Are rotifer indices suitable for assessing the trophic status in slow-flowing waters of canals?

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Abstract Zooplankton indicators based on rotifers (TSI_{ROT}) and an indicator based on Secchi disk visibility (TSI_{SD}) were used to assess trophic state changes in artificial, slow-flowing, and stagnant canal waters. The study was conducted in the summers of 2019, 2021, and 2022 in the Bydgoszcz Canal and the Noteć Canal (Poland). Water samples were taken from five sites once in the month of July and once in August. In terms of the species number and density, rotifers dominated among zooplankton (at almost all sites), which reflected the high trophic state. Our results showed statistically significant correlations between TSI_{ROT} and TSI_{SD} as well as between the individual indicators TSI_{ROT1} (Rotifer numbers), TSI_{ROT2} (Rotifer biomass), TSI_{ROT3} (bacterivorous numbers of rotifers), TSI_{ROT6} (rotifers indicating high trophic state), and TSI_{SD}. According to our study, the presented indices most likely determine the trends between TSI_{ROT} cumulative and TSI_{SD} in the studied canals. Similarly to previous studies performed on lakes and small reservoirs, zooplankton constituted a useful indicator of trophic state. It seems that, for stagnant and slowly flowing waters of canals such as the Bydgoszcz Canal and the Noteć Canal, the method of zooplankton trophic status indicators based on rotifers may be applied.

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Introduction

At the end of the twentieth century and the beginning of the 21st, the eutrophication of stagnant or slow-flowing waters became a major anthropogenic threat not only in Polish surface waters but in most freshwater systems worldwide (Kundu et al., 2015; Bowes et al., 2016; Ochocka, 2021). Eutrophication is caused by intensive loading of nutrients, especially nitrogen (N) and phosphorous (P) (Dembowska et al., 2015).

An uncontrolled increase in N and P pollution leads to an increase in nutrient-rich wastewater discharge and more intense nutrient area runoff into aquatic ecosystems (Glibert et al., 2014; Paerl et al., 2016). Deteriorations in water quality can be especially dangerous for shallow, slow-flowing canals

(Shields et al., 2010) because they are exposed to anthropogenic pollutants from huge river catchments (Biggs et al., 2016). Most studies have focused on water pollution problems in natural freshwaters, like rivers, streams, or lakes, with few data describing canals. A slight excess of nutrients (initial level) in fact stimulates primary production (macrophytes and algae growth) and positively affects the diversity of aquatic organisms. However, the overload of nutrients and resulting overproduction can lead to an excess of organic matter, which bacteria then break down, consuming oxygen in the process and thus leading to oxygen deficits. This can degrade environmental conditions. Excessive amounts of nutrients can cause the development of cyanobacteria, which can be toxic to aquatic organisms (Chislock et al., 2013; Paerl & Otten, 2013; Olsen et al., 2016).

The level of nutrients can be assessed by determining the trophic status of waters. Carlson (1977) introduced one of the first and most widely used classification schemes for lake trophic state assessment—the Trophic State Index (TSI). It is usually numerically assessed from data on Secchi disk visibility (SD), total phosphorus (TP), and the concentration of the phytoplankton pigment chlorophyll *a* (chl *a*). Carlson's trophic state index is constructed on a scale of 0 to 100. A Trophic State Index increase of 10 units describes a halving of Secchi disk visibility and a doubling of phosphorus and chlorophyll concentrations. Equally, a trophic state can be indicated based on reaction of planktonic organisms. A change in water trophy may completely or partially change the zooplankton community by, for example, increasing biomass and abundance (Hanson & Peters, 1984), decreasing body size (Pace, 1986; Karpowicz et al., 2020), and reducing species diversity (Andronikova, 1996; Haberman & Haldna, 2014). According to several authors (Ejsmont-Karabin, 2012; Ejsmont-Karabin & Karabin, 2013; Ochocka & Pasztaleniec, 2016; Pociecha et al., 2018; Stamou et al., 2019; García-Chicote et al., 2019; Mashkova et al., 2020; Muñoz-Colmenares et al., 2021), zooplankton can be a useful indicator for monitoring and assessing trophic level in freshwater ecosystems. For example, rotifers seem to serve as good indicators of water quality (Wallace et al., 2015), e.g., short development time, high reproduction rate, and short lifespans (Ricci & Balsamo, 2000;

Ejsmont-Karabin, 2019). Zooplankton organisms play an important role in the trophic web of aquatic habitats. Their position was introduced on the example of bottom-up control (shaped by algae population) and top-down control (the impact of planktivorous fish) (Jeppesen et al., 2011; Ochocka, 2021). The release of nutrients to the water column favors phytoplankton production (Persson, 1999; Kraska et al., 2013) and deeply impacts the composition of the zooplankton community (Xiao et al., 2020). Cyanobacteria and large inedible algae affect zooplankton by disturbing feeding, by being of poor nutritional quality as food, and by producing toxins (Vanni & Lampert, 1992; Ferrão-Filho & Kozlowsky-Suzuki, 2011).

Rotifers are among the groups of zooplankton most sensitive to trophic changes. Changes in rotifer abundance and species composition may be a good indicator of water quality associated with, e.g., total phosphorus and chlorophyll-*a* concentrations (May et al., 2014). Since the rotifers are cosmopolitan organisms suited to a range of habitats, they are ecologically resilient, short life cycles, and quick response to local environmental factors (Ejsmont-Karabin, 2019). Thus they may prove useful for biological monitoring (May & O'Hare, 2005; Lodi et al., 2011; Ejsmont-Karabin, 2012).

The *European Water Framework Directive* (*WFD*) (Directive 2000) presents requirements and assessments for controlling water quality and classifying waterbodies ("Ecological Status"). The fundamental goal of the *WFD* is to achieve good ecological status which is reflected by indicators that include biological quality elements (BQE) that are especially sensitive to nutrient loads (Lyche-Solheim et al., 2013; Dudley et al., 2013). Zooplankton is not listed among the BQEs, although it is sensitive to changes in nutrient concentrations and could be considered as a good indicator for assessing trophic status of aquatic ecosystems. Besides the *WFD* requirements and within new EU revisions, it is worth to strength the need of incorporating the zooplankton among biological components for monitoring of water quality and assessing trophic state in water bodies.

The aim of the study was to apply zooplankton indicators (TSI$_{Rot}$) to assess the trophic level in canals. We assumed that the rotifers index (TSI$_{Rot}$) would reflect trophic changes in artificial, slow-flowing, and stagnant canal waters, similarly as

for lakes. We hypothesized that zooplankton is a useful indicator of trophic state in the stagnant and slow-flowing waters of the Bydgoszcz Canal and its tributary the Noteć Canal.

Materials and methods

The research was conducted during the summers (July–August) of 2019, 2021, and 2022 in the Bydgoszcz Canal (part of which is located in the industrial area of Bydgoszcz city) and the Noteć Canal (located in the agricultural area near the town of Nakło). The study was performed in close proximity to locks—four in the Bydgoszcz Canal (Józefínki, Osowa Góra, Prądy, and Okole) and one in the Noteć Canal (Łochowo) (Fig. 1).

The Bydgoszcz Canal is a very important artificial waterway in north-west Poland. It is part of international waterway E70, which connects the two largest rivers in Poland—the Vistula and the Oder. The canal was built at the end of the eighteenth century. The total length of the Bydgoszcz Canal is 24.77 km, of which 15.7 km lies within the catchment of the Noteć River (a tributary of the Oder) and 9.0 km within the catchment of the Brda River (a tributary of the Vistula). The average depth of studied sites was 1.8 m depending on water level and the average width was 29 m (water flow was ~ 0.004 m/s).

The Noteć Canal comprises two sections (one simply referred to as the Noteć Canal and the other as the Upper Noteć Canal). The canal waterway covers the course of the Noteć river. The Upper Noteć Canal (where the samples were taken) is 25 km long and is strongly affected by anthropogenic contaminants due to human activities, including agriculture. At the study site, the canal was shallow, with an average depth of 1 m and an average width of about 15 m (water flow was ~ 0.14 m/s).

Water samples were collected at five sampling sites in two areas: Area 1: the Bydgoszcz Canal: (site 1) Józefinki upstream of the lock 53° 07′ 49.7″ N 17° 38′ 23.9″ E; (site 2) Osowa Góra upstream and downstream of the lock 53° 08′ 48.9″ N 17° 52′ 49.2″ E; (site 3) Prądy upstream and downstream of the lock 53° 08′ 38.6″ N 17° 53′ 37.8″ E; and (site 4) Okole downstream of the lock 53° 08′ 11.9″ N 17° 58′ 06.1″ E and Area 2: (site 5) the Noteć Canal—Łochowo upstream and downstream of the lock 53° 07′ 56.5″ N 17° 51′ 18.1″ E. Water samples were collected once a month in July and August of 2019, 2021, and 2022. Additional samples were taken from sites 2, 3, and 5 in 2022. A total of 36 samples were collected. Water samples were taken at different depths using a 1-L Patalas bucket. To obtain one qualitative and quantitative sample of zooplankton, 20 l of water was filtered through a plankton net, mesh size 25 μm. All samples were preserved with

Fig. 1 Map of investigated area. Bydgoszcz Canal: site 1—Józefinki; site 2—Osowa Góra; site 3—Prądy; site 4—Okole; and site 5—Noteć Canal, (Kolarova & Napiórkowski 2022—changed)
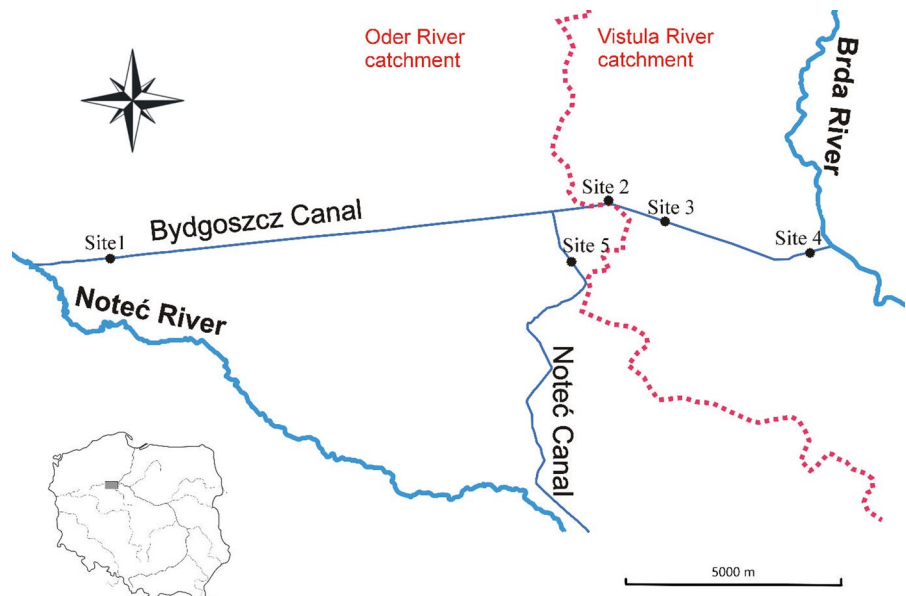
Lugol's iodine solution (Wallace et al., 1993; Harris et al., 2000). The samples were prepared for counting under a microscope according to the methodology described previously by Wallace et al., (1993). Zooplankton density and biomass were calculated per 1 l of water.

The identification of zooplankton was performed using an Olympus BX 43 light microscope as well as an Olympus LC 30 soft imaging camera at ×10 magnification. The commonly available keys were used for taxonomical identification of zooplankton (Wallace et al., 1993; Radwan et al., 2004; Błędzki & Rybak, 2016). The rotifers biomass was calculated using the formula according to Radwan et al. (2004) and Ruttner-Kolisko (1977). At the same time as zooplankton sampling, the following environmental parameters of water were measured: water temperature (WT, °C), Secchi disk visibility (SD, m), conductivity (EC, μS/cm), oxygen concentration (DO, mg/l), chlorophyll (chl-a, μg/l), nitrates (NNO_3^-, mg/l), phosphates (PPO_4^{2-}, mg/l), and pH (Table 1). Measurements were taken using Multimeter WTW Multi 3430SET F Xylem Analytics field probes (Weilheim, Germany). The surface water flow was measured during the sampling period using the electromagnetic hydrometric mill (Model 801).

Zooplankton seems to be a good indicator of trophic state in canals. This is because their slow water flow is similar to summer stagnant water period in lakes, for which zooplankton are proven to be an effective indicator. In the vicinity of the locks, the canals resembled small polymictic waterbodies. The season (July and August) was suggested by Ejsmont-Karabin (2012) as the best for comparative analysis of zooplankton because the stable summer

communities are mainly influenced by trophic factors. A similar relationship was observed in previous studies conducted on the zooplankton of the Bydgoszcz Canal (Kolarova & Napiórkowski 2022). The water trophy in the canals was assessed based on the species composition, abundance, and biomass of rotifers.

In accordance with Ejsmont-Karabin (2012), the following indices were used to assess the Trophic State Index (TSI_{ROT}): (1) rotifer number; (2) total biomass of rotifer community; (3) percentage of bacterivores in total rotifer number; (4) ratio of biomass to number; (5) percentage of tecta form in the population of *Keratella cochlearis* (Gosse, 1851); and (6) contribution of species that indicate a high trophic state in the indicatory group's number. TSI_{ROT} was obtained as the mean value of the mentioned indices. The small bacterivorous and detritophagous rotifers increase with trophic state (Obertegger & Wallace, 2023).

According to Carlson (1977), we used an index based on the Secchi disk visibility (SD) to determine the trophic state of the canals (TSI_{SD}). The TSI_{SD} was calculated using the formula: 60–14.41 ln(SD), where SD was measured in meters. According to some authors, TSI_{SD} is often used as an indicator for evaluating eutrophication in different types of water bodies (Jekatierynczuk-Rudczyk et al., 2012; Kordi et al., 2012; Haberman & Haldna, 2014; Heddam, 2016; Ochocka & Pasztaleniec, 2016).

Statistical analysis was performed using Statistica 14.0.0.15 software (TIBCO Software Inc., Palo Alto, CA, USA). Scatterplot with linear regression line was applied to analyze the relationship between the rotifer index TSI_{ROT} and the index based on the Secchi

Table 1 Mean values of environmental parameters in the Bydgoszcz Canal and Noteć Canal sites

Water temperature (WT, °C), Secchi disk visibility (SD, m), conductivity (EC, μS/cm), oxygen concentration (DO, mg/l), pH, chlorophyll (chl-a, μg/l), nitrate (NNO^{3-}, mg/l), and phosphate (PPO_4^{2-}, mg/l)

| | Bydgoszcz Canal | | | | | Noteć Canal | |
	Site 1	Site 2	Site 3	Site 4	Mean (range)	Site 5 Mean	(Range)
WT (°C)	20.8	20.7	21.1	20.8	20.9 (18.0–24.3)	20.8	(17.0–23.9)
SD (m)	1.5	1.8	1.8	0.9	1.5 (0.50–2.20)	1.8	(1.30–2.00)
EC (μS/cm)	945	896	891	820	888 (400–1796)	896	(593–1791)
DO (mg/l)	7.1	7.8	8.6	9.5	8.2 (4.5–14.2)	6.5	(4.9–7.9)
pH	7.3	7.2	7.3	7.3	7.3 (6.5–8.3)	7.1	(6.4–8.0)
chl-a (μg/l)	10.6	6.2	7.3	13.8	9.5 (2.0–40.2)	4.1	(0.9–9.9)
NNO_3^- (mg/l)	0.27	0.33	0.28	0.38	0.32 (0.05–0.79)	0.30	(0.07–0.59)
PPO_4^{2-} (mg/l)	0.13	0.13	0.11	0.13	0.12 (0.02–0.42)	0.18	(0.03–0.41)

disk TSI_{SD}. Pearson simple correlation coefficient was calculated to compare the rotifers indices ($TSI_{ROT1-ROT6}$) and TSI_{SD}.

The level ($P < 0.05$) was indicated for statistically significant correlations. The normality of data distribution was tested by the Shapiro–Wilk W test (Shapiro & Wilk, 1965).

Results

Environmental characteristic

The water temperatures in the Bydgoszcz Canal and Noteć Canal were similar during the studies, averaging 21 °C. The average water transparency in the Bydgoszcz Canal was 1.5 m and increased from 0.9 m at Site 4 to 1.8 m at Site 2 and 3. Meanwhile, the average water transparency in the Noteć Canal came to 1.8 m and ranged from 1.3 to 2.0 m. The average water pH at all sites was slightly above 7, indicating alkaline conditions. The average value of dissolved oxygen concentration ranged from 6.5 mg/l in the Noteć Canal (site 5) up to 9.5 mg/l in the Bydgoszcz Canal (site 4). The conductivity was similar at all sites. The average chlorophyll concentration varied from 4.1 mg/l in the Noteć Canal up to 13.8 mg/l in the Bydgoszcz Canal at Site 4. There was no significant difference in the concentration of NNO_3^- and PPO_4^{2-} between the Bydgoszcz Canal and the Noteć Canal (Table 1).

Rotifers characteristic

Samples analysis revealed the presence of 77 rotifer species, (i.e., 73% of all zooplankton species). In the Noteć Canal, 42 rotifer species were identified (i.e., 82% of all zooplankton species). The lowest number of rotifer species was recorded in the Bydgoszcz Canal at Site 1 (36 species). The highest number of rotifer species was recorded in the Bydgoszcz Canal at Site 4 (56 species). A list of all rotifers species at individual sites has been added as an attachment.

The highest average number of species in a single sample was observed at Site 4 (23 species) and the lowest at Site 1 (10 species). The highest and the lowest number of rotifer species were found at the same sites, like the average number of species, in one sample.

The average rotifer density was the highest in the Bydgoszcz Canal (148 ind/l) (ranging from 35 ind/l at Site 2 to 445 ind/l at Site 4) and lowest in the Noteć Canal—Site 5 (30 ind/l) (Table 2). Rotifers dominate in terms of the number of species and abundance in all studied sites. The dominant rotifer species were *Anuraeopsis fissa* (Gosse, 1851), *Polyarthra remata* Skorikov, 1896 and *Brachionus calyciflorus* Pallas, 1766.

The average rotifer biomass was five times higher in the Bydgoszcz Canal (0.049 mg/l) than in the Noteć Canal (0.009 mg/l). The rotifer biomass was lowest at site 5 in the Noteć Canal and highest at Site 4 in the Bydgoszcz Canal (0.150 mg/l) (Table 2).

During the study period, the α-diversity index ($H' = 2.49 \pm 0.40$) was highest at Site 2 in the Bydgoszcz Canal and lowest ($H' = 1.68 \pm 0.41$) at Site 1 in the Bydgoszcz Canal. The eveness index was highest ($J' = 0.72 \pm 0.13$) in the Bydgoszcz Canal, at Site 2 and lowest ($J' = 0.39 \pm 0.20$) at Site 4 in the Bydgoszcz Canal (Table 2).

Trophic State Index

Average TSI_{SD} value ranged from 51 at Site 2 to 62 at Site 4 in the Bydgoszcz Canal. According to the

Table 2 Mean values of rotifer species, density (ind/l) and biomass (mg/l)

Tax Rot—number of rotifer species; N Rot—density of rotifers; B Rot—biomass of rotifers. Shannon–Weaver α-diversity index (H' index); Pielou's evenness index (J' index)

	Bydgoszcz Canal					Noteć Canal	
	Site 1	Site 2	Site 3	Site 4	Mean (range)	Site 5 Mean	(Range)
Tax Rot	10	18	14	23	16 (3–30)	16	(11–24)
N Rot	73	35	40	445	148 (5–1548)	30	(14–44)
B Rot	0.019	0.011	0.016	0.150	0.049 (0.004–0.406)	0.009	(0.003– 0.020)
H' index	1.68	2.49	2.15	2.05	2.09	2.18	
J' index	0.60	0.72	0.64	0.39	0.59	0.61	

average value of TSI_{SD}, the trophic states of the sites in the Bydgoszcz Canal were classified from high mesotrophic (Site 2 and Site 3) to high eutrophic (Site 4) (Table 3). Thus, the average value of TSI_{SD} in the Bydgoszcz Canal was classified as eutrophic.

Average TSI value based on Chl-*a* varied from 32 in the Noteć Canal (Site 5) to 53 in the Bydgoszcz Canal (Site 3). The value of indices indicated from oligotrophic (Site 5) to meso-eutrophic state (Site 3). According to the trophic state value calculated based on Chl-*a*, the canals were classified from oligotrophic to high meso-eutrophic state (Table 3). During the study in 2019, 2021, and 2022, the average value of TSI_{SD} in the Bydgoszcz Canal increased from the rural agriculture area to the industrial area near Bydgoszcz city.

Average TSI_{ROT} (cumulative index) varied from 45 (Site 1, Site 2, Site 3) in the Bydgoszcz Canal) to 52 (Site 4—Bydgoszcz Canal). Most sites were classified from high mesotrophic to low meso-eutrophic state. Only Site 4 was classified as being in a high meso-eutrophic state. The average value of TSI_{ROT} in the Bydgoszcz Canal and in the Noteć Canal was 47 (Table 3). The highest values of rotifer indexes (TSI_{ROT1-6}) were at Site 4 (Bydgoszcz Canal). Only the value of TSI_{ROT5} was higher at Site 1, Site 3 (Bydgoszcz Canal), and at Site 5 in the Noteć Canal than at Site 4 (Bydgoszcz Canal). The highest TSI_{ROT3} (percentage of bacterivorous species; 59.3%) and TSI_{ROT6} (species indicating high trophic state; 75.3%) in the total numbers of rotifers were found in the Bydgoszcz Canal at Site 4. The dominant species was *A. fissa* (56.2%).

Comparison of indices

The TSI was developed by Carlson based on water transparency (SD). Therefore, in order to verify the TSI_{ROT} in the analyzed canals, the authors first took into account TSI_{SD}. Our study showed that TSI_{ROT} correlates with the TSI_{SD} in slow-flowing and stagnant water of canals ($r = 0.6037$, $P = 0.0001$) (Fig. 2).
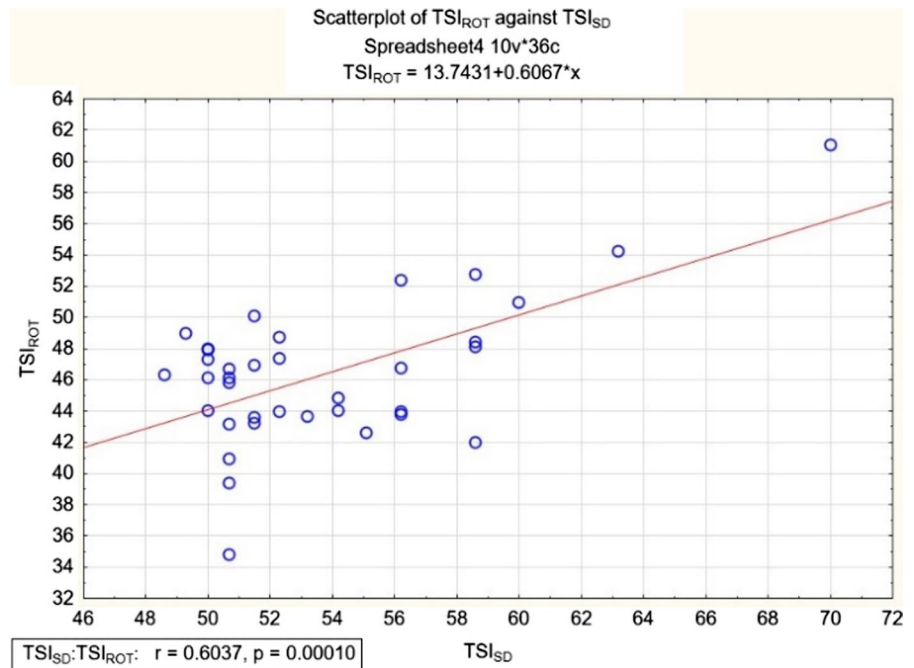
During the analysis of individual indicators that make up the cumulative indicator TSI_{ROT}, it was noted that TSI_{ROT1} based on the number of rotifers are statistically significant and correlate at the level of $r = 0.6216$ with trophic state index of Secchi disk visibility (TSI_{SD}) ($P < 00001$). TSI_{ROT2} based on rotifer biomass depends on TSI_{SD}. Correlation coeficients are statistically significant at the level of $r = 0.4849$, $P < 0.05$. However, the relationship between the biomass and canal's TSI_{SD} is weaker than the relationship between the numbers and TSI_{SD}. TSI_{ROT3} (percentage of bacterivorous species—*A. fissa*, *Filinia* spp., *Brachionus angularis* Gosse, 1851, *Keratella cochlearis* (Gosse, 1851), *Pompholyx sulcata* Hudson, 1885 in the total number of rotifers) correlates with TSI_{SD} at the level of $r = 0.6498$, $P < 0.0001$. Rotifers index of individual indicator (TSI_{ROT6}) calculated on numbers of rotifer indicators of high trophic state in the indicative ecological group (IHT, %) is also well correlated with TSI_{SD} ($r = 0.5656$, $P < 0.05$) (Table 4).

Table 3 Mean values of Trophic State Indexes of rotifers ($TSI_{ROT,ROT1-6}$) (Ejsmont-Karabin, 2012) and Carlson's Trophic State Indexes (TSI_{SD}, TSI_{Chl-a}) in the summers of 2019, 2021, and 2022 (July–August) in the Bydgoszcz Canal and the Noteć Canal sites

| | Bydgoszcz Canal | | | | | Noteć Canal | |
	Site 1	Site 2	Site 3	Site 4	Mean (range)	Site 5 Mean	(Range)
TSI_{ROT1}	40	36	38	48	41 (28–59)	38	(35–42)
$TS1_{ROT2}$	39	38	39	51	42 (29–60)	39	(32–49)
TSI_{ROT3}	45	47	46	51	47 (44–65)	48	(45–55)
TSI_{ROT4}	57	60	63	64	61 (50–69)	63	(50–69)
TSI_{ROT5}	54	48	50	48	50 (40–59)	50	(37–60)
TSI_{ROT6}	42	43	44	51	45 (40–60)	45	(40–57)
TSI_{ROT}*	45	45	45	52	47 (39–61)	47	(43–52)
TSI_{SD}	55	51	52	62	55 (49–70)	52	(50–56)
TSI_{Chl-a}	51	42	53	50	49 (26–70)	32	(16–50)

*Cumulative value

Fig. 2 Relationship between rotifers index (TSI_{ROT}) and trophic state index calculated (acc. Carlson 1977) for Secchi disk visibility (TSI_{SD}), mean values at sites in the studied canals

Scatterplot of TSI_{ROT} against TSI_{SD}
Spreadsheet4 10v*36c
$TSI_{ROT} = 13.7431+0.6067*x$

$TSI_{SD}:TSI_{ROT}$: r = 0.6037, p = 0.00010

Table 4 Pearson's simple correlation r coefficient for parameters in Bydgoszcz Canal and Noteć Canal

Trophic State Indexes of rotifers	TSI_{SD}	P
TSI_{ROT1}	**0.6216**	$P < 00001$
TSI_{ROT2}	**0.4849**	$P < 0.05$
TSI_{ROT3}	**0.6498**	$P < 0.0001$
TSI_{ROT4}	0.1408	$P > 0.05$
TSI_{ROT5}	0.2707	$P > 0.05$
TSI_{ROT6}	**0.5656**	$P < 0.05$

Trophic State Indexes of rotifers ($TSI_{ROT1–6}$), Trophic State Index based on Secchi disk visibility (TSI_{SD}), p—significance level

Bold significant correlation

Discussion

During the research, the trophic status of the canals was assessed on the basis of the species composition, abundance and biomass of zooplankton (rotifers), as well as on the basis of physical and chemical data.

The chlorophyll concentration decreased at most sites, which contributed to an increase in water transparency. The lowest Secchi disk visibility (0.9 m on average) was recorded at Site 4 and indicated high chlorophyll concentration (Table 1). Algal

bloom coincided with high summer temperatures (21 °C on average). Many authors noted that the water transparency is a significant integrative indicator of phytoplankton biomass and primary production searched in the river basins (Kolarova & Napiórkowski, 2022; Shelyuk, 2019; Wilkerson et al., 2015). The concentration of oxygen was also the highest at Site 4. Algae are mainly responsible for the production of oxygen in water (Dembowska et al., 2012), which is confirmed by our research. Other physical and chemical parameters were at approximately uniform levels across all sites in the 3 years of the research (Table 1). During the study, rotifers dominated in species number (78%) and density (65%). Such a significant share of rotifers in zooplankton formation allows the use of this group as indicators (Ejsmont-Karabin, 2012). The highest number of rotifer species (23) and average density (445 ind/l) were found at Site 4, while the lowest number of rotifer species (10) at Site 1 and average density (30 ind/l) were found in the Noteć Canal (Table 2). Rotifer density increased from the sites outside of the city to the sites nearer to the city. Dembowska et al. (2015) suggest that rotifer density may be a more sensitive indicator of changes in trophic state than is species diversity. An increase in small-bodied rotifers and low individual biomasses

indicate trophic conditions (Arndt, 1993; Radwan et al., 2004). For example, bacterioplankton-detritus-eating rotifers, which occur during the summer blooms, indicate high trophy (Ejsmont-Karabin, 2012; Ejsmont-Karabin & Hillbricht-Ilkowska, 1994). A similar regularity was observed in the trophic gradient on the studied canals.

A previous study has noted that zooplankton density clearly correlates to Secchi disk visibility as a recommended indicator of trophic conditions (Ochocka, 2021). The results of our studies confirmed that rotifer density increased with TSI_{SD}. On the other hand, changes in TSI_{SD} seemed to have less influence on the number of rotifer species. At most sites, the rotifer index (TSI_{ROT}) increased along with rotifer density and number of species (Tables 2 and 3).

We found a positive correlation between TSI_{ROT} and TSI_{SD} in the studied canals (Fig. 2). It is clear that an increase in trophic pollution of waters causes an increase in TSI_{SD} and thus also an increase in TSI_{ROT} together with individual sub-indicators. Based on TSI_{SD}, most of the sites were classified as meso-eutrophic, whereas Site 4 was classified as high eutrophic. The sites with higher trophic status had lower transparency, which was the result of their exposure to higher-nutrient loads from anthropogenic sources. However, shallow water catchments are less resistant to eutrophication and pollution (Sługocki & Czerniawski, 2018). During the study, we found that the dominant species [*K. cochlearis*, *Keratella tecta* (Gosse, 1851), *B. calyciflorus,* and *A. fissa]* prefer high trophic states. The species found during our research were typical of eutrophic waters (Ejsmont-Karabin, 2012; Pociecha et al., 2018).

Based on TSI_{ROT}, the studied canals were characterized by low meso-eutrophy. TSI_{ROT} increased toward the city in the Bydgoszcz Canal. The part of the Bydgoszcz Canal catchment exposed to the city showed greater trophic pollution. At Site 4, the TSI_{ROT} value was highest (52—high meso-eutrophy). In this part of the canal, we observed the highest rotifer biomass and the highest chlorophyll-*a* concentration.

This study constitutes the first time that trophic state indices have ever been used in canals. Similar dependences have appeared only in research by Ejsmont-Kararbin (2012, 2013) but that was performed on lakes.

The results of our study showed that the rotifer indices are a functional and useful tool for assessing the trophic state of canals. We noticed that TSI_{ROT} correlates with the TSI_{SD} in slow-flowing and stagnant water of canals (Fig. 2, Table 4). Previous studies showed that rotifer indices are best for assessing the trophic state of ponds, dam reservoirs, coastal lagoons, or inland lakes (Ejsmont-Karabin, 2012; Gutkowska et al., 2013; Pociecha et al., 2018; Stamou et al., 2019; Kim et al., 2020; Kuczyńska-Kippen et al., 2021). Unfortunately, there is only a very small number of studies using rotifer indices to assess trophic conditions in slow-flowing waters (Sor et al., 2015; Liang et al., 2020). However, many authors suggest using zooplankton abundance, species composition, and biomass for assessing trophic conditions and controlling long-term changes in water quality (Montagud et al., 2019; Muñoz-Colmenares et al., 2021; Spoljar, 2013).

The *European Water Framework Directive* (WFD) requires the ecological quality of waters to be maintained based on the assessment of biological quality elements (BQE) and supported by a set of physical and chemical and hydro-morphological elements (Directive 2000). However, zooplankton have been omitted as a biological indicator from the water quality assessment. Nevertheless, zooplankton communities are an important component in the pelagic food web, as they respond quickly to environmental changes (Shurin et al., 2010). Thus, they may be an effective and useful indicator of water quality (Jeppesen et al., 2011), as our research shows.

Conclusion

Rotifers were the dominant group of zooplankton in the studied canals. Their taxonomic composition was typical of eutrophic and shallow waters.

Our research involved the first use of the rotifer index (TSI_{ROT}) and Secchi disk visibility index (TSI_{SD}) to assess trophic level in the slow-flowing and stagnant water of canals.

We found a positive correlation between TSI_{ROT} and TSI_{SD}. An increase in trophic pollution in waters causes an increase in TSI_{SD} and thus also increases in TSI_{ROT} and individual sub-indicators. We emphasized the importance of rotifers as indicators of trophic state in canals. Rotifers are functional groups of

zooplankton species and could be included in the list of BQEs.

Declarations

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