Ecohydrology & Hydrobiology

The influence of locks on zooplankton in canals (Bydgoszcz canal and Noteć canal, Poland)

--Manuscript Draft--

Manuscript Number:	
Article Type:	Original article
Keywords:	Rotifers; Crustaceans; Bydgoszcz Canal; water flow; environmental parameters
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Abstract:	Artificial waterways are characterized by series of dams and locks that slow the flow of water. Such conditions can influence the structure of zooplankton communities. The aim of our research was to assess the impact of environmental and hydrological conditions on the zooplankton of sites upstream and downstream of canal locks. The study was carried out in 2021 and 2022. Water samples were collected monthly from the Bydgoszcz Canal and the Noteć Canal (Poland) during the growing season. We evaluated how water flow velocity and selected environmental parameters (i.e., water temperature, Secchi disk visibility, conductivity, oxygen concentration, saturation, pH and chl-a concentrations) influence the zooplankton diversity (T) density (N) and biomass (B). The results of our study showed that density and biomass of rotifers changed approximately proportionally to changes in chlorophyll at sites upstream of locks. Zooplankton diversity also increased upstream of locks. A habitat of low flow velocity and characterized by macrophytes favored high diversity and density of zooplankton. The growth of crustaceans (density and biomass) as well as total zooplankton biomass was affected by water temperature at sites downstream of the lock. Sites 2 and 3 share a pattern of abundance and biomass. Site 1 differs probably due to a one-off increase in the number of crustaceans that probably originated within inside the lock. This was likely the result of internal loading (organic matter and nutrients) after the re-suspension of bottom sediments due to increased water movement inside the lock. Water enriched in suspension drained below the sluice.
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Bydgoszcz, 2023-06-27

Dear Editors,

This cover letter accompanies our paper **The influence of locks on zooplankton in canals (Bydgoszcz canal and Noteć canal, Poland)**

authored by *Nikola Kolarova and Paweł Napiórkowski.*

Article deals with the impact of environmental and hydrological conditions on the zooplankton of sites upstream and downstream of canal locks. The study was carried out in 2021 and 2022. Water samples were collected monthly from the Bydgoszcz Canal and the Noteć Canal (Poland) during the growing season. We chose three sites where samples were taken upstream and downstream of the locks. We evaluated how water flow velocity and selected environmental parameters (i.e., water temperature, Secchi disk visibility, conductivity, oxygen concentration, saturation, pH and chl-a concentrations) influence the zooplankton diversity (T) density (N) and biomass (B). The results of our study showed that density and biomass of rotifers changed approximately proportionally to changes in chlorophyll at sites upstream of locks. Zooplankton diversity also increased upstream of locks. A habitat of low flow velocity and characterized by macrophytes favored high diversity and density of zooplankton. The growth of crustaceans (density and biomass) as well as total zooplankton biomass was affected by water temperature at sites downstream of the locks. We found that hydrotechnical constructions on canals have a significant impact on the structure of zooplankton. We decided to do this study because few literature items were devoted to zooplankton of artificial waterways.

We believe that our paper is relevant to a broad international audience and well suited for the readers of **Ecohydrology and Hydrobiology**.

We hope that you will consider this manuscript for review and we look forward to your response.

Yours sincerely,
Nikola Koralova
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The influence of locks on zooplankton in canals (Bydgoszcz canal and Noteć canal, Poland)

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Abstract

Artificial waterways are characterized by series of dams and locks that slow the flow of water. Such conditions can influence the structure of zooplankton communities.

The aim of our research was to assess the impact of environmental and hydrological conditions on the zooplankton of sites upstream and downstream of canal locks.

The study was carried out in 2021 and 2022. Water samples were collected monthly from the Bydgoszcz Canal and the Noteć Canal (Poland) during the growing season. We evaluated how water flow velocity and selected environmental parameters (i.e., water temperature, Secchi disk visibility, conductivity, oxygen concentration, saturation, pH and chl-a concentrations) influence the zooplankton diversity (T) density (N) and biomass (B).

The results of our study showed that density and biomass of rotifers changed approximately proportionally to changes in chlorophyll at sites upstream of locks. Zooplankton diversity also increased upstream of locks. A habitat of low flow velocity and characterized by macrophytes favored high diversity and density of zooplankton. The growth of crustaceans (density and biomass) as well as total zooplankton biomass was affected by water temperature at sites downstream of the lock.

Sites 2 and 3 share a pattern of abundance and biomass. Site 1 differs probably due to a one-off increase in the number of crustaceans that probably originated within inside the lock. This was likely the result of internal loading (organic matter and nutrients) after the re-suspension of bottom sediments due to increased water movement inside the lock. Water enriched in suspension drained below the sluice.

Keywords: Rotifers, Crustaceans, Bydgoszcz Canal, water flow, environmental parameters.

Introduction

Artificial canals are important waterways connecting natural rivers into a large-scale inland water system (Gorączko, 2015). Such an artificial waterway is divided into sections that differ in water table height by means of locks, lifts or slipways. Many canals have a series of dams and locks that slow the flow of water, creating small reservoirs (Bydgoszcz canal). They often have an important navigational role in providing navigability past weirs and dams by maintaining appropriate water levels and depths while also allowing boats to ascend and descend between sections of differing elevations (Segovia et al., 2019).

Locks are inherent structures of canals whose main function is to raise water levels and enable travel in both directions, i.e., transporting boats across a water level differential – from lower to higher and *vice versa*. In combination with the construction of artificial canals and regulation of rivers, the building of locks allowed inland transport water connections to be developed (Muszyńska-Jeleszyńska & Marciniak, 2016).

Canals vary in hydrological regime, environmental conditions and organism communities. They are useful corridors for the spread of aquatic species (Kim & Mandrak, 2016; Pagnucco et al., 2015). These waterways provide direct (dispersal) or indirect (shipping) transportation routes for non-indigenous species, including of planktonic organisms (Dexter et al., 2020). Some studies report that large rivers connected with canals differ in terms of hydrological and environmental characteristics, what influence the diversity of aquatic biota such as zooplankton species (Appel et al., 2020; Kelly et al., 2013; Ball et al., 2018), phytoplankton species (Dembowska, 2021; Kelly & Hassall, 2018), macrophytes (Tarkowska-Kukuryk & Grzywna, 2022; Dorotovičová, 2013), benthic invertebrates (McCabe et al., 1998; Weber, 2017) and fish (Chester & Robson, 2013; Onikura, 2015; Roberts & Rahel, 2008). The water flow velocity near locks determines the reproductive success of aquatic organisms and consequently influences growing potential.

Zooplankton organisms can affect biodiversity in canals (Furst et al., 2014). Locks reduce water flow in canals and thus increase the number of zooplankton species. Artificial waterways within large river systems provide shelter from the high flow conditions of an open river, allowing large-bodied crustacean zooplankton to flourish (Dickerson et al., 2010). Locks may serve as retention areas and sustain crustacean species in the canals. Some fast-reproducing, small-bodied groups such as rotifers can be found in high densities in higher-flow conditions in canals (Havel et al., 2009).

Freshwater zooplankton have an essential position in aquatic food webs as primary and secondary consumers (Majagi et al., 2019). They take part in nutrient cycling, regulate the biomass of phytoplankton (Gianuca et al., 2016) and provide food for fish (Ning et al., 2010), especially for larval stages and fish fry (Medeiros & Arthington, 2008). The zooplankton community is essential to ensuring a healthy ecosystem. Each species differently affects ecosystem functioning (Venkatraju et al., 2010; Manickam et al., 2018; Jeelani et al., 2008; Symons & Arnott, 2013).

Hydrological conditions are an important factor shaping the structure and functioning of zooplankton community in rivers and other waterways (Napiórkowski et al., 2019; Zhao et al., 2018; Czerniawski & Sługocki, 2017). Canals seem to be transitional between flowing and stagnant waters. Therefore, hydrological conditions may vary depending on the nature of the water flow (velocity, direction, average and seasonal variation) in the canal, but also depending on the distance between the locks and the way the locks work.

The aim of the study was to compare zooplankton species compositions between sites upstream and downstream of locks in two artificial waterways. We also compare the environmental conditions upstream and downstream of the locks and their impact on the zooplankton communities.

We assumed that zooplankton communities would differ in diversity, density and biomass between the two sides of the lock based on the differences in hydrological and environmental conditions.

We hypothesized that the canal waters upstream of the lock will stagnate, thereby creating better conditions for the development of zooplankton. Conversely, we hypothesized that the water flowing down from the lock would temporarily increase the water flow velocity, resulting in a decrease in zooplankton diversity and density.

Materials and methods

The study was carried out during the growing season from April to September in 2021 and 2022 in the Bydgoszcz Canal (part of which is located in the industrial zone of Bydgoszcz city) and the Noteć Canal (located in the agricultural rural zone near the town of Nakło). The study was conducted in close proximity to (downstream and upstream of) locks on both canals. Two locks are located on the Bydgoszcz Canal (Osowa Góra and Prądy) and one is located in the Noteć Canal (Łochowo). The Bydgoszcz Canal is located in north-west of Poland between

Bydgoszcz city and Nakło town. The canal was built at the end of the 18th century. It is an important part of the E70 international waterway linking the water systems of Western, Central and Eastern Europe. This artificial watercourse connects the two largest rivers in Poland – the Vistula and the Oder – through their tributaries. The total length of the canal is 24.7 km, of which 15.7 km is located in the Noteć catchment (a tributary of the Odra River) and 9.0 km in the Brda catchment (a tributary of the Vistula River).

The Osowa Góra and Prądy locks were initially built at the end of 18th century. However, their final shape was determined during reconstruction works at the beginning of the 20th century. The locks water elevations are, respectively, 3.55 m up to 3.82 m, the total height of walls is 7 m and width is about 29 m. The average water depth was 1.5 m at the sites upstream of the locks and 1.7 m downstream. The water flow velocity was ~0.07 m/s at sites upstream of the lock and ~0.004 m/s downstream.

The Noteć Canal consists of two parts (one referred to as simply the "Noteć Canal" and the other as the "Upper Noteć Canal"). This waterway covers the course of the Noteć River. The total length of the canal is 25 km. It is characterized by low water discharge and a strong impact of anthropogenic contaminants due to human activities, including agriculture. The Łochowo lock on the Upper Noteć Canal is ~15 m wide. The average depth was 1.4 m at the site upstream of the lock and 1.6 m downstream. The water flow velocity was ~0.14 m/s at the site upstream of the lock and ~0.3 m/s downstream.

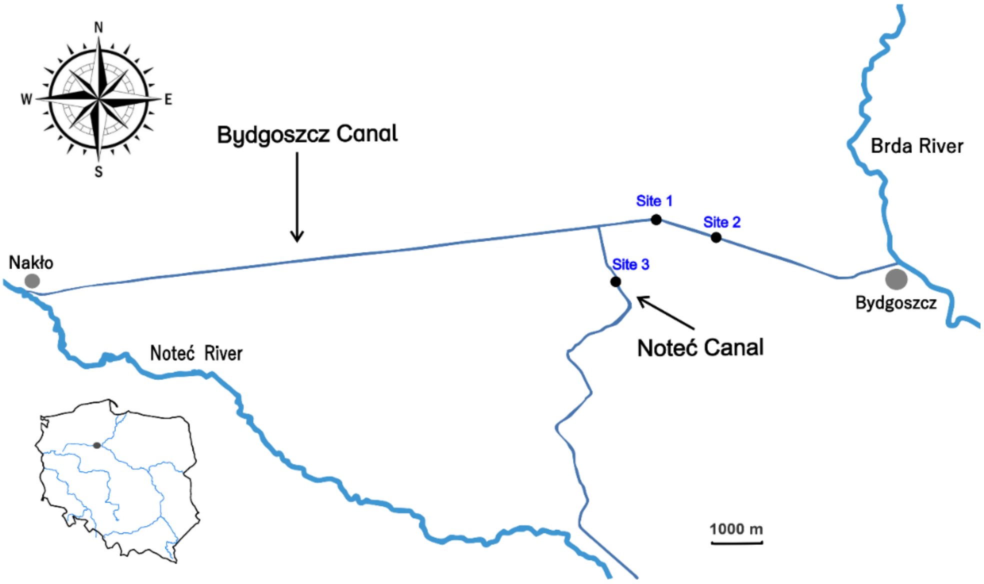


Figure 1. Map of investigated area. Bydgoszcz Canal: site 1 – Osowa Góra; site 2 – Prądy; site 3 – Noteć Canal

Water samples were collected at three sampling sites: in the Bydgoszcz Canal: (site 1) Osowa Góra upstream and downstream of the lock 53°08'48.9"N 17°52'49.2"E; (site 2) Prądy upstream and downstream of the lock 53°08'38.6"N 17°53'37.8"E and (site 3) in the Noteć Canal- Lochowo upstream and downstream of the lock 53°07'56.5"N 17°51'18.1"E. Samples were collected from different depths with a 1-L Patalas bucket once a month, for a total of 36 samples. To obtain one qualitative and quantitative sample of zooplankton, 20 L of water was filtered through a plankton net of mesh size 25 μm. All samples were preserved with Lugol's iodine solution (Harris et al., 2000; Wallence et al., 1993). The zooplankton density was determined under a microscope using a Sedgewick Rafter-type chamber (1 mL) by a methodology after McCauley (1984) and counted per 1 L of water. The rotifers' wet weight was calculated using the formula according to Radwan (2004). The zooplankton species were identified using an Olympus BX 43 light microscope and an Olympus LC 30 soft imaging camera at 10× magnification according to commonly available keys (Wallace et al., 1993; Einsle, 1996; Radwan et al., 2004; Błędzki & Rybak, 2016). Concurrently with zooplankton sampling, the selected environmental parameters of water were measured: water temperature (WT, °C), Secchi disk visibility (SD, m), conductivity (EC, µS cm^{-1}), oxygen concentration (DO, mg/L), saturation (%), chlorophyll (chl-a, µg/L) and pH (Table 1). In the laboratory, biological material was poured into a glass 25-ml cuvette and analyzed using a spectral ALA fluorimeter (AlgaeLabAnalyser, BBE Germany). One measurement was an arithmetic mean of three "fast analyses". In this way, we collected data about total Chl-a concentration (TChl-a, μg/L) and its concentration in four taxonomic groups: the Chlorophyta, Bacillariophyta, Cyanobacteria, and Cryptophyta (μg/L). For proper calculation of TChl-a, we corrected for yellow substances using the chromophoric dissolved organic matter correction. The whole procedure was performed within 72 h from *in-situ* sample collection. For a detailed description, see Nguyen et al. (2015). Multimeter WTW Multi 3430SET F Xylem Analytics field probes (Weilheim, Germany) were used for measurements. During the sampling period, the surface water flow was measured using the electromagnetic hydrometric mill (Model 801).

The hierarchical clustering analysis and redundancy analyses (RDA) were used to determine the environmental variables responsible for variations in the zooplankton taxonomic composition, density and biomass during the growing seasons at the study sites.

The explanatory response variables used in the analyses were: WT, SD, pH, DO, EC, Chl-a and number of zooplankton species (total number of zooplankton species, number of rotifer and crustacean species), zooplankton density (total zooplankton density, rotifer and crustacean density), and zooplankton biomass (total zooplankton biomass, rotifer and crustacean biomass). For statistical analysis were used all data variability (environmental and biological) including all investigated months.

Pearson simple coefficient was tested to analyze statistically significant correlations between environmental and biological parameters by Past 4.03 software (Hammer et al., 2001). The hierarchical clustering analysis was performed by grouping the sites downstream and upstream of the lock depending on their similarity in terms of environmental and biological data in Past 4.03 software (Hammer et al., 2001). The pairwise distances between environmental parameters were measured by Euclidean similarity index and between biological parameters by the Bray–Curtis similarity index. The dataset was log (x+1) transformed to minimize differences in variables.

Redundancy analysis (RDA) was performed using the constrained linear method to determine the relationships between selected environmental parameters and biological data (Rao, 1964; van den Wollenberg, 1977). The dataset was log (x+1) transformed to eliminate the effect of outliers on the results. The data used in RDA analysis were taken from the Bydgoszcz Canal and the Noteć Canal at sites downstream and upstream of each lock. The presented results were processed statistically by using Canoco 5.0 software (ter Braak & Šmilauer, 2002).

Results

Physico-chemical parameters

The average water temperature, concentration of dissolved oxygen, saturation and of pH value at sites in the Bydgoszcz Canal and in the Noteć Canal were similar upstream of the locks to the average values recorded at sites downstream. The average Secchi disk visibility differed at Site 3. At this site, 1.5 m was recorded upstream of the lock and slightly less (1.4 m) downstream. The average conductivity was higher at all upstream sites. The greatest differences were found at Site 1 upstream. The highest value of this parameter was 2684 µS cm^{-1} while the lowest value was 595 µS cm^{-1}. The average chlorophyll concentration varied most widely at Site 1. The average concentration ranged from 21.2 µg/L upstream to 31.2 µg/L downstream. The highest concentration of chlorophyll (103.3 µg/L) was recorded at Site 2 upstream, and the lowest concentration (1.6 µg/L) was recorded at Site 3 downstream (Table 1).

Table 1. Mean values of environmental parameters in Bydgoszcz Canal and Noteć Canal, upstream and downstream of the lock. Water temperature (WT, °C), Secchi disk visibility (SD, m), conductivity (EC, µS cm^{-1}), oxygen concentration (DO, mg/ L), saturation (%), pH, chlorophyll (chl-a, µg/L)

	Bydgoszcz Canal				Noteć Canal	
	Site 1 A		**Site 2 A**		**Site 3 A**	
	mean	range	Mean	range	mean	range
WT (°C)	18.1	(10.1–25.2)	18.2	(10.8–25.9)	17.4	(8.9–25.1)
SD (m)	1.6	(0.6–2.1)	1.5	(0.4–2.3)	1.5	(0.6–2.0)
EC (µS cm^{-1})	1471	(595–2684)	1324	(595–2030)	1349	(593–2137)
DO (mg/L	9.4	(3.5–16.5)	10.3	(5.9–17.0)	8.6	(5.4–13.3)
SAT (%)	107	(63–179)	119	(86–181)	83	(67–107)
pH	7.7	(6.8–8.3)	7.7	(6.8–8.5)	7.7	(6.4–8.4)
Chl-a (µg/L)	21.2	(2.2–81.7)	34.9	(7.5–103.3)	22.9	(1.9–87.7)

	Bydgoszcz Canal				Noteć Canal	
	Site 1 B		**Site 2 B**		**Site 3 B**	
	mean	range	Mean	range	mean	range
WT (°C)	17.5	(8.6–26.2)	17.3	(8.9–25.8)	16.0	(8.0–24.3)
SD (m)	1.6	(0.6–2.2)	1.5	(0.4–2.2)	1.4	(0.6–1.9)
EC (µS cm^{-1})	938	(598–1812)	925	(592–1805)	949	(594–1840)
DO (mg/L	10.3	(7.9–15.8)	10.3	(7.6–14.0)	8.8	(6.5–12.0)
SAT (%)	109	(81–170)	108	(84–148)	87	(67–100)
pH	7.6	(6.8–8.4)	7.5	(6.7–8.5)	7.6	(6.5–8.6)
Chl-a (µg/L)	31.2	(2.8–100.2)	36.6	(8.0–102.7)	19.5	(1.6–84.2)

(sites A – upstream of the locks, sites B – downstream of the locks)

Zooplankton diversity, density and biomass

During the study, a total of 119 zooplankton species were identified. The highest richness was of rotifers, with 93 species (i.e., 78% of all species) followed by crustaceans, with 26 species (i.e., 22% of all species). At sites upstream, 103 zooplankton species were recorded, comprising 82 rotifer species (i.e., 80% of all species) and 21 crustacean species (i.e., 20% of all species) alongside nauplii and copepodites (larval forms of copepods). At sites downstream, 89 zooplankton species were recorded, comprising 71 rotifer species (i.e., 80% of all species) and 18 crustacean species (i.e., 20% of all species) accounted with larval forms of copepods. The highest total number of species was recorded at Site 1 upstream (82, comprising 66 rotifer species and 16 crustacean species). The lowest number of species was recorded at Site 2 and Site 3 downstream (61, comprising 51 rotifer species and 10 crustacean species) (Table 2). The complete list of zooplankton species identified during the study period is provide in the supplementary materials. The highest number of species in a single sample was observed at Site 1 upstream (21 species) while downstream the lock (17 species). The lowest number of species was recorded at Site 2 downstream (16 species) while upstream (20 species) (Table 3).

Table 2. Total number of species (diversity) and dominants (density) in the zooplankton community during 2021 and 2022 growing seasons in Bydgoszcz Canal and Noteć Canal sites

	Bydgoszcz Canal				**Noteć Canal**	
	Site 1 A	**Site 1 B**	**Site 2 A**	**Site 2 B**	**Site 3 A**	**Site 3 B**
Rotifers	66	51	65	51	53	51
Crustaceans	16	11	11	10	15	10
Total	82	62	76	61	68	61
Dominant species and percent of domination	*Keratella cochlearis * 64%*	*Keratella cochlearis * 40%*	*Keratella cochlearis * 50%*	*Keratella cochlearis * 66%*	*Keratella cochlearis * 71%*	*Keratella cochlearis * 72%*
	Keratella quadrata 9%*	*Keratella quadrata * 5%*	*Keratella quadrata * 6%*	*Keratella quadrata* 5%*	*Keratella quadrata * 6%*	*Keratella quadrata * 12%*
	*Euchlanis dilatata * 15%*	*Polyarthra dolichoptera* 2%*	*Brachionus calyciflorus * 3%*	*Keratella tecta* 4%*	*Keratella tecta * 8%*	*Keratella tecta* 8%*
	*Chydorus sphaericus** 7%*	*Bosmina longirostris** 50%*	*Bosmina longirostris** 33%*	*Bosmina longirostris** 20%*	*Bosmina longirostris** 5%*	*Chydorus sphaericus** 2%*
	nauplius** *5%*	nauplius** *3%*	*Ceriodaphnia pulchella** 8%*	nauplius** *5%*	*Chydorus sphaericus** 10%*	nauplius** *6%*

(*rotifer, **crustacean, sites A – upstream of locks, sites B – downstream of locks)

The average zooplankton density was highest at Site 1 downstream of the lock (456 ind/L) and was two times higher than upstream (227 ind/L). The lowest average zooplankton density was at Site 3 downstream (172 ind/L) and was almost two times lower than upstream (261 ind/L). Average rotifer density was highest at Site 1 downstream (226 ind/L) and was higher than upstream (195 ind/L). The lowest average rotifer density was at Site 3 downstream (158 ind/L) and was lower than upstream (216 ind/L). Average crustacean density was highest at Site 1 downstream (230 ind/L) and was seven times higher than upstream (32 ind/L). The lowest average crustacean density was found at Site 3 downstream (14 ind/L) and was three times lower than upstream (45 ind/L) (Table 3).

During the study rotifers, were the most dominant (in terms of diversity and abundance) in all collected samples. *Keratella cochlearis* (from 40% to 72%), *Keratella quadrata* (from 5% to 12%), *Keratella tecta* (~4%) prevailed at all sites. Among crustacean species, the most dominant were *Bosmina longirostris* (from 2% to 50%), *Chydorus sphaericus* (from 2% to 10%) and nauplii (from 3% to 6%) (Table 2).

The average zooplankton biomass was highest at Site 1 downstream (4.321 mg/L) and was five times higher than upstream (0.825 mg/L). The lowest average zooplankton biomass was at Site 3 downstream (0.217 mg/L) and was five times lower than upstream (1.024 mg/L). Average rotifer biomass was highest at Site 2 upstream (0.101 mg/L) and lowest at the same site downstream (0.053 mg/L). The lowest average rotifer biomass was also recorded at Site 3 downstream (0.053 mg/L) which was sligtly lower than upstream (0.056 mg/L). Average crustacean biomass was the highest at Site 1 upstream (4.250 mg/L) and was almost six times higher than downstream (0.728 mg/L). The lowest crustacean biomas was at Site 3 downstream (0.164 ind/L) and was eight times lower than upstream (0.968 ind/L) (Table 3). In terms of biomass, crustacean was the most dominant in almost all collected samples. *B. longirostris* (61%), *Ceriodaphnia pulchella* (13%) and *Ch. Sphaericus* (8%) prevailed at all sites. Among rotifer species *K. cochlearis* (28%), *Euchlanis dilatata* (19%), *K. quadrata* (17%) were the most dominant.

At upstream sites, the α-diversity index (H'=2.23±0.20) was at Site 1 and lowest (H'=1.84±0.19) at Site 2. At sites downstream α-diversity index (H'=2.21±0.19) was highest at Site 3 and lowest (H'=1.92±0.10) at Site 1 and Site 2.

At upstream sites, the eveness index (J'=0.52±0.06) was highest at Site 1 and lowest (J'=0.40±0.06) at Site 2. At downstream sites, the eveness index (J'=0.54±0.03) was highest at Site 3 and lowest (H'=0.49 ± 0.02) at Site 2 (Table 3).

Table 3. Mean values of zooplankton species, density (ind/L) and biomass (mg/L) in Bydgoszcz Canal and Noteć Canal, upstream and downstream of the lock.Tax total – number of zooplankton species;Tax Rot – number of rotifer species; Tax Crust – number of crustacean

species; N total – density of zooplankton; N Rot – density of rotifers; N Crust – density of crustaceans; B total – biomass of zooplankton; B Rot – biomass of rotifers; B Crust – biomass of crustaceans. Shannon–Weaver α-diversity index (H' index); Pielou's evenness index (J' index)

	Bydgoszcz Canal				Noteć Canal	
	Site 1 A		**Site 2 A**		**Site 3 A**	
	mean	range	mean	range	mean	range
Tax total	21	(13–38)	20	(11–30)	19	(13–28)
Tax Rot	17	(7–30)	16	(8–23)	15	(8–24)
Tax Crust	4	(2–8)	4	(2–7)	4	(2–9)
N total	227	(12–1488)	333	(16–1462)	261	(17–1378)
N Rot	195	(5–1402)	211	(15–1409)	216	(8–1290)
N Crust	32	(1–86)	122	(1–876)	45	(2–223)
B total	0.825	(0.021–3.117)	2.873	(0.014–23.037)	1.024	(0.031–2.697)
B Rot	0.097	(0.002–0.491)	0.101	(0.004–0.544)	0.056	(0.002–0.231)
B Crust	0.728	(0.011–2.973)	2.772	(0.008–23.001)	0.968	(0.028–2.626)
H’ index	2.23	(1.01–2.89)	1.84	(0.38–2.62)	2.02	(0.83–2.76)
J’ index	0.52	(0.11–0.82)	0.40	(0.11–0.72)	0.47	(0.12–0.82)

	Bydgoszcz Canal				Noteć Canal	
	Site 1 B		**Site 2 B**		**Site 3 B**	
	mean	range	mean	range	mean	range
Tax total	17	(5–27)	16	(13–20)	19	(15–24)
Tax Rot	13	(1–20)	12	(7–16)	15	(12–21)
Tax Crust	4	(2–9)	4	(2–7)	4	(2–5)
N total	456	(12–1980)	258	(18–1507)	172	(28–962)
N Rot	226	(4–1912)	193	(14–1445)	158	(15–925)
N Crust	230	(2–1941)	65	(3–293)	14	(5–37)
B total	4.321	(0.026–36.333)	1.304	(0.023–5.388)	0.217	(0.042–0.664)
B Rot	0.068	(0.001–0.503)	0.053	(0.004–0.320)	0.053	(0.004–0.199)
B Crust	4.250	(0.014–36.320)	1.251	(0.019–5.381)	0.164	(0.029–0.488)
H’ index	1.92	(0.07–2.75)	1.92	(0.71–2.61)	2.21	(0.93–2.69)
J’ index	0.50	(0.11–0.83)	0.49	(0.12–0.77)	0.54	(0.11–0.77)

(sites A – upstream of the locks, sites B – downstream of the locks)

Table 4. Pearson’s simple correlation r coefficient for environmental variables and zooplankton species composition

	Tax total	Tax Rot	Tax Crust	N total	N Rot	N Crust	B total	B Rot	B Crust
Sites A									
WT	0.28	0.18	0.28	-0.14	-0.25	0.11	0.02	-0.20	0.07
SD	-0.22	-0.24	-0.12	-0.72	-0.83	-0.36	-0.28	-0.84	-0.23
EC	0.00	-0.09	0.10	0.16	0.04	0.32	0.50	0.17	0.33
DO	-0.18	-0.01	-0.23	0.36	0.53	-0.08	-0.04	0.54	-0.10
pH	0.06	0.17	-0.16	0.35	0.42	0.03	-0.02	0.45	-0.10
chl-a	0.23	0.25	0.04	0.55	0.69	0.11	0.08	0.63	0.06
Sites B									
WT	0.00	-0.04	0.30	-0.16	-0.32	0.49	0.41	-0.04	0.40
SD	-0.42	-0.43	0.09	-0.77	-0.88	0.11	0.14	-0.75	0.25
EC	-0.31	-0.25	-0.06	-0.11	-0.10	0.12	0.06	-0.22	0.11
DO	0.33	0.27	-0.14	0.59	0.72	-0.30	-0.21	0.52	-0.35
pH	0.12	0.10	-0.20	0.45	0.34	-0.15	-0.19	0.36	-0.20
chl-a	0.20	0.06	0.04	0.75	0.77	0.04	0.11	0.63	-0.01

(Sites A – upstream the lock, Sites B – downstream the lock)
p<0.05; statistical significances are underlined

The hierarchical clustering analysis showed that sites located upstream of locks (1A, 2A, 3A) are more similar to each other than to other sites, as are the sites located downstream of locks (1B, 2B, 3B). The first dendrogram grouped the sites based on similar environmental parameters (physico-chemical data). The second dendrogram grouped the sites based on similar biological parameters (zooplankton data) (Figure 2A and Figure 2B).

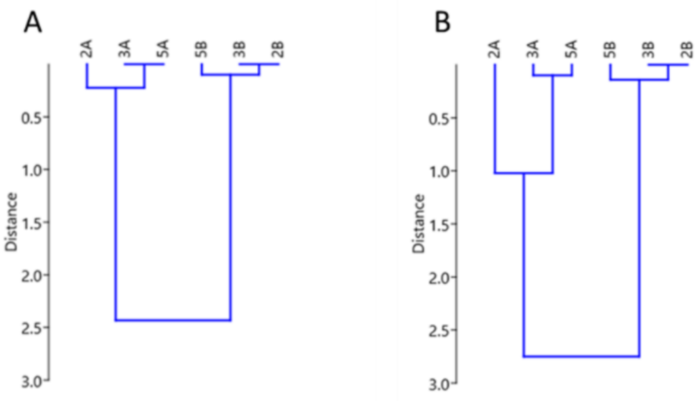
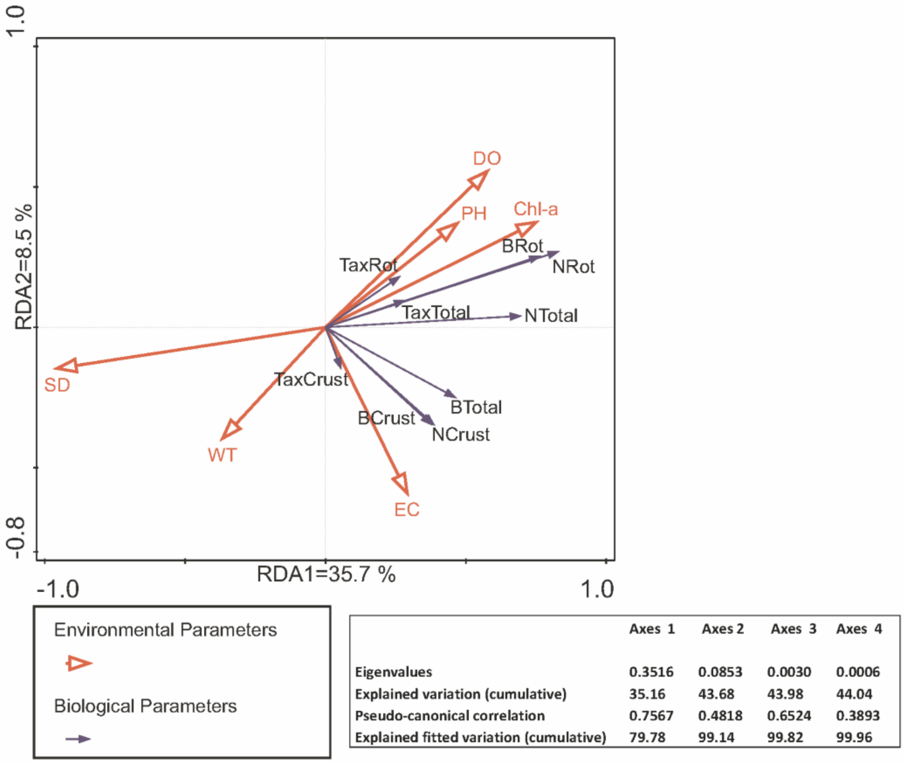


Figure 2A and 2B. Tree diagrams of cluster analysis of study sites based on environmental parameters (**A**) obtained using Euclidean similarity index and biological parameters (**B**) (zooplankton data) obtained by the Bray–Curtis similarity index.

RDA analysis described the relationship between zooplankton species composition and environmental parameters in the Bydgoszcz Canal and the Noteć Canal upstream and downstream of locks. The length of environmental parameters (vectors) indicated their significance alongside the corresponding axes. Statistical significances described below are confirmed by results of RDA using the Pearson test. Correlations and RDA were calculated based on the original dataset. At upstream sites, the results of the ordination showed that the eigenvalues of the first (λRDA1=0.357) and second (λRDA2=0.085) RDA axes accounted for 44.2% of the variation in the environmental data. The longest vector Secchi disk visibility showed highest negative correlation with total zooplankton density ($r=-0.72$, $p<0.05$), total rotifers density ($r=-0.83$, $p<0.05$) and their biomass ($r=-0.84$, $p<0.05$). Conversely, dissolved oxygen showed a positive relationship with total rotifer density ($r=0.53$, $p<0.05$) and total rotifer biomass ($r=0.54$, $p<0.05$). Chlorophyll concentration had also a positive relationship with density ($r=0.69$, $p<0.05$), total rotifer biomass ($r=0.63$, $p<0.05$) and total zooplankton density ($r=0.55$, $p<0.05$). Conductivity exhibited a positive relationship with zooplankton biomass ($r=0.50$, $p<0.05$) (Table 4). The vectors for pH and water temperature were short, which means that these parameters are of less importance and statistically not significant in correlation with zooplankton species (Figure 3).

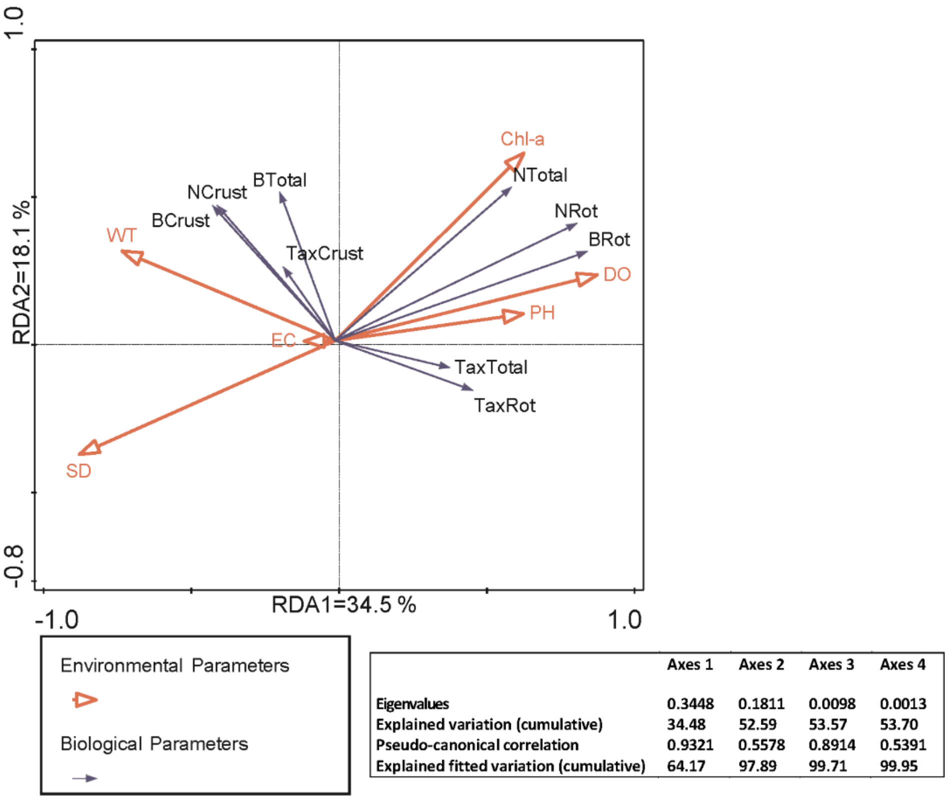


	Axes 1	Axes 2	Axes 3	Axes 4
Eigenvalues	0.3516	0.0853	0.0030	0.0006
Explained variation (cumulative)	35.16	43.68	43.98	44.04
Pseudo-canonical correlation	0.7567	0.4818	0.6524	0.3893
Explained fitted variation (cumulative)	79.78	99.14	99.82	99.96

Figure 3. Results of Redundancy analysis (RDA) performed on zooplankton and environmental data during growing season in the Bydgoszcz Canal and the Noteć Canal

upstream of locks using forward selection of variables ($p<0.05$). Triplot of significant environmental variables (WT – Water temperature, SD – Secchi disk visibility, EC – conductivity, DO – oxygen concentration, pH, Chl-a – chlorophyll-a), number of zooplankton species (Tax total, Tax Rot, Tax Crust), zooplankton density (N total, N Rot, N Crust) and zooplankton biomass (B total, B Rot, B Crust)

At sites downstream of locks, the results of the ordination showed that the eigenvalues of the first (λRDA1=0.345) and second (λRDA2=0.181) RDA axes accounted for 52.6% of the variation in the environmental data. The longest vector Secchi disk visibility showed highest negative correlation with rotifers density ($r=-0.88$, $p<0.05$) their biomass ($r=-0.75$, $p<0.05$) and zooplankton density ($r=-0.77$, $p<0.05$). On the other hand, water temperature was positively correlated with crustacean density ($r=0.49$, $p<0.05$). Dissolved oxygen showed a positive relationship with total zooplankton density ($r=0.59$, $p<0.05$), rotifer density ($r=0.72$, $p<0.05$) and rotifer biomass ($r=0.52$, $p<0.05$). Chlorophyll concentration also had a positive relationship with total zooplankton density ($r=0.75$, $p<0.05$), rotifer density (0.77, $p<0.05$) and rotifer biomass ($r=0.63$, $p<0.05$) (Table 4). The vectors for pH and conductivity were short, which means that these parameters are of less importance and statistically not significant in correlation with zooplankton species (Figure 4).



	Axes 1	Axes 2	Axes 3	Axes 4
Eigenvalues	0.3448	0.1811	0.0098	0.0013
Explained variation (cumulative)	34.48	52.59	53.57	53.70
Pseudo-canonical correlation	0.9321	0.5578	0.8914	0.5391
Explained fitted variation (cumulative)	64.17	97.89	99.71	99.95

Figure 4. Results of Redundancy analysis (RDA) performed on zooplankton and environmental data during vegetation season in the Bydgoszcz Canal and the Noteć Canal downstream of locks using forward selection of variables (p<0.05). Triplot of significant environmental variables (WT – Water temperature, SD – Secchi disk visibility, EC – conductivity, DO – oxygen concentration, pH, Chl-a – chlorophyll-a), number of zooplankton species (Tax total, Tax Rot, Tax Crust), zooplankton density (N total, N Rot, N Crust) and zooplankton biomass (B total, B Rot, B Crust)

Discussion

Zooplankton was studied in the Bydgoszcz Canal and the Noteć Canal upstream and downstream of the selected locks in 2021 and 2022. The hierarchical cluster analysis showed differences in environmental and biological conditions between habitats located upstream and downstream of locks. According to the results, the environmental (Figure 2A) and biological conditions (Figure 2B) at sites upstream of locks in Bydgoszcz Canal and Noteć Canal were distinct from the sites downstream of the locks (Figure 2A and Figure 2B).

RDA analysis identified that environmental variables were closely related to changes in the zooplankton community structure and niche differentiation. Chlorophyll concentration and water temperature were the main limiting factors and played important roles in shaping the zooplankton community structure (Figure 3 and Figure 4).

The average values of environmental parameters were similar upstream and downstream of locks on the studied canals. However, our study showed that chlorophyll concentration was higher downstream of the lock at site 1 in the Bydgoszcz Canal than upstream (Table 1). The increase in chlorophyll concentration indicated an increase in zooplankton density (rotifers and crustaceans) at this site. According to Sommer et al. (2004) the high chlorophyll concentration suggested greater food availability for zooplankton development in the floodplain lake. The level of chlorophyll (phytoplankton) increased during high flow, particularly in shallow water habitats (such as in the Bydgoszcz Canal downstream of locks).

In our study, we noticed that zooplankton diversity was higher at sites upstream of locks than downstream (Table 2 and Table 3).

During the study, rotifers dominated over crustaceans in density and diversity. The number of rotifer species upstream slightly prevailed of the number downstream (Table 2 and Table 3). Rotifers represented 80% of all zooplankton species. The most dominant were *K. cochlearis*, *K. quadrata* and *K. tecta*.

Crustaceans represented 20% of all zooplankton species. The most dominant among crustaceans were Cladocera – *B. longirostris*, *C. pulchella*, *Ch. sphaericus* and nauplii (copepod larval forms) (Table 2). Similar zooplankton species have been observed in a slow-flowing section of the lower Oder river (Czerniawski et al., 2013) and in man-made ditches (Czerniawski and Sługocki, 2017). In those studies, the authors confirmed that slow water flow favored the development of zooplankton communities.

Kuczyńska-Kippen et al. (2021) suggested that high rotifer density was associated with the presence of submerged macrophytes. Thus, the distribution and abundance of rotifers are influenced by the presence of submerged macrophytes and the flow velocity of the water. Therefore, the sections upstream of locks (low flow velocity and high macrophyte vegetation) favored high density and diversity of rotifers. Several authors have reported that rotifers are less susceptible than crustaceans to changes in environmental and hydrological conditions (Marneffe et al., 1996; Demetraki-Paleolog, 2004; Śpoljar et al., 2012).

The zooplankton biomass, including rotifer biomass, was also higher upstream of locks than downstream (site 2 and site 3). This happened because the zooplankton density increased at these sites. According to some authors, the zooplankton biomass in turbulent is much lower waters (e.g., downstream of locks) than in calm waters (e.g., upstream of locks) (Baranayi et al., 2002; Dickerson et al., 2010; Czerniawski and Domagała, 2012; Zhou et al., 2016). Therefore, the zooplankton community is probably shaped primarily by intensity of water movement. Only site 1 showed higher total zooplankton density, rotifer density, crustacean density, total zooplankton biomass and crustacean biomass downstream of locks than upstream.

Presumably, this difference is the result of internal loading (organic matter and nutrients) after the re-suspension of bottom sediments due to increased water movement inside the lock. Similar changes have been reported by Jeppesen et al. (2014). The sediment deposition downstream of the lock creates a more nutrient-rich environment, which can support increased primary production, including algal growth (higher chlorophyll concentration) (Cottingham et al., 1997; Chaparro et al., 2011). The increased availability of food resources can contribute to higher densities and biomass of rotifers and crustaceans (Kolarova & Napiórkowski, 2022).

RDA analysis indicated that the density and biomass of rotifers changed similarly to chlorophyll at sites upstream of locks (Figure 3). Our results support the hypothesis that rotifer communities are defined by bottom-up effects linked to food supply, such as small phytoplankton (chlorophyll – probably Cryptophyta) (Yoshida et al., 2003; Felpeto et al., 2013; Dembowska, 2021; Wang et al., 2022). Shayestehfar et al. (2008) pointed out that rotifer density and distribution depend on the variety of ecological and physicochemical factors such as food availability, but also dissolved oxygen and pH. All these factors are essential to determine the variations in rotifer density (Li et al., 2014; Wang et al., 2016; Banerjee et al., 2019; Kim et al., 2022).

According to RDA analysis, the main factor affecting the density and biomass of crustacean zooplankton, as well as total zooplankton biomass, at sites downstream of locks was water temperature (Figure 4). This relationship was observed in the triplot of significant environmental variables and was confirmed by Pearson’s simple correlation r coefficient.

Similarly, a study by Wei et al. (2017) showed that crustacean zooplankton was positively correlated with water temperature in a large river–lake system. Moore et al. (1996) suggested that temperature is an important compositional factor for crustaceans because temperature controls feeding, respiration, egg production velocity and other metabolic processes. All studied sites were similar in terms of abundance and biomass, except for site 1 downstream of the lock. The effects that water movement inside locks have on environmental conditions and zooplankton development need further study.

Conclusions

In the studied canals, zooplankton was shaped by different environmental and hydrological conditions.

- Density and biomass of rotifers changed similarly to chlorophyll at sites upstream of locks.
- Zooplankton diversity also increased upstream of locks.
- Low flow velocity and macrophytes as habitat favored high diversity and density of zooplankton.
- Water temperature stimulated the growth of crustaceans (density and biomass) and the total zooplankton biomass at sites downstream of locks.
- Only site 1 zooplankton density (rotifers and crustaceans), zooplankton biomass and crustacean biomass to be higher downstream of the lock than upstream. This is likely the result of internal loading (organic matter and nutrients) after the re-suspension of bottom sediments due to increased water movement inside the lock.

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We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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