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*Original Research*

# Zooplankton of Fish Culture Ponds Periodically Fed with Treated Wastewater

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### Abstract

This study investigated three earth fish ponds fed with biologically treated wastewater from the treatment plant in Olsztynek. The ponds were stocked with the following fish species with a varied age structure: common carp (*Cyprinus carpio*), tench (*Tinca tinca*), European pike-perch (*Sander lucioperca*), and roach (*Rutilus rutilus*). Zooplankton samples were collected once a month, from April to October 2007. Rotatoria were the most diverse and the most abundant zooplankton community. The zooplankton biomass in all ponds was dominated by crustaceans, including such species as *Keratella cochlearis*, *Keratella quadrata*, *Polyarthra longiremis*, *Brachionus angularis*, young forms of Copepoda (nauplii and copepodites), as well as *Daphnia longispina* and *Thermocyclops crassus*. The greatest faunal similarities between the analyzed zooplankton groups were determined in ponds 1 and 2, while the greatest differences were noted between ponds 2 and 3. The structure and dynamics of zooplankton changes in the investigated ponds were determined mostly by trophic relationships and interspecies interactions, while fish predation pressure supported greater species diversity and its reinstatement.

**Keywords:** zooplankton, Cladocera, Copepoda, Rotatoria, ponds, fish, wastewater

## Introduction

Wastewater recirculation in fish culture ponds supports the growth of fish biomass and final wastewater treatment. The practice of using wastewater in fish culture ponds is popular in many Asian countries [1]. In Europe, research into the use of raw or preliminarily treated wastewater was carried out by Danielewski [2], Olach et al. [3], and Faina et al. [4]. The option of deploying biologically purified wastewater was investigated by Wolny [5], Tucholski [6], and Kuczyński et al. [7]. Sewage treated by the activated sludge method is characterized by low organic matter content, but owing to high nitrogen and phosphorus levels [8], it requires further treatment before evacuation to waters. As demonstrated by previous studies [9], an effective solution is delivered by fish ponds that act as the third stage of the wastewater treatment process.

The biogenic elements found in wastewater fertilize and contribute to the eutrophication of pond ecosystems, affecting species composition, abundance, and biomass of zooplankton. The above parameters can serve as indicators of the productivity of fish ponds, since zooplankton are the main food base and the most valuable source of natural protein for developing fish.

The moment of transition from endogenous nutrition, via the yolk sac, to exogenous food sources is a crucial stage in the lifecycle of fish when food availability becomes an important consideration. As shown by numerous studies,

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zooplankton are usually the first source of exogenous nutrition for larval fish [10, 11]. Various aspects of larval feeding on zooplankton were investigated. Marmulla and Rosch [12] and Sutela and Huusko [13] discuss the nutritional preferences of various larval species in the context of prey taxonomy. The above authors have observed that larvae are capable of precise food selection, and they choose, for example, only certain developmental forms of a given Copepoda taxon, while ignoring other similarly-sized organisms [14, 15]. Rajasilta and Vourinen [16] studied the food selectivity of larvae of several freshwater fish species in two ecosystems characterized by different levels of productivity. In the more productive environment, larvae preferred Copepoda (*Eurytemora*, *Acartia*) and rejected Cladocera. In the ecosystem marked by lower plankton availability, larval fish showed a preference for Cladocera (*Bosmina*, *Pleopsis*). The food selectivity of larvae was also examined in view of the energy value and the digestibility of various zooplankton taxa [17]. According to Sutela and Huusko [18, 19] fish larvae preyed on rotifers only during a shortage of crustacean organisms, and their choices were determined by the calorific value of prey, which is higher in crustaceans than in rotifers.

Fish choose food types marked by the greatest nutritional suitability and availability, but the key factor determining the availability of different foods is the size (width) of planktonic organisms that supports their ingestion [20-22] as well as prey density [23]. Larval fish begin preying on small organisms such as rotifers and the early developmental forms of planktonic crustaceans – nauplii and copepodites [24]. The range of available food particles increases with the growth of larvae (Cladocera, adult forms of Copepoda, Gastropoda larvae, and others).

In the light of published data, the environmental pressure exerted by fish is powerful enough to modify the composition and the abundance of zooplankton communities. These changes affect not only the population and biomass of zooplankton, but may also influence their age structure, size and species composition, thus decreasing the biodiversity of aquatic ecosystems [25].

The objective of this study was to determine the growth rate and the structure of zooplankton communities in fish culture ponds fed with wastewater treated by the activated sludge method in sequencing batch reactors (SBR).

## Materials and Methods

### Field Experiment

A field experiment investigating fish stocking material was carried out in the production season from April to October 2007 in three earth fish ponds on the premises of a wastewater treatment plant in Olsztynek in northeastern Poland (N=53º36’14.66” E=20º17’23.24”) (www.geoportal.gov.pl). Raw wastewater fed to the treatment plant comprised household sewage as well as wastewater from a fruit and vegetable processing plant. Following preliminary treatment and the removal of screenings and sand, wastewater was treated in sequencing batch reactors (SBR).

Table 1. The species, age, and average individual weight ($g \cdot fish^{-1}$) of fish stock in the experimental ponds of the waste treatment plant in Olsztynek.

| Fish species and age | No. of ponds | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Common carp (1+)* | 375.0 | 365.0 | 559.1 |
| Common carp (0+)** | 1.6 | 1.6 | 1.6 |
| Tench spawner* | 944.4 | 653.8 | 342.8 |
| Tench (1+)* | 18.3 | - | 18.2 |
| Tench (0+)* | 1.0 | - | 1.0 |
| Pike-perch (0+)** | - | 0.15 | - |
| Roach (0+)* | 2.5 | 2.5 | - |

* stocked in mid-November 2006
** stocked in mid-June 2007

The experimental ponds had a surface area in the range of 0.94 ha (pond No. 2) to 1.04 ha (pond No. 1), with a maximum depth of 1.5 m in the summer. The studied reservoirs were filled with water from underground springs at the bottom of ponds No. 2 and 3. They were fertilized with treated wastewater from the treatment plant. The ponds were stocked with the common carp (*Cyprinus carpio* L.), tench (*Tinca tinca* L.), European pike-perch (*Sander lucioperca* L.), and roach (*Rutilus rutilus* L.). The species and the age structure of fish used for pond stocking are presented in Table 1. The average weight of individual carp aged 1+ ranged from 365.0 g $fish^{-1}$ in pond No. 2 to 559.1 g $fish^{-1}$ in pond No. 3, and the weight of carp aged 0+ was 1.6 $fish^{-1}$ in all experimental ponds. The average weight of tench spawners reached from 342.8 g $fish^{-1}$ in pond No. 3 to 944.4 $fish^{-1}$ in pond No. 1. Tench aged 1+,weighed 18.3 g $fish^{-1}$ in pond No. 1 and 18.2 g $fish^{-1}$ in pond No. 3, and tench in the 0+ age category – 1.0 g $fish^{-1}$ in ponds No. 1 and 3. The average individual weight of roach hatchlings and European pike perch hatchlings was 2.5 g $fish^{-1}$ and 0.15 g $fish^{-1}$, respectively. The presence of tench fry aged 0+ was noted during fish harvest in ponds No. 1 and 3 in the autumn of 2007. The hatchlings were most probably the natural offspring of tench spawners in those ponds.

### Zooplankton Analysis Methods

Zooplankton samples were collected once a month, from April to October 2007, using a 5-liter Ruttner water sampler, at a depth of approximately 1 m. The samples were collected around noon. A test site was set up on each pond, and every sampling session involved the collection of 25 liters of water, which was passed through a plankton net with a 60 μm mesh size and fixed in 4% formalin.

The collected material was analyzed to determine the qualitative and quantitative composition and zooplankton biomass. Zooplankton were identified to the lowest possible taxonomic unit and developmental stage [26-29].

Table 2. Measures of zooplankton qualitative structure in experimental ponds.

| Pond<br>Measure/indicator | 1 | 2 | 3 |
|---|---|---|---|
| Species richness | 0.767 | 0.618 | 0.579 |
| Species diversity | 2.83 | 2.81 | 2.07 |
| Species evenness | 0.724 | 0.756 | 0.561 |
| Faunal similarity | 0.685 | 0.654 | 0.608 |
| Faunal dissimilarity | 0.443 | 0.583 | 0.614 |

Nauplius and copepodite stages of copepods were not subjected to a taxonomic analysis. Plankton counts (individuals per $dm^{-3}$) were determined in accordance with the method proposed by Hansen [30]. The individual biomass of zooplankton organisms was determined based on the weight standards for rotifers [28]. Individual crustaceans and protozoa were measured under a microscope equipped with an eyepiece reticule with an accuracy of up to 0.01 mm under transmitted light. Biomass was examined on the assumption that the density of zooplankton organisms was equal to 1, i.e. 1 $mm^3$=1 mg [31]. The obtained results were used to calculate the volume of organisms, and their shape was compared to that of geometric figures.

## Methods for Evaluating the Qualitative Structure of Zooplankton

The qualitative structure of zooplankton was determined based on Margalef's species richness index [32], the Shannon-Weiner diversity index [33], Pielou's evenness index [34], the Jacckard index of species similarity and diversity [35] and the Bray-Curtis index of similarity [36].

## Statistical Analysis

The results were processed statistically in accordance with the methodology proposed by Sokal and Rohlf [37] and Zar [38] using the STATISTICA 8.0 application. The coefficients of correlation between the abundance and biomass of high-rank taxonomic groups and the total abundance and biomass of zooplankton were determined. The statistical significance of differences in mean zooplankton biomass and abundance values between experimental ponds was evaluated with the Mann-Whitney U-test.

# Results

## Qualitative Structure of Zooplankton

The presence of 41 Rotifera taxa, 7 Cladocera taxa, 6 Copepoda species and their juvenile forms, as well as 6 Protozoan species were identified in the zooplankton of fish ponds in Olsztynek (Table 3). Species diversity and biocenotic relationships in the studied ponds were determined by the number of species and variations in the population size of each taxon. The total number of taxa was highest in pond No. 1 (48) and comparable in ponds No. 2 and 3 (39 and 40). The greatest faunal similarity between zooplankton communities was observed in ponds No. 1 and 2, while the greatest dissimilarity was noted between ponds No. 2 and 3 (Fig. 1). The zooplankton of ponds No. 1 and 2 was highly diverse and characterized by similar values determined with the use of the Shannon index (2.83 and 2.81, respectively), the evenness index (0.724 and 0.756) and the species richness index (0.767 and 0.618) (Table 2). The zooplankton of pond No. 3 was marked by the lowest diversity index (2.07), an evenness index of 0.561 and the highest zooplankton abundance (7442 individuals $dm^{-3}$). The above is indicative of the dominance of several taxa, which reached high densities in pond No. 3, namely *Bosmina longirostris* (39%), members of the genus *Polyarthra* sp. (37%), copepod nauplii (25%) and *Daphnia longispina* (16%) (Table 3).

Rotifers were the most abundant and the most diverse zooplankton group in the studied ponds (Table 3). Pond No. 1 showed the highest number of rotifer taxa at 34, followed by ponds No. 2 and 3 at 26 and 27, respectively. The list of the most abundant and the most frequently occurring species, which periodically assumed the role of eudominants or dominants in the biocenosis, included *Keratella cochlearis*, *Keratella quadrata*, *Polyarthra longiremis*, *Polyarthra major*, *Brachionus angularis*, and *Asplanchna priodonta*. Their maximum share of the total zooplankton abundance reached 38.4% (pond No. 1), 21% (pond No. 2), 35% (pond No. 2), 20.3% (pond No. 3), 28.3% (pond No. 2), and 28.2% (pond No. 2), respectively. Selected species were marked by high or very high abundance only during individual sampling sessions. They were: *Ascomorpha saltans* (11.3%), *Brachionus rubens* (37.8%), *Filinia longiseta* (42.8%), *Hexarthra mira* (15%), and *Pompholyx*

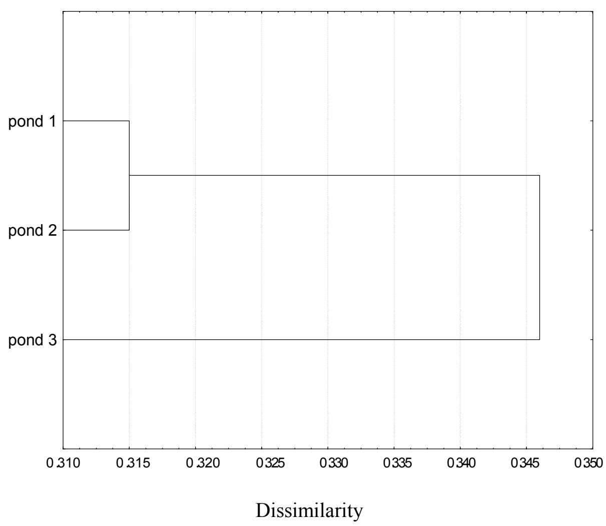


Fig. 1. Dendrogram of faunal similarities between zooplankton communities in culture ponds in Olsztynek. Pair-group method with arithmetic means.

Table 3. Species composition and abundance of zooplankton in culture ponds in Olsztynek in 2007, (individuals per dm$^{-3}$).

| Date, pond No. | 02.04.2007 | | | 07.05.2007 | | | 04.06.2007 | | | 02.07.2007 | | | 01.08.2007 | | | 03.09.2007 | | | 02.10.2007 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Taxon | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
| *Ascomorpha ecaudis* Perty | 6 | 2 | | | | 1 | 9 | | | | | | | | | | | | | | |
| *Ascomorphella volvocicola* Plate | 5 | 3 | | | | | | 60** | 2 | <1 | <1 | 10 | | | | | | | | | |
| *Asplanchna priodonta* Gosse | | | | 24 | 46 | 2 | 18 | 5 | 2 | <1 | | 3 | 208** | 91 | 25 | 6 | 48** | | 1 | 24 | 85 |
| *Brachionus angularis* Gosse | 1 | 19 | | 2 | 1 | 1 | | | | | 2 | | 8 | 1 | 3 | 3 | 27* | 6 | 77** | 448** | |
| *Brachionus calyciflorus* Pallas | | 2 | | 1 | 4 | | | | | | 1 | <1 | 2 | 2 | 2 | | | | | 11 | 1 |
| *Brachionus diversicornis* Daday | | | | | | | | | | | | | | | | 11 | 1 | | 7 | 51 | |
| *Brachionus quadridentatus* Hermann | | | | | | | | | | | | | 11 | | 1 | | | | | | |
| *Brachionus rubens* Ehrenberg | 4 | 1 | <1 | | 3 | 1 | 95** | 200** | 11 | 4 | | 4 | 2 | 1 | | | | | | | |
| *Cephalodella gibba* Ehrenberg | 2 | 1 | <1 | | | | | | | | | | | | | | | | | | |
| *Cephalodella psammophila* Koch-Althaus | | | | | | | | | | | | | | | | | | | 1 | | |
| *Colurella colurus* Ehrenberg | 5 | | | | | | | | | | | | | | | | 1 | | | | |
| *Enteroplea lacustris* Ehrenberg | | <1 | | | | | | | | | | | | | | | | | | | |
| *Euchlanis dilatata* Ehrenberg | 1 | | | | | | | | | <1 | | | | | | | | | | | |
| *Filinia longiseta* Ehrenberg | | | | | | | | | | | | | | | | 2 | 16 | 16 | 61** | 678** | |
| *Filinia longiseta passa* O.F. Müller | <1 | <1 | 1 | | | | | 1 | | | | | | | | | | | | | |
| *Hexarthra mira* Hudson | | 1 | | | | | | 3 | 1 | 12 | 12* | 27** | 8 | 240* | 136** | | 2 | | | | |
| *Keratella cochlearis* Gosse | 163** | 154** | 2 | 208** | 295** | 19* | 1 | | | 1 | 7* | 1 | 1 | | | | | | | | |
| *Keratella cochlearis* var. *robusta* Gosse | | | | | | | | | | | | | | 240* | 16 | 6 | 6 | 2 | 5 | 18 | 306** |
| *Keratella cochlearis* var. *tecta* Gosse | | | | 2 | | | | | | | 3 | <1 | | | | 2 | | | | | |
| *Keratella quadrata* O.F. Müller | 1 | <1 | | 15 | 150** | 10 | | 1 | | 1 | 2 | <1 | 40 | 512** | 61* | 12 | 16 | 19 | 5 | 33 | 53* |
| *Lecane bifurca* Bryce | 3 | | | | | | | | | | | | | | | | 1 | | | | |
| *Lecane bulla* Gosse | | | | | | | | | 1 | | | | | | | | | | | | |
| *Lecane closterocerca* Schmarda | <1 | | | | | | | | 1 | | <1 | <1 | 1 | | 2 | | 2 | | | 1 | |
| *Lecane hamata* Stokes | | | | | | | | | | | | | 2 | | | | | | 1 | | |
| *Lecane stenroosi* Meissner | | | | | | | | | | <1 | | | | | | | | | | | |

Table 3. Continued.

| Date, pond No. | 02.04.2007 | | | 07.05.2007 | | | 04.06.2007 | | | 02.07.2007 | | | 01.08.2007 | | | 03.09.2007 | | | 02.10.2007 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Taxon | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
| *Lepadella ovalis* O.F. Müller | | | | | | | | | | <1 | | | | | | | | | | | |
| *Lepadella patella* O.F. Müller | | | | | | | | | 1 | | | | | | | | | | | | |
| *Mytilina mucronata* O.F. Müller | | | | | | | | | | | | | | | 1 | | | | | | |
| *Polyarthra dolichoptera* Idelson | | | | | | | | | | | | | | | | 1 | 10 | | | | 38 |
| *Polyarthra longiremis* Carlin | 138** | 147** | | 27 | 38 | 4 | | | 1 | <1 | | | 232** | 592** | 280** | 11 | 80** | | 5 | 3 | 45* |
| *Polyarthra major* Burckardt | | | | | | | | | | | 1 | | 224** | 440** | 184** | 6 | 29* | 100 | 13 | 27 | 114** |
| *Polyarthra remata* Skorikov | 1 | | | | | | | | | | | | | | | | | | | | |
| *Pompholyx sulcata* Hudson | | | | | | | | | | | | | 4 | | | 128** | | | 18 | | |
| *Proales* sp. | | | | 2 | | | | 1 | | | | 5 | 1 | | | | | | | | |
| *Synchaeta* sp. | 4 | 5 | <1 | | | | 2 | 5 | | | | | | | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| *Testudinella patina* Hermann | | | | | 1 | | | | | | | | 5 | | | | | | | | |
| *Trichocerca pusilla* Lauterborn | | | | | | | | | | | | | | | | 1 | | | 2 | | |
| *Trichocerca rattus* O.F. Müller | | | | | | | | | | | | 1 | | | | | | | | | |
| *Trichocerca Rousseleti* Voigt | | <1 | | | | | | | | | | | | | | | | | | | |
| *Trichocerca stylata* Gosse | | | | | | | | | | | | | | | | 1 | | | | | |
| *Trichocerca weberi* Jennings | | | | | | 1 | | | | | | | | | 1 | | | | | | |
| **Rotatoria** – **total** | **332** | **335** | **4** | **282** | **538** | **38** | **125** | **276** | **19** | **20** | **28** | **51** | **748** | **2118** | **713** | **190** | **239** | **144** | **196** | **1295** | **643** |
| *Alona karelica* Stenroos | | | | | 1 | | | | | | | | | | | | | | | | |
| *Bosmina longirostris* O.F.Müller | | | 1 | | 4 | | 3 | 30* | | | 13** | | | 96 | 32 | 8 | | | 57* | 176** | |
| *Bosmina longirostris* var. *cornuta* O.F.Müller | | | | | | | | | | | | | | | | | | 2850** | | | |
| *Ceriodaphnia quadrangula* O.F.Müller | | | | | | | | | | | | | | | | | | | | 1 | |
| *Chydorus sphaericus* O.F.Müller | 8 | 4 | 2 | 32 | 12 | 1 | 1 | | | | 1 | | 2 | | | | | | | 4 | |
| *Daphnia longispina* O.F.Müller | 18 | 2 | 15 | 128** | 140** | 108** | 210** | 175** | 132** | 80** | 22** | 28** | 34 | 6 | 5 | 29 | 34* | 16 | 2 | 6 | 3 |
| *Daphnia magna* Straus | 1 | | | 1 | | | | 1 | | 1 | | | | | | | | | | | |
| Cladocera juv. | 6 | | | 68** | 170** | 8 | | 9 | 24* | 8 | 2 | 28** | 10 | 10 | 12 | 6 | 3 | 1350** | | 4 | 1 |
| **Cladocera** – **total** | **33** | **6** | **18** | **229** | **327** | **116** | **214** | **215** | **156** | **89** | **38** | **56** | **45** | **111** | **49** | **43** | **37** | **4216** | **65** | **192** | **4** |

Table 3. Continued.

| Date, pond No. | 02.04.2007 | | | 07.05.2007 | | | 04.06.2007 | | | 02.07.2007 | | | 01.08.2007 | | | 03.09.2007 | | | 02.10.2007 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Taxon | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
| *Acanthocyclops vernalis* Fischer | | | | | | | | | | | | | | | | | | | | 3 | |
| *Cyclops strenuus* Fischer | | | | 40* | 10 | | 8 | | | 46** | | | 24 | | | 14 | 1 | 2 | 30 | | 2 |
| *Cyclops vicinus* Uljanin | 3 | 5 | 20* | 6 | | 1 | 5 | | | 4 | 1 | | 6 | 2 | 10 | 9 | | | 8 | | |
| *Eucyclops macruroides* Lilljeborg | | | | | | | | | | <1 | | | | | | | | | | | |
| *Eudiaptomus graciloides* Lilljeborg | | | | | | | | | | | | | | | | 1 | | | | | |
| *Thermocyclops crassus* Fischer | 2 | <1 | 3 | 20 | 1 | 2 | 4 | 1 | 42** | 8 | 26** | 40** | 68* | 40 | 21 | 45* | 72** | 1 | 16 | 27 | 26 |
| kopepodit Copepoda | 5 | 7 | 13 | 26 | 6 | 8 | 24* | 9 | 24* | 26* | 7* | 35** | 124** | 120 | 32 | 80** | 60** | 5 | 49* | 50 | 69* |
| nauplius Copepoda | 48** | 56** | 266** | 35* | 80* | 26** | 16 | 28* | 96** | 180** | 30** | 58** | 128** | 43 | 80* | 196** | 43* | 250* | 132** | 18 | 63* |
| **Copepoda – total** | **57** | **68** | **302** | **127** | **97** | **38** | **57** | **38** | **162** | **263** | **63** | **133** | **350** | **206** | **142** | **344** | **176** | **258** | **235** | **97** | **160** |
| **Crustacea – total** | **90** | **74** | **320** | **356** | **424** | **154** | **271** | **253** | **318** | **352** | **101** | **188** | **395** | **317** | **191** | **387** | **213** | **4474** | **301** | **289** | **164** |
| *Arcella discoides* Ehrenberg | | | | 2 | 2 | 3 | | | 2 | 1 | <1 | | 1 | 4 | 4 | 80** | 24 | | 9 | | 3 |
| *Centropyxis aculeata* Ehrenberg | | | | | | | | | 1 | | | | | | | | | | | | 2 |
| *Codonella cratera* Leidy | 1 | | | | | | | | | | | 1 | | | | | | | 1 | | |
| *Difflugia limnetica* Levander | | | | 1 | 2 | | | | 2 | | | | 2 | | | 4 | 2 | | 72** | 2 | |
| *Difflugia pyriformis* Ehrenberg | | | | | | | | | | | | | | | | | | | 24 | | 3 |
| *Vorticella nebulifera* Ehrenberg | 2 | 12 | | | | | | | | | | | | | | | | | | | |
| **Protozoa – total** | **2** | **12** | | **2** | **4** | **3** | | | **5** | **1** | **<1** | **1** | **2** | **4** | **4** | **84** | **26** | | **106** | **2** | **8** |
| **Zooplankton – total** | **425** | **421** | **324** | **640** | **966** | **196** | **396** | **529** | **342** | **374** | **130** | **240** | **1146** | **2439** | **908** | **661** | **478** | **4618** | **602** | **1587** | **814** |

**strong domination >10%
*domination 5.5 – 10%

*complanata* (19.4%). The intensive growth of the above species was most frequently noted in ponds No. 1 and 2. The recedent species were mostly small organisms dwelling in the proximity of plants and/or psammon rotifers of the genera *Cephalodella*, *Colurella*, *Lecane*, and *Lapadella*.

In the group of crustaceans, the highest constancy of occurrence (100%) was noted in respect of *Daphnia longispina*, *Thermocyclops crassus*, copepod nauplii, and copepodites. A high share of juvenile forms in the total abundance of Cladocera was usually related to the dominance of adult forms of *D. longispina* and *B. longirosris* var. *cornuta*. *Daphnia magna*, a large cladoceran species, was rarely observed (between April and June) or it was noted as the sub-recedent species only in ponds No. 1 and 2. Cladocerans outnumbered copepods only in May and June and during the intensive growth of *Bosmina longirostris* populations and their juvenile forms in September in pond No. 3. The predominance of copepods resulted from a high number of nauplii, which had more than a 10% share of more than 50% analyzed samples. *Thermocyclops crassus* (all ponds) and *Cyclops strenuus* (pond No. 1) populations were large and stable throughout the experiment. The presence of *Acanthocyclops vernalis*, *Eucyclops macruroides*, and *Eudiaptomus graciloides* – a representative of Calanoida, was noted once only during the entire experimental period.

The qualitative structure of the protozoan community comprised six identified species, of which only *Codonella cratera* is classified as a typical planktonic organism. Two amoeba species, *Arcella discoides* and *Difflugia limnetica*, dominated in the biocenosis of pond No. 1 in the fall, accounting for 12% of the total zooplankton abundance.

## Quantitative Structure of Zooplankton

No statistically significant differences were noted in the average values of zooplankton abundance and biomass between the analyzed ponds (U-test, $p<0.05$) (Figs. 2a and 2b). Pond No. 1 showed the lowest average values of zooplankton abundance (606 individuals per $dm^{-3}$) and the highest average values of zooplankton biomass (16,139 $mg \cdot m^{-3}$). The investigated parameters reached similar values in ponds No. 2 and 3 at 936 and 1,063 organisms per $dm^{-3}$, and 13,119 and 13,019 $mg \cdot m^{-3}$, respectively.

The highest zooplankton abundance was noted in pond No. 3 in September (4,618 individuals per $dm^{-3}$), and in pond No. 2 in August (2,439 individuals per $dm^{-3}$) (Fig. 3).

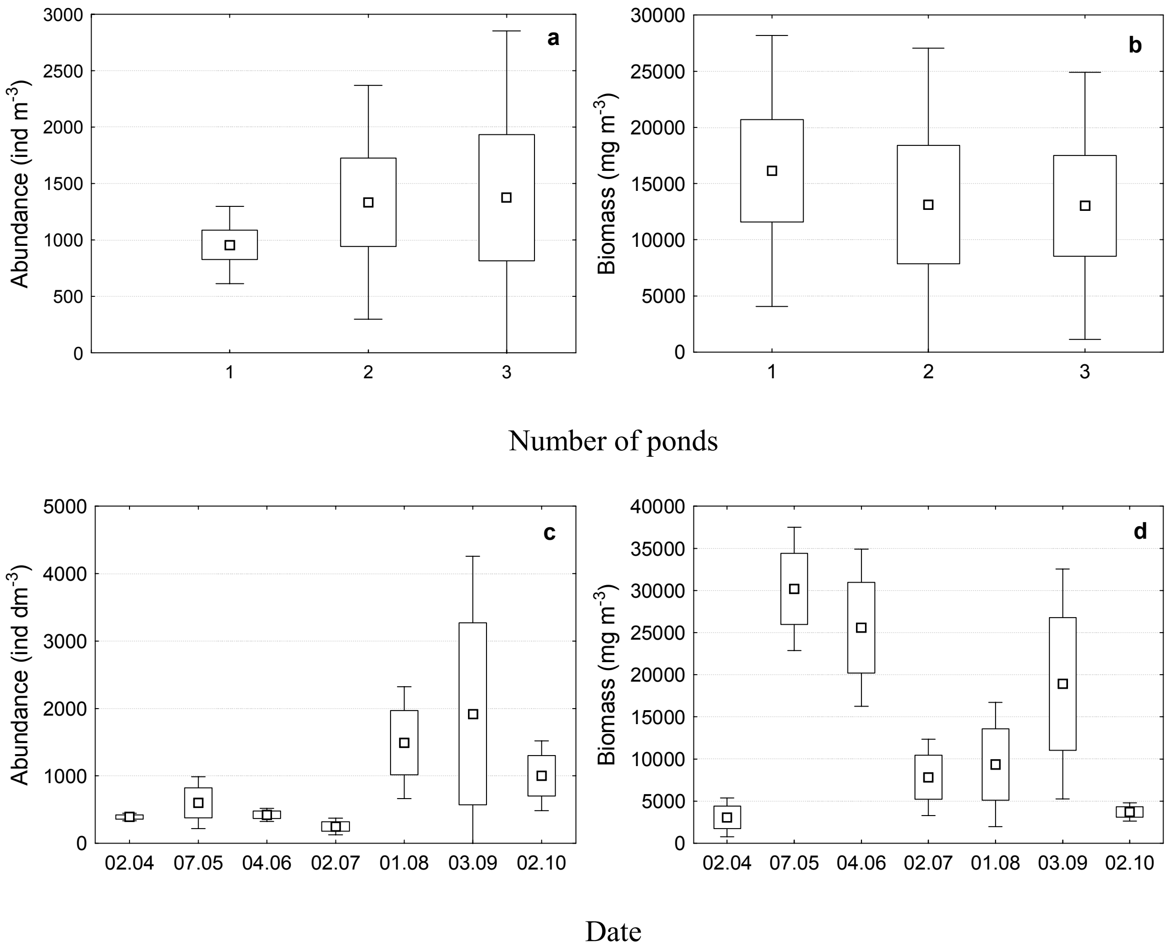


Fig. 2. Average abundance and biomass of zooplankton in each pond on different sampling days in 2007.
Small square: average, rectangle: ± standard error, "swirls": ± standard deviation.

In pond No. 3 it was related to the rapid growth of *Bosmina longirostris* var. *cornuta* and young cladoceran forms, which had a 91% share of the population, while in pond No. 2 it resulted from the dominance of rotifers of the genera *Polyarthra* and *Keratella* (83%) (Table 3). The above contributed to high average zooplankton abundance in ponds No. 2 and 3 and high density values in August and September (Figs. 2a and 2c). The highest stability of zooplankton biocenosis was observed in pond No. 1, where zooplankton abundance remained at an average level throughout the experiment (Fig. 3).

Zooplankton abundance in all ponds was determined by the population density of rotifers. The highest abundance of rotifers (28 – 2,118 individuals $dm^{-3}$) and their highest share (21.7 – 86.6%) of the total zooplankton densities were noted throughout the experimental period in pond No. 2. In pond No. 1 the population size of rotifers and crustaceans varied during the study. A greater abundance of protozoa was noted only in September and October, when they accounted for 12.7% and 17.5% of the zooplankton structure, respectively. In pond No. 3, zooplankton density was determined by crustaceans (except for August and October)

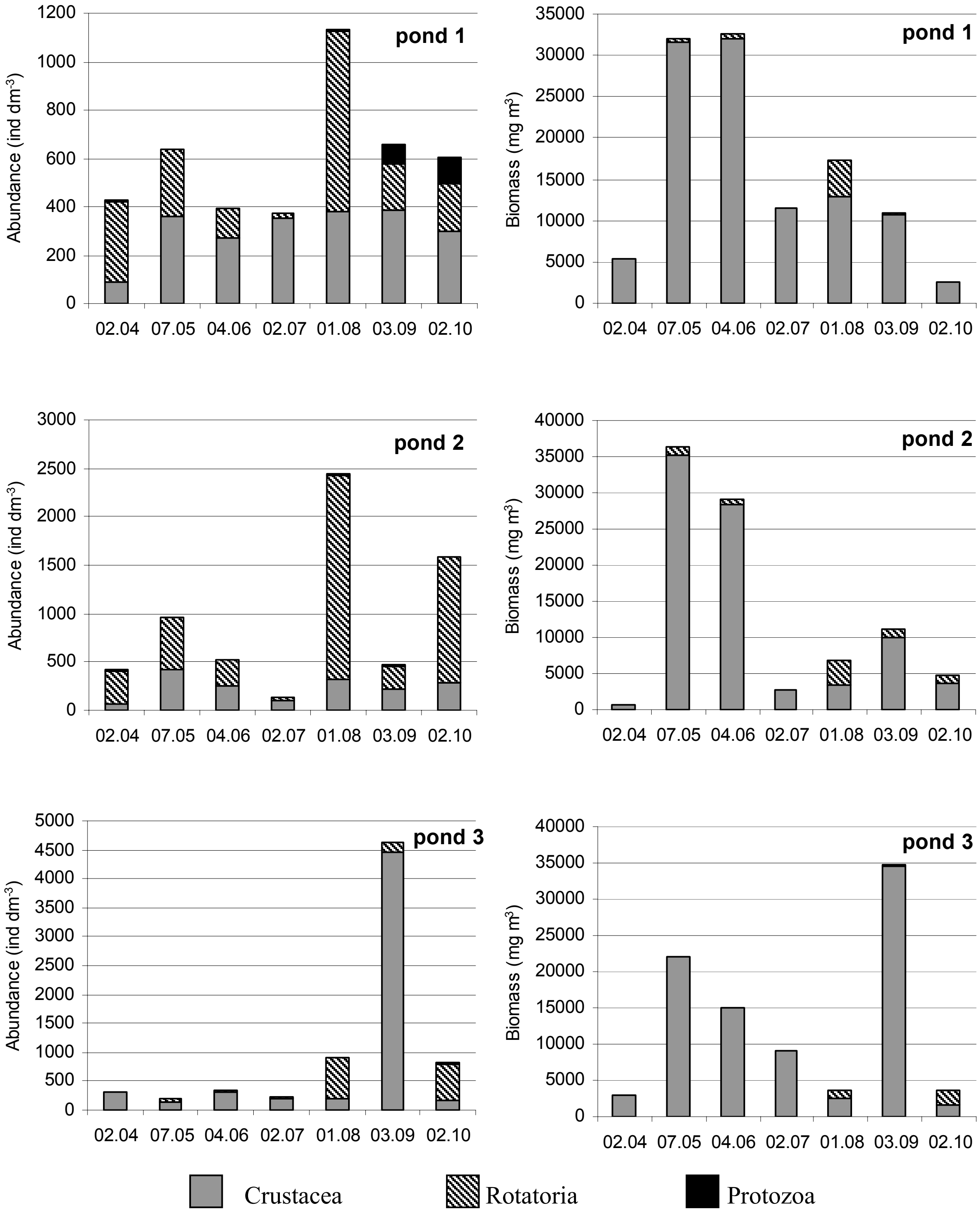


Fig. 3. Dynamics of seasonal changes in zooplankton abundance and biomass in each pond.

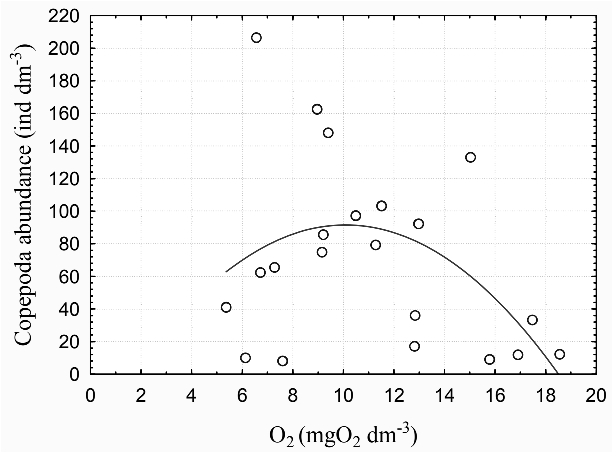


Fig. 4. Abundance of adult copepods and copepodites subject to dissolved oxygen concentrations in pond water.

which had on average a 69.5% share (max. 98.8%) of the population (Fig. 3).

Crustaceans had the highest share of the zooplankton biomass in all ponds. There was a strong direct relationship between cladoceran biomass and total zooplankton biomass. The highest biomass of Cladocera was observed during the spring peak – *Daphnia longispina* in May and June (22,114 – 36,363 mg·m$^{-3}$) and during the autumn appearance of *Bosmina longirostris* var. *cornuta* (34,673 mg·m$^{-3}$) in pond No. 3 in September. This contributed to a clear increase in the average values of zooplankton biomass in the above months (Fig. 2d), but the noted differences were statistically non-significant.

## Environmental Factors

The results relating to zooplankton abundance and biomass in fish ponds were analyzed in view of the physical and chemical parameters of water, including temperature, pH, dissolved oxygen concentrations, oxygen saturation, and $BOD_5$. A significant, inversely proportional relationship was determined between dissolved oxygen concentrations and copepod abundance in the biocenosis (r=-0.51, P<0.05) (Fig. 4). Total copepod counts were determined mostly by the high share of nauplii and copepodite forms and, in the summer, the rapid growth of *Thermocyclops crassus* and *Cyclops strenuus* populations. Oxygen saturation levels were satisfactory in all ponds throughout the experiment. Dissolved oxygen concentrations ranged between 5.37 mg $O_2$·dm$^{-3}$ in pond No. 1 in June to 18.56 mg $O_2$·dm$^{-3}$ in pond No. 2 in April. The drop in dissolved oxygen concentrations and oxygen saturation levels in the late spring/early summer and in the early autumn did not inhibit the development of older and adult forms of copepods, which were determined in large numbers owing to the high availability of food (rotifers) and the fact that fish preyed on the cladoceran species *Daphnia longispina* in the spring. Following a drop in *D. longispina* counts in July, the predominant crustacean populations in pond No. 1 comprised *T. crassus* and *C. strenuus*.

The organic matter content of the studied ponds, expressed by $BOD_5$, was determined by cladoceran populations (Fig. 5). A statistically significant, inversely proportional relationship between the above parameters was observed (r=-0.546, P<0.05). Highly abundant *D. longispina* populations in May and June, in particular in pond No. 1 (128 and 210 individuals per dm$^{-3}$, respectively) and in pond No. 2 (140 and 175 individuals per dm$^{-3}$, respectively), eliminated phytoplankton from the water column and lowered $BOD_5$ values to the lowest level of 3 mg $O_2$·dm$^{-3}$ in pond No. 1 and 2.9 mg $O_2$·dm$^{-3}$ in pond No. 2.

## Discussion

The zooplankton of ponds in Olsztynek was studied several times in the 1990s [39, 40]. In the investigated oxidation and waste stabilization ponds, most of the identified species were indicative of the mesotrophic state of the analyzed reservoirs, and species abundance exceeded 25,000 individuals per dm$^{-3}$ [40]. In this study, taxa that are believed to be reliable indicators of water trophy [41, 42] were found in small numbers and/or sporadically, and their total abundance reached a maximum of only 4,618 individuals per dm$^{-3}$. They were: *Brachionus diversicornis*, *Filinia longiseta*, *F. longiseta passa*, *Keratella cochlearis* var. *tecta*, *Pompholyx sulcata*, *Proales* sp., *Trichocerca pusilla*, and *Chydorus sphaericus*. The populations of *Brachionus angularis*, *K. quadrata*, and *Bosmina longirostris* were marked by only a periodic increase, becoming the dominant species. The above indicators of an increased content of biogenic elements are determined in anthropogenic ecosystems, such as fish ponds [40, Goździejewska, unpublished materials], in the summer plankton of lakes, and in coastal brackish lakes [43]. They are eurytopic organisms that adapt to a wide range of environmental conditions and are capable of surviving in changing habitats, including in shallow pond ecosystems. Roche [44] described extreme impoverishment of the zooplankton community resulting from the massive growth of *Brachionus calyciflorus* and

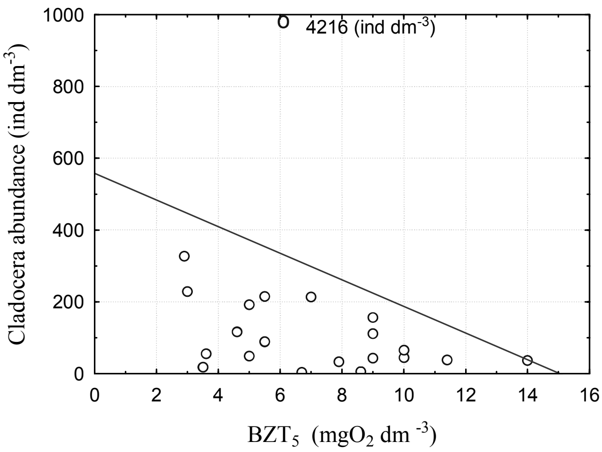


Fig. 5. Organic matter content of pond water subject to cladoceran abundance in the zooplankton community.

*B. angularis* due to excessive fertilization of stabilization ponds fed with treated dairy wastewater. The dominance of the above species has been frequently noted by the authors of previous studies investigating the ponds in Olsztynek and the zooplankton of carp ponds in Górowo-Woryny [Widuto, unpublished data].

The most abundant and the most frequently noted species in this study were rotifers of the genera *Keratella* and *Polyarthra*, as well as *Brachionus angularis*, *B. calyciflorus* and *B. rubens*. A similar species structure of zooplankton in recreational fishing ponds, fertilized with bait, was noted by Goździejewska [unpublished data]. According to Bieniarz et al. [45], apart from the above species, typical members of pond zooplankton communities, found also in Olsztynek, are *Brachionus diversicornis*, *Asplanchna priodonta*, and *Hexarthra mira*. A large group of psammon-periphyton rotifers [28, 45], not noted in previous studies of zooplankton in Olsztynek ponds [40], was represented by small species of the genera *Lecane*, *Colurella*, *Euchlanis*, *Lepadella*, *Cephalodella*, and *Testudinella*. They were observed sporadically or in small numbers, mostly in the summer and fall. A similar seasonal growth trend in species populations classified as psammophiles by Wiszniewski [46], represented by *Cephalodella gibba*, *Colurella colurus*, *Lecane closterocerca*, *Lepadella patella,* and the psammoxenic species *Trichocerca weberi* in this study, was described by Bielańska-Grajner [47]. Numerous researchers emphasize the eurytopic character of the above taxa whose presence was noted in stagnant waters of various trophy levels [28] in different climate zones [48, 49], as well as in watercourses and dammed reservoirs [50]. From among five species of the genus *Lecane*, *L. bifurca* is classified as a rare species in Poland [28].

The structure of rotifers revealed variations in the quantitative relations between dominant species resulting from the seasonal growth of some of them. In the spring, the abundance of *K. cochlearis* and *Polyarthra longiremis* reached its maximum values. July and August were marked by the dominance of thermophilous species that thrive in oxygenated water, including *P. longiremis*, *P. major*, *Hexarthra mira*, and *Asplanchna priodonta*. *Brachionus angularis* and *Filinia longiseta*, typical summer species [28], reached their maximum abundance only in October at a temperature of around 14ºC. The crustacean group was dominated by small and medium-sized cladocerans, including *Daphnia longispina*, *Bosmina longirostris*, and *Chydorus sphaericus*, juvenile forms of Copepoda (nauplii and copepodites) as well the adult form of *Thermocyclops crassus*. *D. longispina* populations were observed throughout the entire experiment, reaching peak abundance in May and June (maximum of 210 individuals per $dm^{-3}$), while Widuto et al. [40] observed the species only in August, with the highest abundance of 36,000 individuals $dm^{-3}$.

Specific interspecies relations were noted in the biocenosis of the analyzed ponds. The intensive growth of *Brachionus rubens* populations in all ponds in June took place only in the complete absence of the remaining species of the genus *Brachionus* and others. This period was marked by the highest abundance of *Daphnia longispina* (up to 210 individuals per $dm^{-3}$), a prey species forming a commensal relationship with *Brachionus* rotifers [28]. A strong *D. longispina* population eliminated rotifers whose abundance in July dropped to the lowest level in the entire experimental period (an average of 33 individuals per dm-3). According to Gilbert [51], the above resulted from competition between rotifers and large cladocerans sharing the same food sources (algae). In consequence of those interactions, small rotifers and algae were ingested by the filtration apparatus of *Daphnia*, and the noted mortality of large species (e.g. *Keratella quadrata*) resulted from a drop in nutrient concentrations in water [52]. An increase in the abundance of Rotatoria (around 700 individuals per $dm^{-3}$) was observed in successive months after cladocerans had been eliminated by fish.

The seasonal quantitative "exchange" between juvenile forms of Copepoda (nauplii and copepodites) and the *D. longispina* population was not as clearly manifested. The density of Cyclopoidal nauplii, which were abundant at the beginning of the study, was reduced even ten-fold in the period of *Daphnia* dominance. The above demonstrates the effects of exploitation when the more effective filtration mechanism of cladocerans deprived copepod larvae of nutritional resources [52]. The mechanism of avoiding food competition during the intensive development of large cladocerans is adopted by selected copepods at growth stage C IV, such as *Cyclops vicinus* and *C. strenuus* [28, 53]. It remains uncertain whether the drop in copepodite populations was affected by the summer diapause and limited access to food due to the dominance of *D. longispina* or by intensified fish predation pressure. The results of environmental analyses indicate that the above was not caused by an oxygen deficiency which could inhibit copepod development or stimulate the formation of spores.

At the same time, during intense blooming of *Volvox* sp. in pond No. 2, the *Acomorphella volvocicola* population, a parasite that feeds exclusively on *Volvox*, rose to the rank of a co-dominant species next to *B. rubens*. The density of green algae of the order *Vovocales* varied throughout the experiment in all ponds. Together with other Chlorophyta species, which developed intensively during that period to form blooms (e.g. *Pediastrum* sp.) in July and thread forms in August and September, they could have inhibited the growth of *Daphnia longispina*, leading to its eradication [45]. The elimination of *Daphnia* supported the development of protozoa: *Arcella discoides* and *Difflugia* sp. In the autumn, green algae of the genus *Volvox* probably stimulated the growth of detritus-feeding *B. angularis* and *Filinia longiseta* populations that also graze on the algae [28]. The emergence of a large *F. longiseta* population could, in turn, stimulate the growth of *Cyclops strenuus*, a predatory copepod species, toward the end of the season. The feeding mechanism adopted by *C. strenuus* to prey on *F. longiseta* and cladocerans (*Daphnia longispina*, *Bosmina* sp.) has been described by Makino and Ban [54]. This predatory copepod probably fed on the above taxa in pond No. 1, where the *C. strenuus* population increased along with prey density in each month of the study. In April, the intense feeding of *Cyclops vicinus* in pond No. 3 led to a radical drop in Rotatoria populations to 4 individuals per liter of water. The predation pressure of the above species on rotifers of the genera *Synchaeta* and *Polyarthra* in the spring has also been described by Plassmann et al. [55], Devetter and Seda [56].

*Daphnia magna* individuals were noted only on four occasions throughout the entire experimental period. The results of the study indicate that *Daphnia magna* populations are largely determined by pond fertility, and their growth is directly proportional to an increase in the content of organic compounds. Their abundance is inhibited by low dissolved oxygen concentrations in water [57]. A drop in the abundance of *D. magna*, leading to their complete eradication, could be indicative of a radical decrease in the biogene content of water, extreme overfertilization, and the predation pressure exerted by fish in an overpopulated environment. The latter is the most probable cause in the discussed case as ponds No. 1 and 2 were stocked with carp and tench fry, and pond No. 2 – with carp and roach fry which, at this stage of development, prey on large cladocerans, copepods, and benthos [58]. Cladocerans are characterized by lower mobility than copepods, therefore they are more readily captured by fish [59-61], and they constitute the predominant food source for juvenile forms of planktivorous fish, including the vendace (*Coregonus albula*) [13], carp beam (*Abramis brama*), and roach (*Rutilus rutilus*) [62].

The youngest larval forms and the fry of fish species inhabiting ponds (carp, roach, tench, European pike perch) first prey on small organisms such as protozoa and rotifers [57], as they are unable to capture and ingest larger prey [20-22, 63]. According to diametric analyses carried out by Osse et al. [64], a carp with a total length (TL) of 16 cm is not capable of ingesting organisms larger than a medium-sized rotifer with a width of up to 0.2 mm.

Fish stock (species, growth stage and population size) determined and diversified the species composition and the quantitative proportions of zooplankton in each pond. The greatest diversity in the taxonomic and age structure of fish was noted in ponds No. 1 and 2. Juvenile tench forms were not detected in pond No. 2, but the presence of European pike perch larvae and fry was noted. Zooplankton colonization indicators showed greatest similarities between ponds No. 1 and No. 2, mostly as regards their taxonomic diversity.

Fish of various species and at different stages of ontogenetic development exert a wide range of influences on zooplankton. Tench larvae and juvenile forms in pond No. 1 penetrated the entire range of the available zooplankton, ingesting evenly all taxa which reproduced quickly (the highest number of species was determined in this pond). The larvae of the predatory European pike perch in pond No. 2 could prey on a wider range of species than the tench because they could switch to larger prey more quickly [65]. Despite the noted differences, the zooplankton of the compared ponds showed similarities as regards the species composition and habitat preferences. Much greater variations in the food preferences of the juvenile forms of predatory fish were noted by Goździejewska [66] in a study of the smelt (*Osmerus eperlanus*). The above is attributed to the ability of juvenile predators to capture fast-moving prey (such as adult copepods), as demonstrated by Hammer [67] and Persson [68], who compared the diets of the larvae of the predatory perch (*Perca fluviatilis*) and the herbivorous roach (*Rutilus rutilus*).

Pond No. 3, marked by the lowest abundance of rotifers, was dominated by small and medium-sized crustaceans. The largest of the studied cladocerans, *D. longispina*, was also less abundant in pond No. 3 than in ponds No. 1 and 2. Pond No. 3 was inhabited by the tench, from larval to adult forms. The carp was not discussed in this study due to similarities in its "qualitative" pressure patterns in all ponds. The differences in the quantitative structure of invertebrates (prey) could result only from variations in the population size of the predator – the carp [69]. The fish showed a distinct preference for small rotifers and predatory invertebrates, which contributed to the dominant status of medium-sized crustaceans in the zooplankton community [52, 70]. A similar zooplankton structure with low biomass levels (2 mg·dm$^3$ on average) was described by Jakubas [71] in carp ponds where natural food was the only source of nutrition.

The results of this study indicate that the pond ecosystem is a complex mechanism of closely intertwined processes and reactions. The structure and dynamics of changes in the biocenosis of culture ponds fed with biologically treated wastewater were affected mostly by trophic relationships and interspecies interactions, while fish predation pressure supported greater species diversity and faster reinstatement of the zooplankton structure.

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