jasser et al., 2009). As species richness is largely associated with primary production (Korhonen et al., 2011), shaded heterotrophic ecosystems are typically characterized by low biodiversity (Biggs et al., 1994). In particular, herbivorous crustacean zooplankton, which are usually an important element of a grazing food chain in shady ponds, are represented by low numbers of taxa and low diversity (Urabe and Sterner, 1996). The exception to this rule may be species of *Daphnia* that can ingest bacteria as efficiently as they can ingest algae (Hessen et al., 1989). Therefore, despite potentially low food quality for zooplankton grazers, heterotrophic ponds are often inhabited by dense populations of daphniids (as was also observed in Bzura-7); in these ponds, the basic foods of daphniids are bacteria and protozoan plankton (flagellates and ciliates) (Mahoney et al., 1990; Yoshida et al., 2001). Additionally, in the case of shallow heterotrophic lakes and ponds, the lack of fish or their highly limited presence, in terms of both number of species and densities, is a characteristic trait (Søndergaard et al., 2005; Radtke et al., 2011; Wolnicki et al., 2011a, 2011b). However, it should be emphasized that low diversity limits the ecosystem's resistance to disturbances, which may be particularly detrimental to urban ponds that are vulnerable to anthropogenic impacts. Consequently, the goals of the restoration efforts for Bzura-7 were not only to reduce the inflow of pollutants but also to enhance habitat potential and thus increase the diversity of this ecosystem. In our study, we paid special attention to zooplankton because, as other authors argue, these animals can be an exceptionally good tool for assessing the success of pond restoration efforts (Jenkins, 2003; Olmo et al., 2012).

The aim of the present study was to investigate how the restoration process affected the water quality of the wooded, urban, shallow and shaded Bzura-7 pond, which is situated among a cascade of reservoirs and was exposed to pollutants introduced not only from its internal load and surrounding catchment but also from the upstream inflow.

2. Materials and methods

2.1. Sampling site

The study was conducted on an upstream stretch of the Bzura River in the north-eastern part of the city of Łódź (Poland). The Bzura-7 pond is located upstream from Wycieczkowa Street in a cascade of 17 small, shallow man-made ponds (Fig. 1) that is in the middle part of the 17th reservoir cascade on the upper part of the Bzura River (51°82′23″N, 19°49′69″E) (Fig. 1A and B). It has an area of 2850 m^2 and a water volume of 3510 m^3 (Kujawa, 2003), where a low concentration of oxygen and an elevated concentration of ammonium were observed in 2010–2012. Due to poor water quality conditions and poor ecosystem function, the Bzura-7 pond was included in the restoration project "Ecohydrologic rehabilitation of recreational reservoirs "Arturówek" (Łódź) as a model approach to rehabilitation of urban reservoirs" for which engineering efforts to restore the pond were undertaken from January to June 2013.

Restoration activities included removal of 360 m^3 of sediment, reduced shading by removal of 10 trees and reduced canopy thickness of 40 trees around the pond and the installation of an SSBS for point source inflows from the river. The constructed SSBS had an area of 165 m^2 and consisted of sedimentation (65 m^2), geochemical (19 m^2) and biological (80 m^2) parts (Fig. 1A, C, 1E). At the inlet to the Bzura-7 pond, a gabion that was 1 m wide, 1 m high and approximately 19 m in an arc shape was constructed. The barrier was made of iron mesh baskets of 6 × 8 cm and mesh made of wire with a diameter of 2.7 mm, and it was filled with dolomite-limestone stones with a diameter of 12–18 cm. This geochemical structure was covered with an RG17 coconut mesh mat (900 g/m^2 x 2) made of 5-cm-thick coconut cord to enhance the suspended matter retention of the gabion construction. Two PVC pipes, with diameters of 0.2 m and 0.1 m, were also installed inside the gabion to force water circulation around the island. Gabion construction divided the SSBS into two parts as follows: upper (sedimentation) and lower (biofiltration). The upper part was reinforced with concrete slabs to collect suspended matter in front of the inflow to the pond and to facilitate servicing of the SSBS. The lower part was planted with the following aquatic vegetation: *Typha angustifolia* (L.), *Carex riparia* William Curtis, *Glyceria maxima* (Hartm.) Holmb., *Iris* sp., and *Ceratophyllum demersum* (L.). These species play an important role as the biofiltration section. All the elements of the SSBS are shown in Fig. 1A, C.

Between 2010 and 2016, water samples for physicochemical (water temperature, oxygen concentration, pH, conductivity and chlorophyll *a* concentration), biological analysis (phytoplankton analyses, zooplankton analyses, fish analyses) and toxicological analysis (microcystin concentration) were collected monthly (except that in 2010, collection was every two weeks) from April to October in the following two periods: before restoration (2010–2012) and after restoration (2013–2016). For phytoplankton, chemical and toxicological analyses, water was sampled from a 1 m column of water using a 5 L Bernatowicz sampler and was transferred into a 5 L container and transported to laboratory immediately after sampling. Zooplankton were sampled twice from a 1 m column of water using a 5 L Bernatowicz sampler and transferred into a 10 L bucket. Sampled water was filtered using a 20 mm mesh net, then the samples were concentrated to 50 mL and preserved in 4% Lugol's solution (distributed by Chempur Company, Poland). For the determination of fish species composition, standardized benthic multi-mesh gillnets (prEN 14757:2005) were used, with two sets each for 2009, 2011 and 2013–2017. Gillnetting was conducted once per year, in the autumn (October–November), to avoid overfishing.

2.2. Analyses of abiotic parameters

Physical parameters were determined *in situ* during water sampling using the WTW Multi 340i (WTW, Weilheim, Germany). Water samples filtered by GF/C membranes were analysed by ion chromatography (Dionex ICS-1000, Sunnyvale, California, USA) for

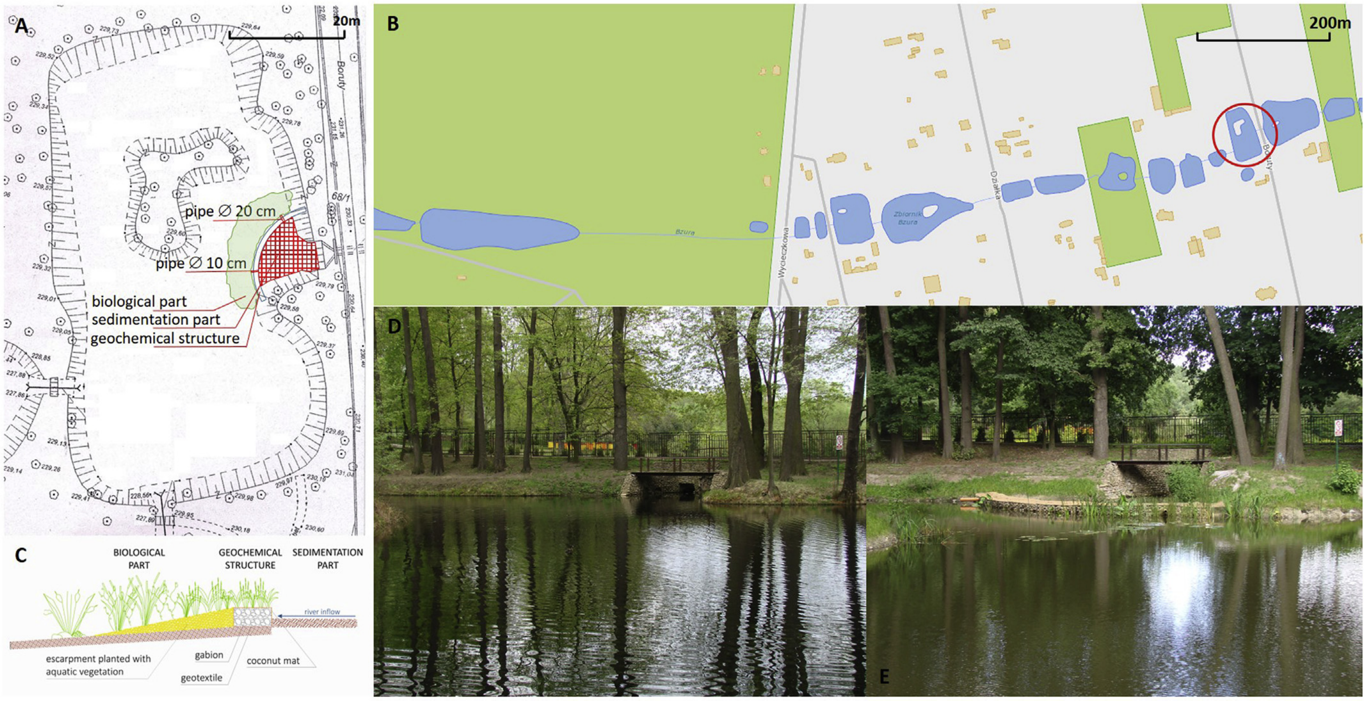


Fig. 1. Ecohydrological restoration of the Bzura-7 reservoir in Łódź city (POLAND). The morphology of the Bzura-7 reservoir (A), the location of the Bzura-7 reservoir in the cascade of urban autotrophic reservoirs (B), scheme of the sequential sedimentation-biofiltration system constructed in the Bzura-7 pond (C), the Bzura-7 reservoir before ecohydrological restoration in 2012 (D), and the Bzura-7 reservoir after ecohydrological restoration in 2013 (E) (photo by T. Jurczak).

determination of ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations. The ion concentrations were calculated automatically by calibration curves prepared from standards. The accuracy for nitrite, nitrate, ammonium and phosphate was between 1% and 3%, the method detection limit was 1 μg/L, and the limit of quantification was 10 μg/L (Urbaniak et al., 2016). The analysis of the TN concentration was performed in unfiltered water using the persulfate digestion method (method no. 10071; HACH, 1997). The samples for the TP analysis were digested with the addition of Oxisolve® Merck reagent (Merck, Darmstadt, Germany) with MerckMV 500 Microwave Digestion System and determined using the ascorbic acid method (Golterman et al., 1978). To check the validity of the measurements, the calibration curve, using the standards of known TN and TP concentrations, was generated with $R^2 = 0.9997$. The accuracy was 5% for TP and 3% for TN. The method detection limits were 0.10 mg/L for TN and 0.03 mg/L for TP (Urbaniak et al., 2016).

The lighting of the reservoir (photosynthetically active radiation, PAR) was measured two times – 21 August 2011 (two years before restoration) and 30 August 2017 (four years after restoration), during sunny days to assess the intensity of incoming sunlight to the pond by using the HD 2302.0 Photo-Radiometer (Delta OHM, Caselle di Selvazzano, Italy). In this case, five transects from the south to the north bank of pond and nine transects from the east to the west bank of pond were planned, resulting in a net of 45 measurement points evenly distributed on the surface of the pond.

2.3. Analyses of biotic parameters

2.3.1. Phytoplankton analyses

The concentration of chlorophyll *a* was measured immediately after sampling using a bbe Algae Online Analyser (AOA, Version 1.5 E[1], bbe-Moldaenke, Kiel, Germany). The principle of the bbe AOA measurement is based on the determination of the fluorescence spectrum and the fluorescence kinetics of the algae. Analysing interactions between chlorophyll *a* and other pigments, AOA discriminates four main groups of algae (green algae, cyanobacteria, diatoms and cryptophytes). This method is recognised as a reliable on-line analysis for chlorophyll *a* measurements (Cagnard et al., 2006) and as a useful tool for monitoring the phytoplankton community composition, particularly as an early warning system for the detection of harmful algal blooms (Richardson et al., 2010).

Phytoplankton samples for microscopic analyses were transferred to a 1 L sedimentation cylinder and fixed with Lugol's solution (Chempur Company, Poland) immediately after sampling. When plankton fell to the bottom of the sample cylinders, they were concentrated into a volume of 50 mL and subjected to microscopic analyses. The qualitative and quantitative analyses of diatoms were based on the methods described by Siemińska (1964), while the method of Starmach (1989) was used for the other groups of phytoplankton.

2.3.2. Zooplankton analyses

In the laboratory 2 mL of 10% formaldehyde was added to every sample (Ciecierska and Dynowska, 2013) and then samples were concentrated to 10 mL to identify the zooplankton species and determine their density. Zooplankton taxa were distinguished under a Nikon 115 microscope (magnification of 6100–200) using a Sedgewick-Rafter counting chamber. Morphological analyses of the collected individuals were performed according to Amoros (1984), Ejsmont-Karabin et al. (2004) and Benzie (2005).

2.3.3. Microcystin analyses

The intracellular microcystins (MCs) were analysed in the plankton material collected from 1 L of water filtered on Whatman GF/C filter paper immediately after sampling. For this purpose, microcystins were extracted in 75% aqueous methanol by sonication in a Misonix ultrasonicator (Farmingdale, NY, USA). The extracts were then centrifuged at 11000 × g for 10 min in an Eppendorf 5804 centrifuge (Hamburg, Germany). The supernatants were collected and evaporated in an SC110A Speedvac Plus (ThermoSavant, Holbrook, NY, USA). Microcystins were analysed by high-performance liquid chromatography (HPLC) using the method described by Jurczak et al. (2004). The microcystins in the cyanobacterial extracts were identified using the microcystin standards MC-LR, MC-RR and MC-YR, with their characteristic absorption spectra and retention times. The detection limit for microcystins was 10 ng/L.

2.3.4. Fish analyses

For fish analyses, two sets of gillnets were set for 12 h in the deeper, southern part of the pond. Each gillnet was 30 m long and 1.5 m deep and was composed of 12 different mesh sizes ranging from 5 mm to 55 mm from knot to knot (mesh panel size and order: 43, 19.5, 6.25, 10, 55, 8, 12.5, 24, 15.5, 5, 35 and 29 mm). The fish were identified to the species level and weighed and measured in the laboratory directly after gillnetting. The total length of each fish was measured from snout to tail tip.

The capture of wild animals for the purpose of taking biometric measurements and determining their taxonomic classification is exempt from the requirements of the Ethics Committee approval in Poland (Art. 1 point 2.4 of the Act on the protection of animals used for scientific or educational purposes of 15 January 2015, which is the Polish implementation of Directive 2010/63/EU of the European Parliament and of the Council of 22 September 2010 on the protection of animals used for scientific purposes (O.J.EUL276 of 20.10.2010, p.33)). After measurement, fish were delivered to the Lodz ZOO. None of the activities in this study involved endangered or protected species.

2.4. Statistical analyses

The analyses were performed in Statistica 10 (StatSoft). The Mann-Whitney test was used to determine whether there were significant differences between the physicochemical and biological parameters before (2010–2012) and after (2013–2016) the restoration of the Bzura-7 pond. A principal component analysis (PCA) was applied to determine the patterns of changes in the biological structure and the dynamics of the physical-chemical parameters in the Bzura-7 ecosystem before and after restoration. All statistical analyses were conducted using log (x+1)-transformed data.

3. Results

3.1. Abiotic parameters

The highest monthly concentrations of TN and TP before restoration were 8.7 mg/L (September 2012) and 0.53 (August 2012), respectively. After restoration, those concentrations were 6.6 mg/L (July 2013, first month after restoration) for TN and 1.68 mg/L (October 2015) for TP (Fig. 2A). Each year before restoration efforts began, we observed lower concentrations of TN and TP in the beginning of the season, i.e., in April and May, than in the other months. Additionally, in August 2012, we observed the highest concentration of TP and the lowest concentration of TN (0.10 mg/L). After restoration, we did not observe such a patterns, except for TP in 2015. Similar dependencies were observed for ammonium and phosphate concentrations (Fig. 2B).

Moreover, we observed a significant decrease in the average concentration of TN, from 2.82 mg/L (2010–2012) to 2.00 mg/L (2013–2016) (Table 1). This decrease corresponds to a significant decrease in the average ammonium concentration, from 1.51 mg/L (before) to 0.1 mg/L (after). However, the average phosphate concentration increased significantly, from 0.12 mg/L (2010–2012) to 0.22 mg/L (2013–2016). A small increase in the average TP concentration was also noted, but these results were not significant. Both the concentrations of nitrate and nitrite were not affected by restoration and were similar through out the study period. The average air and water temperatures in the Bzura-7 pond before (2010–2012) and after (2013–2016) the restoration process were comparable and did not show any significant differences. The average oxygen concentration in the water significantly increased with restoration, shifting from 3.06 mg/L in the period before restoration to 8.90 mg/L after the restoration effort was completed. In addition, slight but significant increases in both conductivity and pH were recorded after restoration, and they were calculated as ranging from 315 to 364 μS/cm and from 7.10 to 7.65, respectively. In addition, analyses performed in 2017 showed that the cutting of the trees and the crown section did not cause significant illumination of the pond. In 2011, 67% of the area of the pond was completely shaded. After cutting 10 trees and limiting the crowns of 40 trees in 2013, the shade of the reservoir reached 69% in 2017. The fully lit part of the pond was 29% in 2011 and 20% in 2017, which indicates that 4 years after crown-section shading, the pond illumination returned to the state before restoration.

3.2. Biotic parameters

Three years before restoration (in 2010), the Bzura-7 pond was characterized by a very low concentration of chlorophyll *a* (below 6 μg/L). During this period, the dominant groups were cyanobacteria and cryptophytes. This low concentration of chlorophyll *a* corresponded to a low phytoplankton biomass dominated mainly by Euglenophyta in 2010 and 2012 and with co-dominant Bacillariophyceae and Chlorophyta in 2011. The chlorophyll *a* concentrations for cyanobacteria in the summers of 2010–2012 were approximately 2–3 μg/L, except for July 2011, when the cyanobacterial chlorophyll *a* concentration increased to 4.60 μg/L, and in July 2012, when it increased to 5.49 μg/L. Cyanobacterial toxins – microcystins – were only identified once on 4 August 2010, when they were present at 23.7 μg/L. Microcystin-RR, microcystin-YR and microcystin-LR were then identified. The high concentration of cyanotoxins was caused by the influx of phytoplankton from the reservoir above, as a result of draining water from that reservoir. Microcystins were not found in the pond during any other time in the study. The concentration of chlorophyll *a* for the other groups of phytoplankton in 2010–2012 ranged from 0.019 to 2.468 μg/L for green algae, from 0.003 to 0.174 μg/L for diatoms and from 0.498 to 0.626 μg/L for cryptophytes. The highest chlorophyll *a* concentrations for green algae (14.81 μg/L) and for cryptophytes (20.87 μg/L) were recorded in April 2012 (Fig. 2C).

In the period before restoration, the zooplankton of the Bzura-7 pond were dominated by Cladocera, represented by two large-bodied species of *Daphnia*: *Daphnia magna* (Straus) and *Daphnia galeata* (Sars). Their densities were 19 ind/L in 2010, 290 ind/L in 2011 and 568 ind/L in 2012. Copepods from the two orders Cyclopoida and Calanoida were also present at densities ranging from 4 to 90 ind/L during 2010–2012. Other species of Cladocera (*Scapholeberis mucronata* (O.F. Müller), *Bosmina longirostris* (O.F. Müller), *Chydorus sphaericus* (O.F. Müller), *Ceriodaphnia* sp. And Rotifera (mainly *Keratella quadrata* (Müller), *Keratella cochlearis* (Gosse) and *Trichocerca* sp.) appeared occasionally (Fig. 2D).

Only three fish species, the gibel carp (*Carassius gibelio* Bloch, 1782), tench (*Tinca tinca* L.), and ide (*Leuciscus idus* L.) (golden form), were observed in the pond before the restoration efforts (Table 2), even though a few attempts were taken to enhance the fish stock before 2009 (common carp (*Cyprinus carpio* L.), ide and pikeperch (*Sander lucioperca* L.)). In both sampling years (2009 and

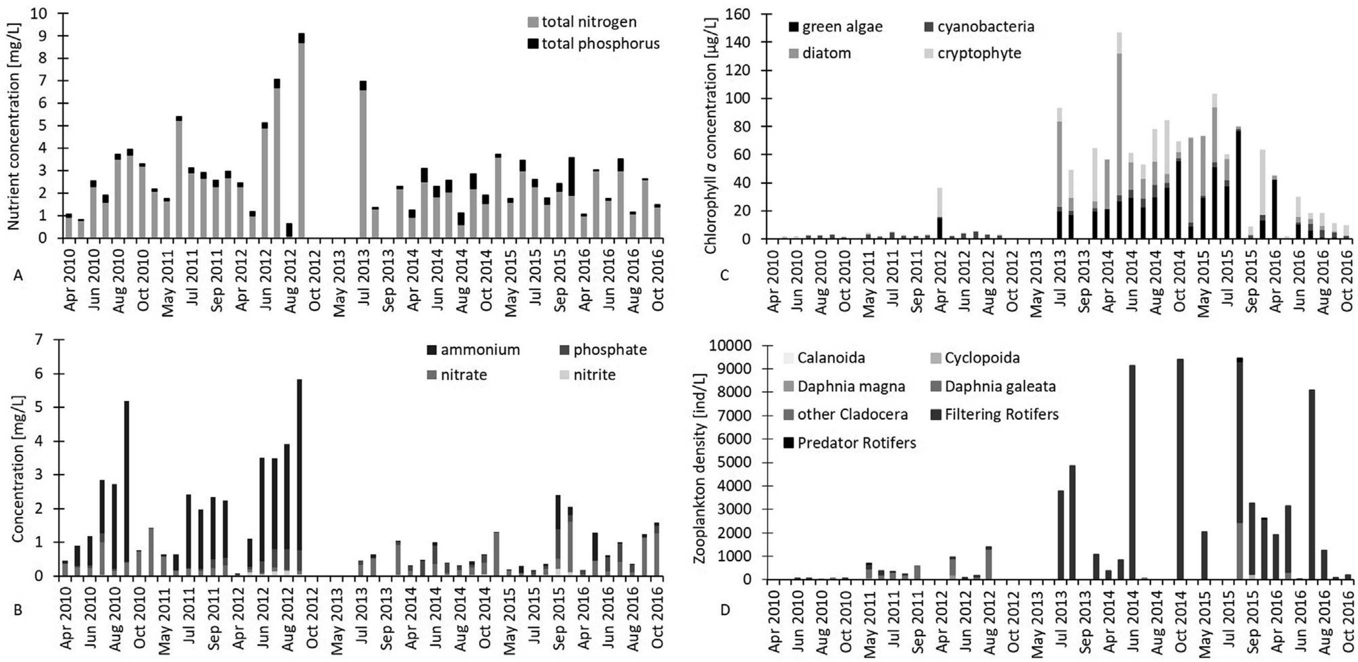


Fig. 2. The dynamic seasonal changes of total nitrogen and phosphorous concentrations (A), ammonium, phosphate, nitrate and nitrite concentrations (B), chlorophyll *a* concentrations (C) and zooplankton density (D) before (2010–2012) and after (2013–2016) restoration (January–June 2013); empty columns – no sampling data.

Table 1
Comparison of physicochemical and biological parameters before (2010–2012) and after (2013–2016) restoration in the Bzura-7 pond, according to the Mann-Whitney test. Statistically significant results are in bold.

Parameters	Mean before	Mean after	Valid N before	Valid N after	SE before	SE after	test value z	p
ABIOTIC FACTORS								
water temperature [°C]	14.800	14.937	35	35	0.86	0.89	−0.08	0.934
conductivity [µS/cm]	315.343	363.943	35	35	4.06	3.16	**−6.47**	**<0.001**
pH	7.104	7.649	35	35	0.04	0.09	**−5.70**	**<0.001**
oxygen [mg/L]	3.058	8.897	35	35	0.58	0.48	**−5.49**	**<0.001**
total nitrogen [mg/L]	2.823	1.997	35	35	0.31	0.20	**2.10**	**0.036**
total phosphorus [mg/L]	0.307	0.368	35	35	0.10	0.05	−1.87	0.061
nitrite [mg/L]	0.025	0.027	35	35	0.01	0.01	0.40	0.69
nitrate [mg/L]	0.414	0.479	35	35	0.09	0.10	−0.11	0.911
phosphate [mg/L]	0.122	0.217	35	35	0.03	0.04	**−2.18**	**0.029**
ammonium [mg/L]	1.510	0.095	35	35	0.24	0.04	**5.81**	**<0.001**
BIOTIC FACTORS								
green algae [µg/L]	0.552	24.212	29	35	0.51	3.20	**−6.18**	**<0.001**
cyanobacteria [µg/L]	2.350	3.297	29	35	0.25	0.52	−1.05	0.293
diatom [µg/L]	0.114	21.190	29	35	0.04	5.57	**−6.22**	**<0.001**
cryptophyte [µg/L]	1.224	11.170	29	35	0.71	2.26	**−3.81**	**<0.001**
Calanoida [ind/L]	8.559	0.000	17	25	2.28	0.00	**n.t.**	
Cyclopoida [ind/L]	5.147	10.560	17	25	2.47	9.59	**2.82**	**0.005**
Daphnia magna [ind/L]	16.118	0.000	17	25	10.86	0.00	**n.t.**	
Daphnia galeata [ind/L]	199.735	0.000	17	25	83.81	0.00	**n.t.**	
Daphnia SUM [ind/L]	215.853	0.000	17	25	88.45	0.00	**n.t.**	
Other Cladocera [ind/L]	30.735	1502.160	17	25	17.51	1388.83	**2.49**	**0.013**
Filtering Rotifers [ind/L]	41.853	5708.520	17	25	16.45	1205.25	**−5.00**	**<0.001**
Predator Rotifers [ind/L]	0.706	6.720	17	25	0.71	5.22	−0.35	0.729

n.t. - not tested.

2011), only a few relatively large fish specimens were caught (Table 2). None of the ide specimens survived the winter fish-killing during the winter of 2009/2010.

After the restoration efforts, significant increases in chlorophyll *a* concentrations, particularly for green algae, diatoms and cryptophytes, were observed (Table 1; Fig. 2). The average concentrations of chlorophyll *a* for these three groups increased from 0.55 to 24.2 µg/L for green algae, from 0.11 to 21.2 µg/L for diatoms and from 1.22 to 11.2 µg/L for cryptophytes. Only the increase in the chlorophyll *a* concentration for cyanobacteria from 2.35 to 3.30 µg/L did not reach statistical significance. In 2013–2015, the average concentration of chlorophyll *a* for all the groups was 71.7 µg/L (in 2010–2012, it was only 4.98 µg/L), but in 2016, the concentration of chlorophyll *a* for all the groups decreased to below 30 µg/L, with an average value of 19.4 µg/L. During this period, the dominant groups were green algae and diatoms, and the maximum concentrations of chlorophyll *a* for these two groups were 55.4 µg/L (October 2014) and 100.4 µg/L (May 2014), respectively. The concentrations of chlorophyll *a* for the other groups ranged from 0.47 to 8.87 µg/L for cyanobacteria and from 0.01 to 46.53 µg/L for cryptophytes.

Table 2
Dominance of fish species and total fish number in the gillnet catch at the Bzura-7 pond before and after restoration (dominant factors in bold; gillnetting in 2016* was unrepresentative due to the very low water level in the pond – below 1.0 m).

Fish species			Before restoration		After restoration				
			2009	2011	2013	2014	2015	2016*	2017
Gibel carp	*Carassius gibelio*	[%]	**50.00**	33.33	**46.53**	15.73	7.04	**66.67**	16.67
Sunbleak	*Leucaspius delineatus*	[%]			32.67	**79.78**	**91.55**	33.33	**79.17**
Tench	*Tinca tinca*	[%]	16.67	**66.67**					4.17
Pike	*Esox lucius*	[%]				3.37	1.41		
Gudgeon	*Gobio gobio*	[%]			18.81	1.12			
Ide	*Leuciscus idus*	[%]	33.33						
Topmouth gudgeon	*Pseudorasbora parva*	[%]			1.98				
Total fish number		[specimens]	6	3	101	89	71	3	24
Gibel carp	*Carassius gibelio*	[cm]	28.6 ± 3.5	32.0	12.5 ± 2.0	17.0 ± 3.5	23.0 ± 1.0	28.2 ± 0.1	31.3 ± 2.3
Sunbleak	*Leucaspius delineatus*	[cm]			7.2 ± 0.7	6.1 ± 0.8	5.6 ± 0.4	5.6	6.1 ± 0.2
Tench	*Tinca tinca*	[cm]	30.0	33.5 ± 0.7					4.8
Pike	*Esox lucius*	[cm]				55.2 ± 1.7	19.3		
Gudgeon	*Gobio gobio*	[cm]			10.4 ± 2.0	9.4			
Ide	*Leuciscus idus*	[cm]	25.9 ± 0.6						
Topmouth gudgeon	*Pseudorasbora parva*	[cm]			5.5 ± 0.7				

Microscopic analyses confirmed the occurrence of Bacillariophyceae and Chlorophyta in 2013–2016.

Significant changes in the species structure of the zooplankton communities after restoration were observed (Table 1; Fig. 2). The dominant group became Rotifera (*K. quadrata*, *K. cochlearis*, *Anuraeopsis* sp., *Brachionus* sp., *Polyarthra* sp., *Trichocerca* sp. And *Synchaeta* spp.), which increased in average density from 42 ind/L (2010–2012) to 5709 ind/L (2013–2016). Large filter feeders, such as *D. magna* and *D. galeata*, as well as calanoid grazers, were not found in the zooplankton community after restoration. We observed significant increases in the density of Cladocera other than *Daphnia* species (*B. longirostris*, *Ch. sphaericus*) from 31 ind/L to 1502 ind/L and in the density of Cyclopoida from 5 ind/L to 11 ind/L (Table 1).

Distinct changes in fish composition and density have been observed since 2013, primarily due to the natural settlement by fish as a result of the drying of the upstream pond. In 2013–2016, the pond was also stocked each year. In 2013, the pond was stocked with pike (*Esox lucius*) and with 10 tench (*Tinca tinca*) specimens (average size: 21.0 cm TL, 127 g). Two-year-old pike were stocked in the autumns of 2013 and 2014 (average size: 39.0 cm TL, 360 g; 10 and 25 specimens, respectively), while summer fry (0+) were used in 2015–2016 (average size: 3.0 cm TL; 250 specimens yearly). Consequently, two to four fish species were noted in gillnets from 2013 to 2016 (Table 1). In 2016, the result of gillnetting was unrepresentative due to a drought that caused very low water levels (below 1.0 m) in the pond. During water sampling operations, single specimens of tench were observed in 2013–2016, and since 2015, numerous pike fingerlings were observed in the late summer around the shoreline of the Bzura-7 pond. During the winter of 2016/2017, the pike population was strongly reduced by winter fish-killing, and only single pike specimens were observed in 2017. Fish samples show that sunbleak was the only species that successfully created a reproducing population. The presence of early life stages of species other than sunbleak was incidental (tench in 2017). Analyses of the length of the gibel carp caught in the Bzura-7 pond clearly show that fish presence is related to stocking. The total length of the gibel carp decreased from approximately 30 cm TL before restoration to 12.5 cm in 2013 and then successfully increased, reaching 31.3 cm in 2017 (Table 2).

3.2.1. Abiotic-biotic interactions before and after restoration (PCA)

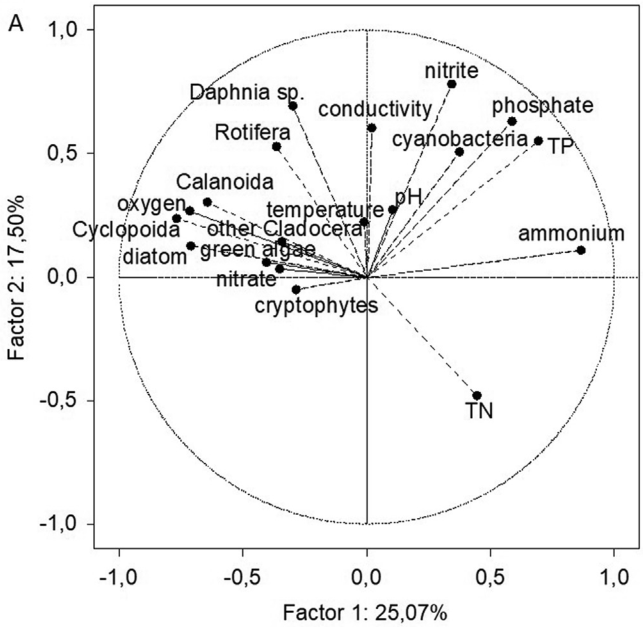
The first two components of the PCA with the highest eigenvalues were plotted to analyse the relationships between the abiotic and biotic variables both before and after the restoration of the Bzura-7 pond, as including other factors did not provide any additional significant information for interpreting the ecological relevance of the data. These two principal components explained 42.57% of the observed variance for values before restoration and 42.0% for values after it.

3.2.1.1. Before restoration. Only parameters showing correlations with the PC axis higher than 0.5 or lower than −0.5 are indicated here and elsewhere. Parameters such as the concentrations of ammonium, TP and phosphate were strongly and positively correlated with PC1, while oxygen concentration and the abundances of diatoms, Cyclopoida and Calanoida were strongly and negatively correlated with PC1. In turn, concentrations of phosphate, nitrite, TP and conductivity as well as abundances of *Daphnia* spp., Rotifera and cyanobacteria were the main (positive) contributors to PC2 (Fig. 3A).

The most significant correlations were observed between TP and phosphate ($r = 0.794$; $p < 0.05$) and between TP and ammonium ($r = 0.74$; $p < 0.05$). Strong correlations between nitrite and phosphate ($r = 0.716$; $p < 0.05$) and TP ($r = 0.586$; $p < 0.05$) were also observed. Both TP and ammonium limited the development of cyanobacteria, as indicated by the following positive correlations: TP – cyanobacteria, $r = 0.545$ ($p < 0.05$) and ammonium – cyanobacteria, $r = 0.521$ ($p < 0.05$). Strong correlations were found between diatoms and green algae ($r = 0.772$; $p < 0.05$). These phytoplankton groups were correlated with oxygen as follows: oxygen – diatoms $r = 0.877$ ($p < 0.05$) and oxygen – green algae $r = 0.601$ ($p < 0.05$). Cyclopoida also showed a positive correlation with oxygen ($r = 0.642$; $p < 0.05$), while these animals were negatively correlated with ammonium ($r = -0.654$; $p < 0.05$). Negative correlations between TN and Calanoida ($r = -0.645$; $p < 0.05$) were also found.

3.2.1.2. After restoration. The first axis (PC1) showed oxygen concentrations, pH and diatom abundance as the main positive contributors and concentrations of ammonium and nitrite and the density of Cyclopoida and "other Cladocera" (*B. coregoni*, *Ch. sphaericus*) as the main negative contributors. The second axis (PC2) was positively linked with temperature, density of Rotifera and abundance of cyanobacteria and was negatively linked with nitrate (Fig. 3B).

After restoration, diatoms showed strong positive correlations with pH ($r = 0.728$; $p < 0.05$) and oxygen ($r = 0.669$; $p < 0.05$) and a weaker negative correlation with "other Cladocera" ($r = -0.42$; $p < 0.05$). The "other Cladocera" were in turn correlated with



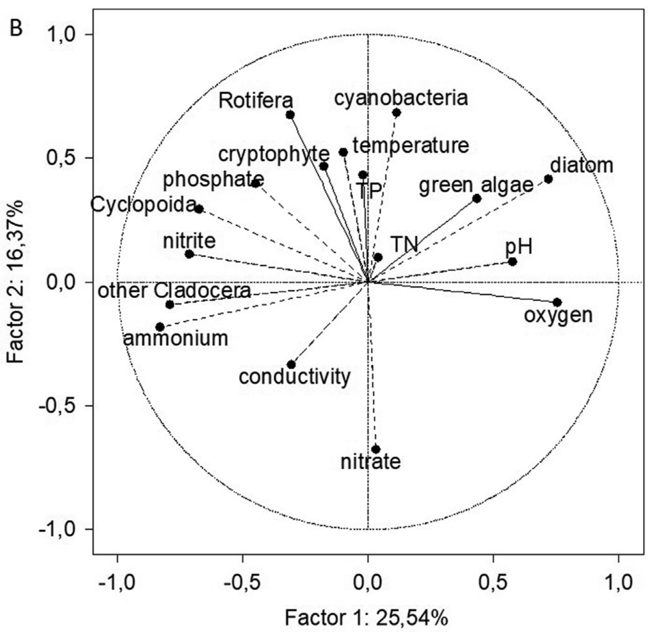


Fig. 3. Comparison of the PCA before (A) and after (B) restoration in the Bzura-7 pond.

ammonium ($r = 0.703$; $p < 0.05$), nitrite ($r = 0.603$; $p < 0.05$) and Cyclopoida ($r = 0.591$; $p < 0.05$). Moreover, negative correlations between ammonium and green algae ($r = -0.56$; $p < 0.05$), diatoms ($r = -0.508$; $p < 0.05$) and oxygen concentration ($r = -0.583$; $p < 0.05$) were detected. Ammonium was also positively correlated with nitrite ($r = 0.581$; $p < 0.05$). Nitrate showed a strong negative correlation with temperature ($r = -0.751$; $p < 0.05$) and a weaker correlation with Rotifera ($r = -0.552$; $p < 0.05$). Cyclopoida were correlated with nitrite ($r = 0.721$; $p < 0.05$) and with phosphate ($r = 0.538$; $p < 0.05$).

The Mann-Whitney *U* test indicated a significantly higher richness of zooplankton species after restoration, in 2013–2016 ($U = 27.50$, $Z = -4.93$, $p < 0.0001$) (Fig. 4).

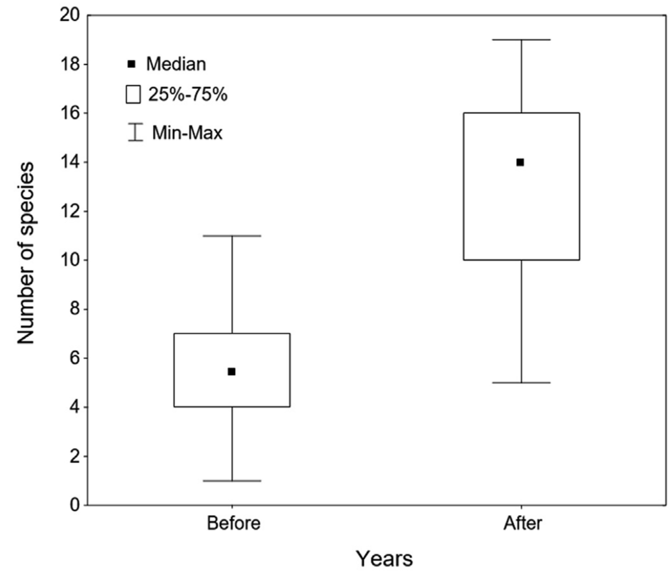


Fig. 4. Number of zooplankton species in the Bzura-7 pond before (2010–2012) and after (2013–2016) restoration.

4. Discussion

Before restoration, the Bzura-7 pond had some features of dystrophic lakes (Nix and Jenkins, 2000), e.g., a high allochthonous input of organic matter (fallen leaves due to the woodland location), low concentration of dissolved oxygen, low diversity of zooplankton, low abundance of phytoplankton and low primary production, but a high activity of microorganisms was likely, as demonstrated by the relatively high nutrient levels. Although our research did not include microorganisms, we hypothesize that bacteria and protozoa formed an important link converting allochthonous dissolved organic matter (DOM) to biomass available to the higher trophic levels (Salonen et al., 1992). This could be confirmed by the high densities of large-bodied *Daphnia* sp., which persisted in the pond despite very limited biomass of phytoplankton. Low primary production was demonstrated in our study by a strong positive correlation between oxygen concentrations and diatom and green algae abundances ($r = 0.877$ and $r = 0.601$, respectively), which indicated that the very low level of dissolved oxygen was the result of limited photosynthesis (Fig. 3A). At the same time, the density of daphniids did not show any significant correlation with the concentration of chlorophyll *a*, which corresponds to the abundance of phytoplankton. Thus, the source of food for daphniids must have been bacteria, fungi and heterotrophic flagellates, which is a typical phenomenon in shaded dystrophic ponds (e.g., Jones et al., 1999; Nix and Jenkins, 2000).

However, in contrast to dystrophic lakes, the Bzura-7 pond was characterized by relatively high pH values and mean levels of humid substances (3.257 r. u. in 2010–2012, 4.13 r. u. in 2013–2015 and 3.59 r. u. in 2016). These features of the pond could suggest its susceptibility to measures aiming to increase its diversity and ecological complexity, if improvements in water quality (e.g., increased oxygen levels) were achieved. Removal or blockage of the internal nutrient loads together with trapping nutrients upstream preventing them from entering the restored system are widely used as restoration activities (Rosińska et al., 2017). Although the river flow through the Bzura-7 pond is limited and the pond seems to be mostly enriched by conversion of allochthonous coarse particle organic matter (CPOM), the incidence with the inflow of cyanobacteria in 2010 showed the potential impacts from the upstream areas of the catchment that should not be disregarded. An SSBS, like that constructed at the inflow to the Bzura-7 pond, can be a highly effective solution to trap nutrients upstream and prevent them from entering the restored system. According to Szklarek et al. (2018), the efficiency of an SSBS in terms of nutrient removal can reach 61.4% for total suspended solids (TSS), 37.3% for TP, 30.4% for PO_4^{3-}, 46.1% for TN, 2.8% for NH_4^+ and 44.8% for NO_3^-. Unfortunately, in 2013–2016, due to the low water level and the low river flow, the efficiency of the system at reducing nutrients could not be measured. Nevertheless, concentrations of TN and TP in the Bzura-7 pond were stable in 2013–2016. On the other hand, the SSBS we used did not completely block the ecological continuity of the system, as proven by the invasion of planktivorous sunbleak in 2013. In turn, the sediment removal from Bzura-7 increased the oxygen concentration and reduced the NH_4^+ concentration. Pokorny and Hauser (2002) reported that during the first year after sediment removal from the Vajgar fish pond (40 ha, Bohemia), the phytoplankton dynamics and structure showed the following signs of improvement: the summer biomass peak was lowered, and the overall species diversity increased. However, they also noted that sediment removal from the Vajgar fish pond resulted in a temporary negative phosphorus budget and that in two years after the sediment removal, the phytoplankton structure and dynamics returned to a state similar to that before restoration. We observed similar situations in the Bzura-7 pond in 2016 (three years after restoration). In addition, we assume that the mechanical removal of the sludge contributed to the removal of resting eggs of *Daphnia*, which affected the structure of the zooplankton in the Bzura-7 pond.

The scope of the restoration effort included increasing the light at the pond by cutting 10 trees and cutting back the crowns of 40 trees to increase the sunlight in the pond in the first several years after restoration. Post-rebuilding studies indicate that the intended purpose was only partially achieved. The effect of lighting the pond was observed in the first 2–3 years after restoration. Then, the crowns of the surrounding trees grew, and the ecosystem began to return to the state that existed prior to the restoration. The range of tree felling was limited during the restoration process to avoid excessively lighting the pond and to limit cyanobacterial growth. We are currently assessing the more restrictive activities in this area, as indicated. The increased penetration of light, mainly during the first 3 years after restoration, resulted in the development of phytoplankton (mainly diatoms and green algae) and enhanced primary production (significant increase in oxygen concentration). These results were demonstrated by the strong positive correlation between diatoms and the concentrations of both pH and oxygen (Fig. 3B). The increase in the oxygen concentration probably enhanced the nitrification process, as evidenced by the negative correlation between ammonium and oxygen, as well as the positive correlation between ammonium and nitrite (Fig. 3B). Ammonium ions were also consumed by diatoms and green algae, as these parameters were significantly negatively correlated. This effect could have been particularly important for the development of diatoms, which often show a strong preference for ammonium, because it requires less energy to assimilate than does nitrate (Ward, 2013). The rate of nitrate intake by phytoplankton was closely related to temperature ($r = -0.751$) and was intense at high temperatures and limited at low temperatures. Biological activity was the key factor causing nitrate concentration changes, and it depended mainly on water temperature, which was indicated in some marine ecosystem research (e.g., Reay et al., 1999).

However, the changes that we observed in the zooplankton community structures were not fully satisfactory. Although we observed a significant increase in the richness of the zooplankton species after restoration (Fig. 4), this was related to the small-bodied groups of zooplankton, rotifers and bosminiids, characteristic of eutrophic environments. The zooplankton community also included copepods. The presence of other Cladocera, mainly represented by *Bosmina* sp., contributed to an increase in the internal pool of nitrogen in the pond, as confirmed by the strong positive correlation between this group of animals and the ammonium and nitrite concentrations (0.703 and 0.603, respectively). The nutrients recycled by consumers may substantially increase the internal pool of dissolved substances during stratification or long retention times in shallow ecosystems (Sterner et al., 1992). The internal resupply of nutrients varies based on the zooplankton species. Cladocera have higher physiological demands for phosphorus (P) relative to their demands for nitrogen (N); thus, they recycle nutrients at a high N:P ratio (Andersen and Hessen, 1991; Sterner et al., 1992). Conversely, copepods have higher intracellular requirements for N than for P (high N:P intracellular ratio); thus, they recycle nutrients at a low N:P ratio (Stemberger and Miller, 1998), as was also demonstrated in our results (positive correlation of Cyclopoida with phosphate). After restoration, the dominant groups in the zooplankton communities were Rotifera (Fig. 2D). Rotifera are widely distributed organisms that, as opportunistic species, are favoured under changing environmental conditions, where they often show high population growth rates resulting from their very short developmental times and a quick hatching response after dormancy (Brendonck and De Meester, 2003; Segers, 2008; Ejsmont-Karabin, 2012). These characteristics of rotifers are used to determine the general tendencies in the changes in environmental conditions over time (Duggan et al., 2001). The most abundant species in Bzura-7 included bacteriophages, such as *Keratella cochlearis* (both typica and tecta forms), *Anuraeopsis fissa, Brachionus angularis, Filinia longiseta* and *Pompholyx sulcata*, and other indicators of a high trophic state, such as *Keratella quadrata* and *Trichocerca pusilla* (Ciecierska and Dynowska, 2013). We assume, however, that very high densities of Rotifera in the Bzura-7 pond resulted primarily from the absence of large-bodied *Daphnia* sp. And not only from the trophic conditions. As demonstrated by Gilbert (1988) in his review paper, rotifers can commonly occur at high densities in the presence of small ($\leq$1.2 mm) cladocerans, but they cannot become abundant in the presence of large ($\geq$1.2 mm) *Daphnia*, which competitively suppress Rotifera. We recognize the absence of large species of *Daphnia* after restoration as an underachievement. In shaded ponds, the main source of food for *Daphnia* are organisms from the heterotrophic food chain (mainly protozoa and bacteria), but on this type of food, daphniids grow poorly (Müller-Navarra and Lampert, 1996). Restoration should theoretically improve the food conditions for daphniids by promoting the development of phytoplankton, which are higher-energy food for the *Daphnia*. Our results were likely different for the following reasons: 1) removal of the resting eggs of *Daphnia* during dredging and thus limiting their reproductive potential; and 2) the pressure of planktivorous fish, mainly sunbleak (*Leucaspius delineatus*), as an unintended side effect of the restoration effort resulting from the fact that the Bzura-7 is situated in a cascade of reservoirs, and fish were able to invade the pond from the drying pond situated upstream, which was assisted by the removal of the closing grids from the sluice construction. Although the fish were present in the pond before the restoration, fish densities and species structures were not able to limit *Daphnia* population development, mostly due to the lack or low efficiency of fish reproduction and differences in food base utilization. Gibel carp can utilize various food sources (Penaz and Kokes, 1981), but a study by Özdilek and Jones (2014) has shown the relatively low trophic position of gibel carp in the Karamenderes River, northwest Turkey, where filamentous algae and detritus were important diet components. It is also likely that gibel carp can quickly shift to benthic food, as is observed in crucian carp

Carassius carassius (L.), which are larger than 3.5 cm long where benthic food predominates (Penttinen and Holopainen, 1992). Even after the restoration, which promoted macrophyte development (spawning substrate) in the pond, only the sunbleak was able to reproduce successfully, as evidenced by the complete disappearance of the gudgeon and lack of the early life stages of other fish species. Additionally, differences in life-trait strategies, such as parental care and small body sizes, allowing access to the shallow pond margins not accessible to more tall-bodied and larger gibel carps or tench, seem to be key factors in the success of the sunbleak in the Bzura-7 pond (Gozlan et al., 2003a, 2003b). It is possible that sunbleak also has longer seasonal activity, as was observed in the case of a similar-sized lake minnow, *Eupallasella percnurus* (Pall.), and crucian carp, which is located in the small water bodies in northern Poland (Radtke, 2011). Additionally, under specific conditions, winter fish-killing can be a factor promoting sunbleak development, as presented by Lischke (2015).

The Bzura-7 pond presented a high richness of colonizing species, mainly rotifers, during the three years following the restoration. Dominance of Rotifera species characteristic of high trophic conditions could be attributed to the post-cultivation nutrient supply (release of nutrients from deeper layers of the sediments as an effect of sediment removal), while their very high densities probably resulted from the weakness of regulatory processes, such as competition or predation in the first stages of community formation. Given that rotifers and copepods colonize restored ponds faster than do cladocerans (Jenkins and Buikema, 1998; Badosa et al., 2010), we consider that the complexity of the zooplankton community in the Bzura-7 pond may be enhanced by large-bodied Cladocera species in the coming years. However, this requires the following: a) further conservation work related to the elimination of planktivorous fish from this pond and b) longer-term succession, as the results from 2016 indicate that the reservoir is likely to slowly return to its pre-investment state over the following few years, a phenomenon that was also found in other studies (Søndergaard et al., 2007).

5. Conclusions

Maintaining healthy shaded ponds is challenging due to their generally small size but very complex ecosystems. In addition, the literature provides limited information regarding the restoration of heterotrophic urban ponds. Thus, the first step of our study, before restoration, was to identify the ecological status of the pond, as well as any potential impacts and threats to the water quality of Bzura-7. Nevertheless, despite the previous monitoring and restoration programme developed for this ecosystem, we have not been able to avoid the unintentional effects of restoration, e.g., sunbleak migration from the upstream pond and, consequently, a loss of daphniid species. We believe, however, that pond management successes and failures can lead to improved knowledge on pond functioning. Therefore, in our opinion, the restoration efforts must be continued. Subsequent actions should be focused on removing sunbleak from the pond through more effective biomanipulation, accompanied by a constant monitoring programme to record seasonal and yearly trends in the pond's water quality and in the occurrence of particular plant and animal species.

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