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Zooplankton diversity of drainage system reservoirs at an opencast mine

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Abstract – The aim of this study was to determine the structure of zooplankton in three artificial water reservoirs, the technological function of which is to pre-treat waters from a drainage system of a brown coal open mine by removing inorganic suspension. The background for the zooplankton qualitative and quantitative analyses was the hydrochemical conditions in the individual reservoirs. The greatest zooplankton abundance (N), number of taxa (n), Shannon's diversity (H'), and species eveness (J') was noted in reservoir Chabielice ($N_{mean} = 1311$ ind. L^{-1}, $n = 26$, $H' = 2.09$, $J' = 0.64$) which was dominated by eurytopic Rotifera species (*Keratella cochlearis, Keratella tecta, Keratella valga, Polyarthra longiremis, Filinia longiseta*). Their abundance was positively correlated with water pH and nutrient concentrations. Reservoir Kamień was characterized by the highest mean values of total suspension (9.6 mg L^{-1}), chlorophyll *a* (Chl *a*) content (10.4 µg L^{-1}), and water temperature (20.0 °C). These factors significantly correlated with crustacean biomass. The thermal-oxygenation conditions, low trophic level, and low productivity of the water (Chl $a = 5.4$ µg L^{-1}) in reservoir Północny determined the overall low zooplankton abundance ($N_{mean} = 153$ ind. L^{-1}). Artificial water bodies of opencast mine drainage systems are biologically unstable, but they do have some characteristics of natural ecosystems, and they do take over their functions. Zooplankton is an indicator of their ecological functionality. Knowledge gained about such reservoirs could contribute to decision-making about strategies for water reclamation and how to manage it.

Keywords: biodiversity / Rotifera / crustacea / hydrochemisty / brown coal opencast mining

Résumé – Diversité zooplanctonique des réservoirs du système de drainage d'une mine à ciel ouvert. L'objectif de cette étude était de déterminer la structure du zooplancton dans trois réservoirs d'eau artificiels, dont la fonction technologique est de prétraiter les eaux d'un système de drainage d'une mine à ciel ouvert de lignite en éliminant la suspension inorganique. Les analyses qualitatives et quantitatives du zooplancton se fondent sur les conditions hydrochimiques dans les différents réservoirs. La plus grande abondance du zooplancton (N), le nombre de taxons (n), la diversité de Shannon (H') et l'uniformité des espèces (J') a été trouvée dans le réservoir Chabielice ($N_{mean} = 1311$ ind. L^{-1}, $n = 26$, $H' = 2.09$, $J' = 0.64$) qui était dominé par des espèces de rotifères eurytopiques (*Keratella cochlearis*, *Keratella tecta, Keratella valga, Polyarthra longiremis, Filinia longiseta*). Leur abondance était corrélée positivement avec le pH de l'eau et les concentrations en nutriments. Le réservoir Kamień a été caractérisé par les valeurs moyennes les plus élevées de la suspension totale (9,6 mg L^{-1}), de la teneur en chlorophylle a (Chl a) (10.4 µg L^{-1}) et de la température de l'eau (20 °C). Ces facteurs étaient en corrélation significative avec la biomasse des crustacés. Les conditions d'oxygénation et de température, le faible niveau trophique et la faible productivité de l'eau (Chl $a = 5.4$ µg L^{-1}) dans le réservoir Północny ont déterminé la faible abondance globale du zooplancton ($N_{mean} = 153$ ind. L^{-1}). Les plans d'eau artificiels des systèmes de drainage de mine à ciel ouvert sont biologiquement instables, mais ils présentent certaines caractéristiques des écosystèmes naturels et assument leurs fonctions. Le zooplancton est un indicateur de leur fonctionnalité écologique. Les connaissances acquises sur ces réservoirs pourraient contribuer à la prise de décisions sur les stratégies d'épuration de l'eau et sur la façon de la gérer.

Mots-clés : biodiversité / Rotifera / crustacea / hydrochimie / extraction à ciel ouvert de lignite

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1 Introduction

Open mining natural minerals has a dramatic impact on the soils, waters, and air in the vicinities of open mines, and these cause changes in both the social fabric and the natural landscape (Lapčík and Lapčíková, 2011). Apart from the easily discernible and immediate changes on the earth's surface, such as the disappearance of forests and human settlements, certain alterations are to be expected in some more distant future (Nixdorf *et al.*, 2005). With time, as open mining areas undergo dewatering, groundwater levels decline. As a result, some natural surface water bodies dry up and certain dysfunctions appear in local hydrographic systems (Younger and Wolkersdorfer, 2004; Sloss, 2013). Possible reasons are the translocation of water courses or the construction of the drainage ditches and technological water tanks that are necessary for strip mines to function (Bian *et al.*, 2010). Meanwhile, the creation of new watercourses and reservoirs that enable an open mine to operate can also be seen as some additional potential resource, which can be used for other purposes beside the primary one, for which they are formed (Stottmeister *et al.*, 2002). This is secondary, but equally important, role of artificial water bodies in urbanized, industrial areas with high population densities, where these reservoirs can serve social and recreational purposes (Rzętała, 2008).

The origin of artificial reservoirs, sets of abiotic factors, and how reservoirs are used are key factors in the directions and rates of biological succession in such new ecosystems. The current use and status of water reservoirs, in turn, influence species composition and hydrobiont density (von Sperling and Grandcham, 2010; Merrix-Johnes *et al.*, 2013; Bielańska-Grajner *et al.*, 2014; Pociecha and Bielańska-Grajner, 2015). When reservoirs serve technological functions and there are large-amplitude fluctuations in environmental parameters, it is difficult to achieve ecosystem biological stabilization.

Zooplankton play an important role in any aquatic ecosystem. They are one of the first links in the consumer chain. They participate in the cycling of matter and energy flux by eliminating plankton algal cells from water depths (Mayer *et al.*, 1997; Dodson *et al.*, 2000). In turn, they serve as food for all fish species at the early ontogenetic development stage (Kerfoot and Sih, 1987; Sutela and Huusko, 2000). Zooplankton are characterized by short life cycles and fast adaptation to environmental changes. They are sensitive indicators of environmental responses to various disruptions (pollution, water flow and level, thermal conditions, acidification, etc.) (Ferrari *et al.*, 2015; Goździejewska *et al.*, 2016; Pociecha *et al.*, 2017). Zooplankton species composition and quantitative parameters reflect ongoing phenomena and processes in water bodies (Dodson *et al.*, 2007; Rönicke *et al.*, 2010, Goździejewska and Tucholski, 2011). For this reason, zooplankton communities are useful in comparative investigations, the bioindication of water ecosystems, and in predicting environmental status (Boix *et al.*, 2008; Ejsmont-Karabin, 2012, 2013; Marszelewski *et al.*, 2017).

Given the above, the research of zooplankton communities in relations to mine water bodies conditions was considered to be necessary. It was assumed that the structure of zooplankton is shaped under the influence of various abiotic factors in the tested reservoirs. To verify the hypothesis stated above, it was appropriate to obtain an answer to the question: How zooplankton can react on the various conditions of examined water bodies? It should be emphasized that this type of research on the structure of zooplankton in artificial reservoirs, the technological function of which is to pre-treat waters originating from the draining system of brown coal open mine by removing inorganic suspension were not carried before. They are crucial from the point of view of the importance of open pit mines in Europe and for general limnology.

2 Material and methods

2.1 Research site

The study was conducted at three artificial reservoirs, which are used for pre-treatment of waters originating from a system of dewatering in Poland's biggest brown coal stripe mine (Fig. 1). Their main function is to reduce suspended matter through sedimentation but they are also exploited for recreational fishing. Reservoir Chabielice (CH; 51°15′58.9″N, 19°06′24.3″E) is supplied with water from the draining system of Szczerców open pit (OM-S); reservoirs Kamień (KA; 51°15′18.9″N, 19°12′15.4″E) and Północny (PN; 51°15′13.9″N, 19°22′01.3″E) are supplied with water from the Bełchatów opencast mining (OM-B; Fig. 1). The reservoirs receive waters from different depths of the draining system, mixed in changeable proportions. They are enclosed by embankments, with the crowns about 3.5 m wide and the slope ratio of 1:2. The embankments are overgrown with meadow vegetation and shrubs. The area of each reservoir is approximately 7.5–8.0 ha; the depth of the main basin is 2.2 m, whereas total volume is 103 000 m^3. At the maximal permissible inflow of 1.8 $m^3 s^{-1}$, water retention time is approximately 16 h.

The technical parameters of the three reservoirs are the same and each of them comprises three functional zones (Fig. 2). The inflow zone collects water from supplying channels and serves for gravitational sedimentation of the coarsest suspended matter fraction (zone A). Next, water flows through the overflow comb baffle and reaches the central zone (the main basin of the reservoirs) measuring 100 × 400 m (zone B), where fine inorganic fractions are deposited and organic compounds are metabolized aerobically. Sedimentation concludes in the plant filter zone, which is 100 m long and approximately 0.25 m deep (zone C). The filter comprises the following species of macrophytes: *Phragmites communis*, *Typha latifolia*, *Glyceria maxima*, *Phalaris arundinacea*, *Acorus calamus*, *Carex acutiformis*, *Mentha aquatica* and *Salix cinerea*.

2.2 Sampling and analytical procedure

Zooplankton were sampled from July to September in 2012 and from June to September in 2013. The sampling sites were in the central part of the basin of each of the three reservoirs (KA, CH, PN). Samples were collected with a 5 L Ruttner sampler from a depth of approximately 1 m beneath the surface. The sampled material of 20 L was passed through a plankton net with a mesh size of 30 µm, preserved with Lugol's solution, and fixed in a 4% formalin solution. The zooplankton was identified under a Zeiss AXIO Imager microscope to the lowest possible taxonomic unit (with the

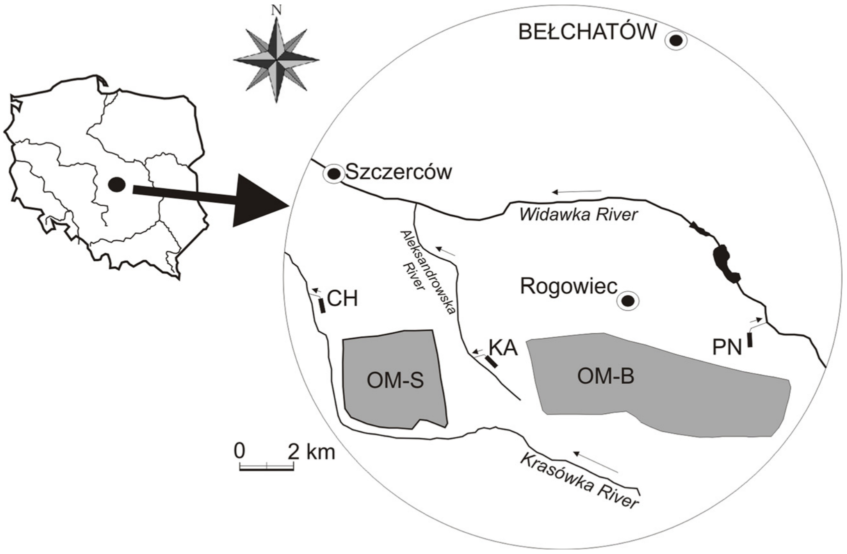

Fig. 1. Location of the study area. Abbreviations: OM-S – opencast mining Szczerców, OM-B – opencast mining Bełchatów; Reservoirs: CH – Chabielice, KA – Kamień, PN – Północny.

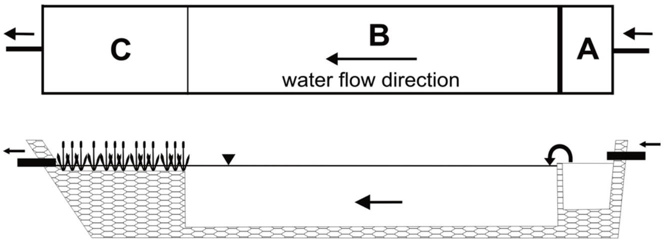

Fig. 2. Construction scheme of the reservoir. (A) The preliminary part with water overflow, (B) the main basin, (C) plant filter.

exception of Copepoda juvenile stages) using methods by von Flössner (1972); Koste (1978); Ejsmont-Karabin *et al.* (2004); Rybak and Błędzki (2010); and Błędzki and Rybak (2016). Quantitative analysis included determining zooplankton abundance using a Sedgewick–Rafter counting chamber. Zooplankton biomass was determined with methods by Ruttner-Kolisko (1977); Ejsmont-Karabin (1998); and Bottrell *et al.* (1976).

The dominance (D) (Kasprzak and Niedbała, 1981), species richness (Margalef's index, d) and diversity (Shannon's index, H'), and species evenness (Pielou's index, J') were analyzed. MVSP 3.22 software was used to analyze the taxonomic differentiation and similarity of the zooplankton communities (Bray–Curtis index) (Kovach, 2015).

The following physico-chemical parameters were analyzed at zooplankton sampling sites at each sampling event: temperature (T, °C), water pH, Secchi disk transparency (SDT, m), water saturation (DO, $\mathrm{mg\,L^{-1}}$, %) and total dissolved solutions (TDS, $\mathrm{mg\,L^{-1}}$). All physico-chemical parameters were measured using a YSI 6600 V2 Multi-Parameter Water Quality Sonde. Water samples were also collected during each sampling event for laboratory analyses of total nitrogen (TN), nitrate (NO_3^-), total phosphorus (TP), orthophosphate (PO_4^{3-}), and chlorophyll a (Chl a). The contents of total suspended matter, were also determined. The hydrochemical analyses were conducted in accordance with APHA guidelines (1999) (Tab. 1).

The trophic state index (TSI) of the analyzed reservoirs was calculated from the: Chl a, SDT, TP and TN (Carlson, 1977; Kratzer and Brezonik, 1981). The chemical composition of bottom sediments was also performed in order to obtain complete data of the hydrochemical conditions underlying the cycling of elements in the analyzed reservoirs.

2.3 Statistical procedures

Non-parametric analysis of variance was applied to assess the general differences in physicochemical indicators of water and in the quantitative parameters determined for the zooplankton among reservoirs, and major taxonomic groups (Statistica 13.0 for Windows, Statsoft, Tulsa). The results were processed with ANOVA and the non-parametric Kruskal–Wallis test to determine statistically significant differences between reservoirs, in terms of physicochemical parameters of water and zooplankton structure (H, $P \leq 0.05$). Correlation coefficients were calculated with the use of Spearmann ranks ($P \leq 0.05$).

The response of zooplankton communities to the environmental variables was analysed with CANOCO 4.5 for Windows (ter Braak and Smilauer, 2002) using multivariate statistical procedures. Redundancy analysis (RDA) was used because the length of the gradient in the dataset checked in DCA ordination was CA 2.2 SD, which indicated a linear variation. RDA as direct gradient analysis was used to summarise the relationship between zooplankton species and environmental parameters. Redundant variables were removed by a step-wise regression (forward selection) with Monte Carlo permutation tests. The dataset was log transformed [log $(n+1)$] and centred on species, as this is obligatory for the constrained linear methods.

RDA was performed for 21 zooplankton taxa and 2 larval stages of Copepoda (share >2%), and 10 environmental

Table 1. Physicochemical parameters and trophic indices for waters of the reservoirs (mean ± SD). Denotations: SDT – Secchi disk transparency, DO – dissolved oxygen, TDS – total dissolved solutions, Chl *a* – chlorophyll *a*,TP – total phosphorus, TN – total nitrogen. Values with the different superscripts are significantly different among reservoirs by non-parametric Kruskal–Wallis test (ANOVA, $P \leq 0.05$).

Reservoir	CH	KA	PN
Water parameters			
Temperature (°C)	19.9 ± 1.9	20.0 ± 2.7	18.2 ± 2.0
SDT (m)	0.71 ± 0.13^{ab}	0.56 ± 0.08^{a}	0.82 ± 0.10^{b}
pH	8.09 ± 0.01^{a}	7.65 ± 0.19^{b}	7.55 ± 0.17^{b}
DO ($mg\,L^{-1}$)	8.15 ± 0.45	8.19 ± 0.72	9.22 ± 1.08
DO (%)	83.7 ± 0.4^{ab}	84.2 ± 1.1^{a}	76.1 ± 1.2^{b}
TDS ($mg\,L^{-1}$)	595.8 ± 116.9^{a}	672.5 ± 78.9^{b}	588.0 ± 39.2^{ab}
Total suspension ($mg\,L^{-1}$)	7.8 ± 5.6^{ab}	9.6 ± 5.8^{a}	4.0 ± 2.1^{b}
Chl *a* ($\mu g\,L^{-1}$)	7.3 ± 0.2^{ab}	10.4 ± 6.2^{a}	5.4 ± 1.4^{b}
TP ($mg\,L^{-1}$)	0.231 ± 0.138	0.182 ± 0.082	0.104 ± 0.033
PO_4^{3-} ($mg\,L^{-1}$)	0.070 ± 0.050	0.022 ± 0.010	0.024 ± 0.010
TN ($mg\,L^{-1}$)	0.468 ± 0.091	0.411 ± 0.114	0.383 ± 0.132
NO_3^- ($mg\,L^{-1}$)	0.180 ± 0.026	0.149 ± 0.077	0.173 ± 0.058
N_{org} ($mg\,L^{-1}$)	0.193 ± 0.120	0.182 ± 0.074	0.139 ± 0.108
Trophic state parameters			
TSI SDT	65.06 ± 2.53^{ab}	68.52 ± 2.16^{a}	62.92 ± 1.62^{b}
TSI Chl *a*	50.05 ± 0.25	52.52 ± 4.90	46.77 ± 2.83
TSI TP	80.33 ± 9.68^{a}	77.94 ± 6.99^{ab}	70.51 ± 4.71^{b}
TSI TN	41.45 ± 5.29^{ab}	38.47 ± 2.02^{a}	44.49 ± 1.44^{b}

variables of water: temperature, pH, DO, total suspension, TDS and trophic variables (TP, PO_4^{3-}, TN, NO_3^-, Chl *a*). The nitrates (NO_3^-) and TDS parameters were excluded from the analysis because their variance inflation factors exceeded 20.

3 Results

3.1 Environmental characteristics

The lowest water temperatures and the highest oxygenation were recorded in reservoir PN. The values of these characteristics were 16.6–21.1 °C and 8.9–10.2 $mg\,O_2\,L^{-1}$, respectively. In CH and KA these parameters were comparable and ranged from 18.4 to 24.1 °C and from 7.2 to 8.8 $mg\,O_2\,L^{-1}$ (Tab. 1). The greatest ranges of TP and TN concentrations were determined in reservoir CH (0.106–0.360 $mg\,L^{-1}$ and 0.350–0.574 $mg\,L^{-1}$, respectively). The mean contents of TP and the mean value of TSI TP was the lowest in reservoir PN ($TP = 0.103\,mg\,L^{-1}$; and TSI $TP = 70.51$), and differed significantly from the values reported in the CH The mean value of the TSI TN index was the highest in PN and differed from the value reported in the KA (Tab. 1).

The concentration of Chl *a* in reservoir KA ranged from 6.64 to 19.60 $\mu g\,L^{-1}$ was significantly higher than that in reservoir PN; and was correlated with DO (%; $r = 0.9856$, $P < 0.05$). The SDT in reservoir KA ranged from 0.4 to 0.65 m was significantly lower than that in reservoir PN (0.8–1.1 m). The mean value of TSI SDT index was the highest in the reservoir KA, and was increasing proportionally to the concentration of total suspended matter ($r = 0.544$, $P < 0.05$) and TDS ($r = 0.790$, $P < 0.05$). The highest concentration of TDS determined in reservoir KA, was significantly differ than in CH (Tab. 1).

Over 50% of the bottom sediment composition in all reservoirs consisted of silica. The reservoir PN was determined to contain the maximum concentrations of both, SiO_2 (69.1%) and aluminium oxides (7.4%). At the same time high concentration of the fractions NaOH-RP = 1.55 $mg\,P\,d.m^{-1}$ and TP = 3.97 $mg\,P\,d.m^{-1}$ was observed in bottom sediments in PN. The sediments in the CH and KA were distinguished by the highest share of organic matter and phosphorus fractions bound organic matter (Tab. 2). Physicochemical determinants of zooplankton community structure have been indicated by RDA and described in the discussion section.

3.2 Zooplankton structure

In the studied reservoirs, in total, 44 taxa of zooplankton were identified, including 34 Rotifera, 5 Cladocera and 5 Copepoda (Tab. 3). The total number of taxa was lowest in KA (21) and comparable in reservoirs PN and CH (27 and 26; Tab. 4). Rotifers were the most diverse group. The highest number of rotifer species were recorded in PN (23) and the lowest, in reservoir KA (12). Twenty rotifer species were identified in CH.

The greatest ranges of zooplankton abundance and biomass were determined in reservoir CH (595–2462 $ind.\,L^{-1}$ and 1.9–15.9 $mg\,L^{-1}$, respectively), with high rotifers and crustaceans contribution (mean 73% and 70%, respectively). The lowest ranges of zooplankton abundance and biomass were determined in reservoir PN (83–308 $ind.\,L^{-1}$ and 0.03–0.93 $mg\,L^{-1}$, respectively), with the greatest contribution of rotifers (mean 93% and 76%, respectively). The mean value of

Table 2. Chemical composition of bottom sediments in the analyzed reservoirs in September 2012.

Reservoir	CH	KA	PN
Bottom sediments parameters (%)			
CO_2	3.95	3.78	2.2
SiO_2	51.68	59.45	69.06
N	0.78	0.54	0.72
CaO	3.56	3.92	3.1
MgO	2.74	2.46	0.34
Fe_2O_3	4.99	4.37	3.98
Al_2O_3	3.42	2.99	7.41
Organic matter	16.69	14.09	14.62
Fractions of phosphorous in bottom sediments (mg P d.m^{-1})			
NH_4Cl-P (labile)	0.016	0.013	0.021
BD-P (bound Fe)	0.188	0.251	0.378
NaOH-RP (bound Al)	0.684	0.440	1.55
NaOH-NRP (bound organic matter)	0.99	1.039	0.857
HCl-P (bound Ca)	0.484	0.530	0.522
Res-P	0.612	0.610	0.637
TP	2.87	3.23	3.97

zooplankton density in reservoir PN was statistically differ among CH ($H = 15.762$, $P < 0.000$; Fig. 3A); whereas zooplankton biomass in PN was differ than in CH and KA ($H = 11.902$, $P < 0.002$; Fig. 3B).

Species diversity and biocenotic relationships in the reservoirs were determined by the number of species and variations in the population size of each taxon. Average number of species was the highest in CH (17) and the lowest in KA (12; Fig. 3C). The zooplankton of reservoirs CH and PN was highly diverse ($H' = 2.09$ and 2.01, $d = 6.72$ and 10.07, $J' = 0.640$ and 0.597, respectively; Tab. 4). The zooplankton of KA was marked by the lowest values of diversity index ($H' = 1.67$), richness and eveness index ($d = 6.16$ and $J' = 0.549$). The differences in H' and J' indexes mean values between KA and the other two reservoirs, were significant (Fig. 3D–F). In reservoirs CH and KA, rotifer *Polyarthra longiremis* predominated (40% and 43%, respectively), followed by larval forms of copepods (19% and 30%, respectively); following species also dominated in these reservoirs: *Keratella valga* (10%; CH); *Filinia longiseta* (5%; CH), *Ascomorpha ovalis* (10%; KA), and cladoceran *Daphnia cucullata* (9% and 6%; KA and CH). Reservoir PN was dominated by the rotifer taxa: *P. longiremis* (33%), *A. ovalis* (27%), *Synchaeta* spp. (12%), *Keratella tecta* (9%). The greatest faunal similarity between zooplankton communities was observed in KA and PN reservoirs by about 47%. The PN was most different in this respect to CH (85%) (Tab. 5).

3.3 Primary gradients affecting zooplankton community

An overall RDA on zooplankton abundance incorporating the environmental variables with significant marginal effects showed that 78% of the variance was explained. The pH and DO had significant relationships ($P = 0.002$ and $P = 0.042$, respectively) with zooplankton, and they explained 34% and 15%, respectively, of the variability (Fig. 4).

The sum of all the canonical eigenvalues was 0.867 (Tab. 6). The first two components of RDA explained 61.3% of the taxonomic variation, while the first axis accounted for 44.9% of total variance. This represents a pH gradient that is correlated negatively with DO. The second axis (16.4% of total variance) was correlated with the chlorophyll *a* gradient and negatively with concentration of PO_4^{3-}.

4 Discussion

Acidification, salinity, and pollution with mineral salts are the most frequent determinants of the biological conditions of post-mining waters (Bielańska-Grajner and Gładysz, 2010; Rönicke *et al.*, 2010; Moser and Weisse, 2011; Bielańska-Grajner and Cudak, 2014; Ferrari *et al.*, 2015; Sienkiewicz and Gąsiorowski, 2016; Pociecha *et al.*, 2017). The physicochemical parameters of the analyzed reservoirs were similar to those of natural water bodies. The waters were slightly alkaline (pH = 7.2–8.2), subsaline (TDS = 500–3000 mg L^{-1}; Hammer, 1993), and water conductivity ranged within 840–1005 µS cm^{-1}. Thus, the hydrochemical water parameters were not a limiting factor in the development of most zooplankton species. The zooplankton richness in the examined reservoirs was shaped mainly by rotifers. The greatest Rotifer abundance and species diversity occurred in reservoir CH. RDA analysis showed a strong positive correlation of the dominant species (*K. tecta*, *P. longiremis*, *Keratella quadrata*, *Brachionus angularis*, *Brachionus calyciflorus*, *F. longiseta*) with pH, PO_4^{3-} and TP, and TN (Figs. 4 and 5). These common pelagic species are most often identified in the Rotifera composition of artificial waters bodies (Balvert *et al.*, 2009; Bielańska-Grajner and Gładysz, 2010; Mallo *et al.*, 2010; Skowronek *et al.*, 2012; Marszelewski *et al.*, 2017; Pociecha *et al.*, 2017). They are also thought to be indicative of water eutrophication (Ejsmont-Karabin, 2012). In the reservoirs analyzed, the concentration of chlorophyll *a* (TSI Chl*a* < 60) indicated meso-eutrophic conditions, while the phosphorus content (TSI TP > 60) indicated eu-hypertrophy (Carlson, 1977). Good trophic conditions in reservoirs CH and KA were confirmed by the constant presence of Cladocera. *D. cucullata* and *Bosmina longirostris* were the most numerous representatives of mature crustacean forms. RDA analysis showed that factors most positively correlated with incidence of mature and juvenile cladocerans and copepods were characteristic for reservoir KA; these were water temperature, chlorophyll *a* concentrations, and total suspensions (Figs. 4 and 5). The high concentration of suspended matter could have been caused by the type of water supply and the resuspension of bottom sediments perhaps because of intense turbulence caused by water flow or the mechanical impact of wind. Moreover, the bottom sediments in reservoir KA were rich in organic bonds of phosphorus, which were regularly activated this way, entered circulation, and were promptly mineralized in the water column because of good oxygenation. This process could shape the intensity of primary production measured with chlorophyll *a* and increase the biomass of crustacean zooplankton. Populations of large and

Table 3. Qualitative and quantitative structure of zooplankton based on dominating and frequent taxa in the individual reservoirs (mean ± SD).

Taxa	CH		KA		PN	
	Mean	±SD	Mean	±SD	Mean	±SD
Rotifera (ind. L^{-1})	**926**	**587**	**255**	**160**	**146**	**95**
Ascomorpha ovalis (Bergendal, 1892)			46**	42	41**	33
Asplanchna priodonta Gosse, 1850	12	18	1	1	5	5
Brachionus angularis Gosse, 1851	6	5			<1	0
Brachionus calyciflorus Pallas,1766	12	21				
Brachionus spp.					1	1
Colurella spp.	<1	0			<1	0
Filinia longiseta (Ehrenberg, 1834)	68*	56			<1	0
Hexarthra mira (Hudson, 1871)	12	13	2	3		
Keratella cochlearis (Gosse, 1851)	42	25	1	1	1	1
Keratella quadrata (Müller, 1786)	4	4				
Keratella tecta (Gosse, 1851)	48	47			14*	20
Keratella valga (Ehrenberg, 1834)	130*	71	1	1	1	1
Lecane spp.	1	1	1	1		
Lepadella ovalis (Müller, 1786)	<1	0			<1	0
Notholca acuminata (Ehrenberg, 1832)					2	2
Notholca squamula (Müller, 1786)					3	2
Polyarthra longiremis Carlin, 1943	526**	495	193**	186	50**	62
Polyarthra vulgaris Carlin, 1943	43	45				
Pompholyx sulcata Hudson, 1885	10	11	7	7	6	5
Synchaeta sp.	11	12	3	3	18**	30
Testudinella patina (Herman, 1783)					1	1
Trichocerca similis (Wierzejski, 1893)					1	1
Rotifera other species	1	1			2	1
Cladocera (ind. L^{-1})	**116**	**125**	**43**	**31**	**3**	**4**
Coronatella rectangula Sars, 1861			<1	0		
Bosmina longirostris (Schoedler, 1866)	31	49	3	2	2	2
Daphnia cucullata Sars, 1862	85*	85	39*	32	1	2
Diaphanosoma brachyurum (Liévin, 1848)			<1	0		
Leptodora kindtii (Focke, 1844)			1	1		
Copepoda (ind. L^{-1})	**269**	**233**	**144**	**129**	**4**	**3**
Cryptocyclops bicolor (Sars, 1863)			3	3		
Cyclops strenuus Fischer, 1851	<1	0	1	1		
Eucyclops speratus (Lilljeborg, 1901)					<1	0
Thermocyclops crassus (Fischer, 1853)	7	9	5	7		
Harpacticoida	7	12	1	2	<1	0
copepodites	112*	68	40*	42	1	1
nauplii	143**	144	94**	71	3	2
Number of species (ind.)	**17**	**1**	**12**	**3**	**14**	**5**
Abundance of zooplankton (ind. L^{-1})	**1311**	**945**	**442**	**319**	**153**	**103**
Rotifera (%)	73.1	23.1	59.4	28.0	93.3	5.6
Cladocera (%)	7.5	10.4	8.9	3.6	2.9	3.8
Copepoda (%)	19.4	14.5	31.7	25.4	3.8	2.4
Biomass of zooplankton (mg L^{-1})	**10.32**	**11.1**	**4.95**	**4.47**	**0.34**	**0.40**
Rotifera (%)	30.3	37.3	8.4	10.3	75.7	20.9
Cladocera (%)	55.2	37.9	73.2	25.0	15.1	22.9
Copepoda (%)	14.6	9.1	18.4	16.1	9.2	12.8

** - eudominant (≥10%), * - dominant (5–9.9%).

Table 4. Measures of zooplankton quantitative and qualitative structure in individual.

Parameter	CH	KA	PN
Number of species (ind.)	26	21	27
Shannon's index, *H'*	2.09	1.67	2.01
Margalef's index, *d*	6.72	6.16	10.07
Pielou's index, *J'*	0.640	0.549	0.597

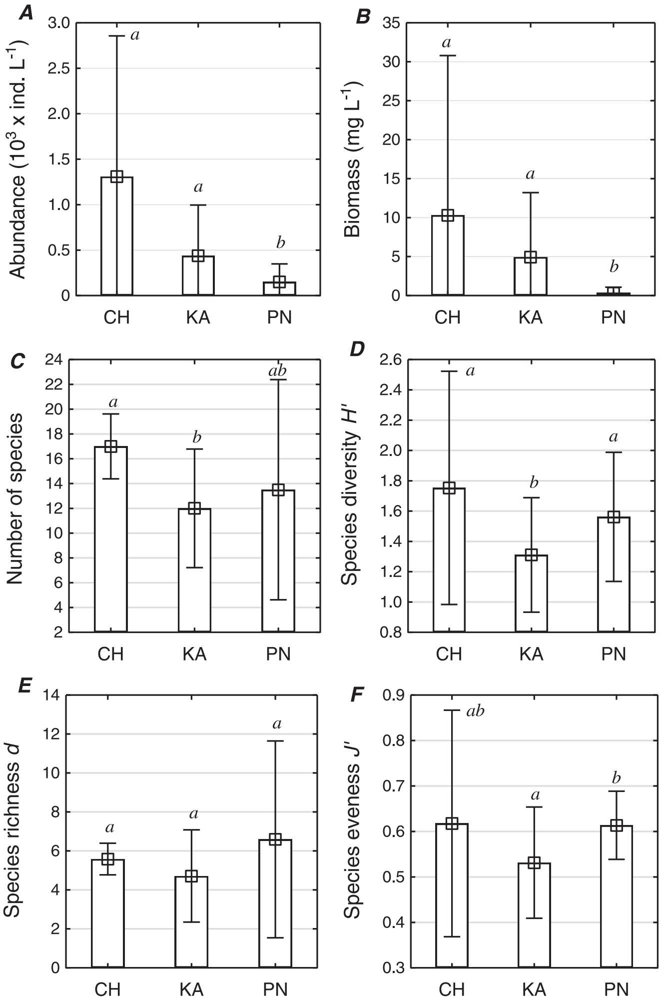

Fig. 3. Mean values of zooplankton quantitative and qualitative measures. Small square: average, rectangle: ±standard error, "swirls": ±SD.

Table 5. Similarity of zooplankton communities between individual reservoirs, based on Bray–Curtis dissimilarity index.

	CH	KA	PN
CH	0.000		
KA	0.624	0.000	
PN	0.847	0.535	0.000

medium-sized cladocerans (*D. cucullata*), in particular, depend on an appropriate density of plankton algae, which depends, in turn, on the productivity of the ecosystem (Beisner, 2001; Zurek, 2006). On the other hand, suspensions that reduce visibility protect zooplankton organisms, mostly larger species (*e.g.*, Cladocera) from being attacked by fish feeding on plankton (Sutela and Huusko, 2000; Špoljar *et al.*, 2011).

Particles of organic and mineral suspension are substrates for the growth of bacteria, which stimulates the mass growth of the rotifers that feed on these bacteria, *e.g.*, *Keratella* spp. and *F. longiseta* (Mayer *et al.*, 1997; Ejsmont-Karabin, 2012). Strong populations of these taxa were observed in reservoir CH. However, their absence or the presence of single individuals were found in reservoir KA, and the general decrease in the number and diversity of Rotifera was most probably a consequence of the development of populations of *D. cucullata* and other cladocerans (Gilbert, 1988). Balvert *et al.* (2009) describe the complete elimination of rotifers subsequent to the mass occurrence of *Daphnia dentifera* in a post-mining pond.

Thermal-oxygen water conditions were closely correlated with zooplankton structure characteristics in reservoir PN (Figs. 4 and 5), where there was a distinctly low total number of zooplankton, and the species identified constituted weak populations with low numbers of individuals. The constant presence of rotifers of the genus *Notholca* was, however, noteworthy. The species *Notholca acuminata* and *Notholca squamula* are moderately psychrophilic stenothermic organisms that are found in temperate geographical latitudes in the early spring months in waters with temperatures below 10 °C (Ejsmont-Karabin *et al.*, 2004). In reservoir PN, these species were present throughout the study period, and when the water temperature was 18 °C, they achieved dominant status (>5%). A similar pattern was observed in May (1980) in a shallow eutrophic lake where the presence of *N. squamula*, irrespective of the water temperature, depended on the constant availability of its preferred food, *i.e.*, *Asterionella formosa* (Bacillariophyceae). The environment of reservoir PN was distinguished by an abundant assemblage of diatoms; there were numerous species of the order Pennales. Pociecha (2008) documents the effect of diatom food resources of a similar composition on the high number (over 100 ind. L^{-1}) of *Notholca squamula salina* in a shallow Arctic lake in May and June.

Diatoms do not require high concentrations of nutrients in the water. They successfully competed for scant phosphorus resources in the waters of this reservoir and eliminated green algae, but they were not a completely available food for most species of plankton filter-feeders. The low primary production in reservoir PN was associated with the absence of phosphorus in the water. Aluminum originating from rock minerals and known under the common name aluminosilicates could simultaneously act as a carrier binding phosphorus from the water (de Vincente *et al.*, 2008). The coagulation processes of silicates and metal hydroxides on the surface of sediments limited the life of phytoplankton. Considering how long reservoir PN has been in use and how important the time factor is for the advancement of coagulation processes, it is plausible that such distortions in the circulation of phosphorus compounds could have come into play (Goedcoop and Pettersson, 2000; de Vincente et al., 2008). In addition, silica compounds in the water and sediments of

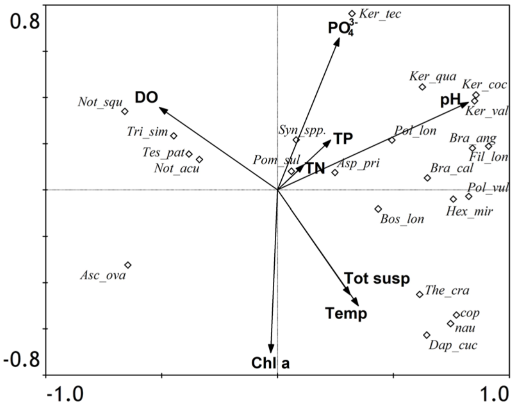

Fig. 4. Ordination biplot of redundancy analysis (RDA) for zooplankton communities (species) and hydrochemical data (environmental variables). Vectors pointing in the same direction indicate a positive correlation, vectors crossing at right angles indicate a near zero correlation, while vectors pointing in opposite direction show a high negative correlation. Abbreviations used in the figures: *Asc_ova, Ascomorpha ovalis*; *Asp_pri, Asplanchna priodonta*; *Bos_lon, Bosmina longirosrtis*; *Bra_ang, Brachionus angularis*; *Bra_cal, Brachionus calyciflorus*; cop, copepodite of cyclopoids; *Dap_cuc, Daphnia cucullata*; *Fil_lon, Filinia longiseta; Hex_mir, Hexarthra* mira; *Ker_coc, Keratella cochlearis; Ker_tec, Keratella tecta; Ker_qua*, *Keratella quadrata*; *Ker_val*, *Keratella valga*; nau, nauplii of cyclopoids; *Not_acu*, *Notholca acuminata*; *Not_sqa*, *Notholca squamula*; *Pol_lon*, *Polyarthra longiremis; Pol_vul*, *Polyarthra vulgaris; Pom_sul*, *Pompholyx sulcata*; *Syn_spp*., *Synchaeta spp*.; *Tes_pat*, *Testudinella patina*; *The_cra*, *Thermocyclops crassus*, *Tri_sim*, *Trichocerca similis*.

Table 6. Summary statistics for the first four axes of RDA of zooplankton data from analyzed reservoirs in June/July (spring/summer season) and August/September (summer/autumn season) in 2012–2013.

Axes	1	2	3	4	Total variance
Eigenvalues	0.449	0.164	0.107	0.061	1.000
Species-envir. correl	0.946	0.988	0.966	0.947	–
Cumulative % variance	–	–	–	–	–
of species data	44.9	61.3	71.9	78.0	–
of species-envir. relation	51.8	70.6	82.9	90.0	–
Sum of all eigenvalues	–	–	–	–	1.000
Sum of all canonical eigenvalues	–	–	–	–	0.867

reservoir PN (8–10% higher than in reservoirs CH and KA) contributed to the development of diatoms. The results published by Tilman *et al.* (1982) and van Donk and Kilham (1990) indicate that the preferred food of the rotifer genus *Notholca* – diatom *Asterionella formosa* develops in proportion to increasing ratios of Si:P in the water.

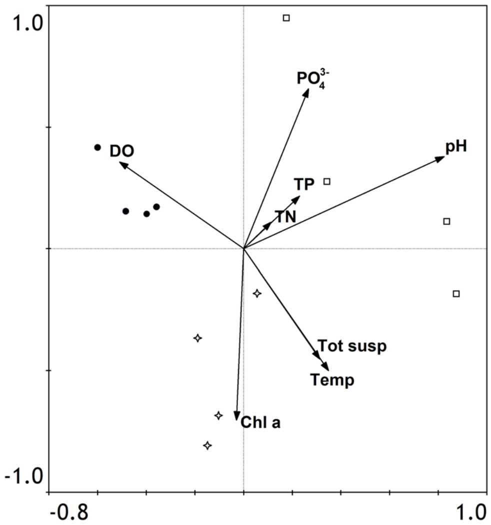

Fig. 5. RDA ordination plot of samples and environmental variables. Denotations: DO – dissolved oxygen, Chl *a* – chlorophyll *a*, TP – total phosphorus, TN – total nitrogen, PO$_4^{3-}$ – orthophosphate, Tot susp – total suspension. Filled circle: PN, open square: CH, open star: KA.

5 Summary

The environment of the studied reservoirs provided good conditions for the development of rich communities of zooplankton. However, each of the reservoirs retained a certain separateness and characteristics of abiotic conditions that determined the structure of zooplankton. At this stage, it is difficult to assess which environment created the best conditions for the development and co-existence of the rich structure of zooplankton. The most clearly outlined aspects of the effects of abiotic factors on plankton biocenosis were analyzed. The eutrophy factor, just like in natural water ecosystems, determined good nutrition conditions and promoted the richness of zooplankton. On the other hand, the high concentration and composition of suspensions have limited these features. The above observations are an initiation to further analyzes directed to the functioning of zooplankton community under turbid water conditions. Apart from abiotic factors stated above, we cannot exclude the role of fish predation on zooplankton structure. Knowledge of the functioning of artificial reservoirs is just as important as that of natural lakes. While contributing to human needs, artificial reservoirs also fulfill important ecological functions.

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