The influence of hydrological and environmental conditions on zooplankton diversity in the Bydgoszcz Canal and in the Noteć Canal

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Combined doctoral thesis

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Kazimierz Wielki University in Bydgoszcz
2023, Bydgoszcz

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Contents

1. ARTICLES INCLUDED IN THE PUBLICATION SERIES

The series of publications, which is a thematically consistent collection of scientific studies entitled: “The influence of hydrological and environmental conditions on zooplankton diversity in the Bydgoszcz Canal and in the Noteć Canal” attached 3 articles, including 2 published and 1 submitted for publication:

A1. Kolarova, N., Napiórkowski, P. (2022). *How Do Specific Environmental Conditions in Canals Affect the Structure and Variability of the Zooplankton Community?* Water, 14(6), 979. https://doi:10.3390/w14060979;

A2. Kolarova, N., Napiórkowski, P. (2023). *Are rotifer indices suitable for assessing the trophic status in slow-flowing waters of canals?* Hydrobiologia, 1-11. https://doi:10.1007/s10750-023-05275-7;

A3. Kolarova, N., Napiórkowski, P. (under review). *The influence of locks on canals zooplankton (Bydgoszcz canal and Noteć canal – Poland).* Ecohydrology & Hydrobiology, 000-000

Table 1 provides metrics on the above publications, while the full texts of the articles have been added as appendices to the doctoral thesis.

Table 1. Information related to bibliometric indices of the articles included in the publication series for the doctoral thesis (*after all papers have been published).

No. of publication attached (reference to particular literature position)	**Impact Factor**	**Number of points**	**Contribution of PhD student (%)**
A1	3.530	100	55
A2	2.822	100	60
A3	2.957	100	60
In total	6.352 (9.309*)	200 (300*)	

2. ABSTRACT

The hydrobiology of canals in Eastern and Western Europe has been sparsely investigated. Therefore, I was motivated to study the hydrological and environmental factors which cause zooplankton diversity in Bydgoszcz Canal and the Noteć Canal (Poland). The first goal of my research was the assessment of zooplankton variability depending on the locations of the designated sites. The Bydgoszcz Canal sites showed the greatest diversity, abundance and biomass of zooplankton compared to sites in the Brda River or the Noteć Canal. The reason may be differences in tolerance to water movement. For example, slower water flow (in the Bydgoszcz Canal's sites) directly effects zooplankton development by creating more stable growth conditions. The locks on the Bydgoszcz Canal reduce water flow. This had an indirect influence by increasing the number of macrophytes that create ecological niches, in turn benefitting the development of zooplankton organisms, especially crustaceans.

I also tried to determine the impact of human activity on the quality of the canals' water. One of the symptoms of human pressure is an increase in trophy; therefore, zooplankton indicators were applied. I used the rotifers to indicate the trophic state in canals, because they were the most numerous group of zooplankton both in terms of quality and quantity. During my study, I assessed trophic state changes based on zooplankton indicators (rotifers [TSI_{ROT}]) and an indicator based on Secchi disk visibility (TSI_{SD}) in the slow-flowing and stagnant waters of artificial canals. The indices calculated on the basis of qualitative and quantitative data of rotifers correlated with the TSI_{SD} index. I found that rotifers taxonomic composition was typical for eutrophic and shallow waters. According to the obtained results the rotifers seem to be an important indicator of trophic state in canals. Therefore, they might be included in the list of biological quality elements.

The canals are rich in various hydrological structures e.g. locks. I also study the variability of zooplankton near the locks, so the next goal of research was to determine how hydrotechnical structures can affect the zooplankton of a canal. I assessed the variability of environmental conditions and zooplankton upstream and downstream of the locks. The hydrotechnical structures (locks) shaped the zooplankton community in the canals. Zooplankton diversity, density and biomass were mostly higher at the sites upstream of the locks compared to the sites downstream. Only at site 1 the pattern was different. Both qualitatively and quantitatively, zooplankton was richer downstream of the lock than upstream of the lock. This may be due to the re-suspension of bottom sediments and the release of organic matter and nutrients into the water. Water movement inside the lock may release additional food resources and organisms associated with these resources. Based on the statistical analysis upstream of the locks, the concentration of chlorophyll affected the number of rotifers (Rotifera). Downstream of the locks, the temperature stimulated the development of zooplankton, especially crustaceans (Crustacea).

The canals seem to be a very attractive place to live for zooplankton organisms and the research conducted as part of the doctoral dissertation provides new data about these artificial ecosystems.

Keywords: artificial waterways, physico-chemical water parameters, rotifers, crustaceans, water flow

3. STRESZCZENIE

Środowisko i hydrobiologia europejskich kanałów wciąż są słabo poznane. W związku z tym postanowiłam zbadać, jak warunki środowiskowe i hydrologia wpływają na różnorodność zooplanktonu w Kanale Bydgoskim i Kanale Noteckim (Polska). Pierwszym celem moich badań była ocena zmienności zooplanktonu w zależności od lokalizacji stanowisk na kanałach. Próby wody ze stanowisk na Kanale Bydgoskim wykazywały większą różnorodność, liczebność i biomasę zooplanktonu w porównaniu z wodami ze stanowisk na Brdzie i Kanale Noteckim. Powodem obserwowanego zróżnicowania mogą być różnice w tolerancji organizmów zooplanktonowych na ruch wody. Na przykład, wolniejszy przepływ wody (na stanowiskach Kanału Bydgoskiego) bezpośrednio wpływał na szybszy rozwój zooplanktonu, tworząc bardziej stabilne warunki wzrostu. Śluzy na Kanale Bydgoskim istotnie zmniejszają przepływ wody. Miało to wpływ na zwiększenie liczby makrofitów, które tworzyły nisze ekologiczne, co korzystnie wpływało na rozwój organizmów zooplanktonowych, zwłaszcza skorupiaków.

Starałam się również określić wpływ działalności człowieka na jakość wody w kanałach. Jednym z przejawów (symptomów) presji człowieka na środowisko wodne jest wzrost trofii, dlatego zastosowałam zooplanktonowe wskaźniki stanu trofii. Do oceny stanu troficznego wód kanałów wykorzystałam wrotki (Rotifera), ponieważ były one najliczniejszą

grupą zooplanktonu zarówno pod względem jakościowym, jak i ilościowym. W trakcie badań oceniałam zmiany stanu troficznego w wodach badanych kanałów na podstawie wskaźników zooplanktonowych (wrotków-TSI_{ROT}) oraz wskaźnika opartego na widzialności krążka Secchiego (TSI_{SD}) w wolno płynących i stojących wodach sztucznych kanałów. Wskaźniki wyliczone w oparciu o dane jakościowe i ilościowe wrotków korelowały ze wskaźnikiem TSI_{SD}. Stwierdziłam, że skład taksonomiczny wrotków był typowy dla wód eutroficznych i płytkich. Zgodnie z uzyskanymi wynikami, wrotki wydają się być dobrym wskaźnikiem trofii wód w badanych kanałach. W związku z tym mogą być (powinny być) włączone do listy biologicznych wskaźników jakości wód dla sztucznych kanałów.

Sztuczne kanały mają wiele różnych konstrukcji hydrotechnicznych, w tym śluzy. Moimi badaniami objęłam również zróżnicowanie zooplanktonu w wodach kanałów w pobliżu śluz. Celem tej części badań było określenie, w jaki sposób struktury hydrotechniczne mogą wpływać na zooplankton kanałów. Oceniłam, jak zmienne warunki środowiskowe wpływają na zooplankton przed i za śluzami. Budowle hydrotechniczne w istotny sposób kształtują strukturę zooplanktonu w wodach badanych kanałów. Różnorodność, liczebność i biomasa zooplanktonu były najczęściej wyższe w wodach przed śluzami w porównaniu do wód poniżej śluz. Prawdopodobnie niska prędkość przepływu wody i nagromadzenie makrofitów sprzyjało rozwojowi zooplanktonu przed śluzami. Jedynie na stanowisku 1 schemat był inny. Zarówno pod względem jakościowym jak i ilościowym, zooplankton był bogatszy poniżej śluzy. Może być to spowodowane resuspensją osadów dennych i uwalnianiem materii organicznej oraz biogenów do wody. Ruch wody na stanowisku 1 wewnątrz śluzy może uwalniać dodatkowe zasoby pokarmowe oraz organizmy z tymi zasobami związane. Na podstawie analizy statystycznej, stężenie chlorofilu przed śluzami wpływało na liczebność wrotków (Rotifera). Natomiast poniżej śluz to temperatura stymulowała rozwój zooplanktonu, przede wszystkim skorupiaków (Crustacea).

Kanały wydają się być bardzo atrakcyjnym miejscem życia dla organizmów zooplanktonowych, a badania prowadzone w ramach rozprawy doktorskiej dostarczają nowych danych na temat tych sztucznych ekosystemów.

Słowa kluczowe: sztuczne drogi wodne, fizyczno-chemiczne parametry wody, wrotki, skorupiaki, przepływ wody

4. INTRODUCTION

4.1. The importance of rivers and canals - a historical outline

River and canal systems have taken a fundamental place in human history since the dawn of the first civilization. Originally they provided water to alluvial plains that built and sustained the first human settlements. This helped to achieve wealth based on agriculture and trade, which in turn allowed great civilizations to flourish (Prideaux et al., 2009). Rivers have provided water for drinking, for food production, for energy and for transport. They have played a principle role in the development of human civilization (Sadoff and Grey, 2002). Canals were primarily constructed for main purposes – to meet human and natural system needs such as irrigation, drainage, flood control, and navigation. They were designed and managed to maintain appropriate water levels and convey water from areas of excess water to areas of too little water, and to move water to areas where it can be conserved. For example, canals in South Florida were constructed to collect and convey water from secondary systems over long distances to provide regional drainage for adjacent lands and for transport of agricultural goods. Later, they were improved to ensure flood protection and modified to build up the hydrological control structures to enhance water supply capabilities (Carter et al., 2010).

Waterways were the oldest transport routes around which mankind gathered and cities developed. Until the mid-twentieth century, waterways were intensively used for the transport of goods and passenger shipping, sports and recreation. From the second half of the twentieth century, as a result of changes in transport technology, waterways began to lose their importance. The processes of degradation and decapitalization of technical infrastructure and areas spatially and functionally connected with the river intensified. This inhibited the development of waterways (Muszyńska-Jeleszyńska, 2013). Nowadays, rivers and canals are a significant source of water tourism (Prideaux, 2023).

In conclusion, from a historical point of view, waterways were of high importance to commerce and the development of a civilization (Sadoff and Grey, 2002). They have been an important part of transport systems, with the advantage of allowing boats to transport loads of great mass. The economic development enforced the need to complement the natural system of waterways with canals, which led to the establishment of trade routes and consequently to the development of numerous cities, towns and agricultural regions (Muszyńska-Jeleszyńska, 2013; Izajasz and Dziedzic, 2014).

4.2. Rivers as natural water ecosystems

4.2.1. General characteristics and classification of natural waterways

Two exemplar definitions of natural waterways are provided:

a) According to Bajkiewicz-Grabowska and Mikulski (2006), "surface waters flowing in a concentrated form under the influence of gravity through a natural bed." Natural waterways include: streams, brooks and small, medium and large rivers. According to the quoted authors, a river is a natural waterway formed from the connection of streams or flowing from the front of a glacier, lake or source, supplied at the surface and underground with precipitation water, having a shaped bed and flowing under the action of gravitational force in the bed and valley that is grooved as a result of its erosive force.

b) According to Giziński and Falkowska (2003), flowing waters are inland waters in which all or most of the water mass moves simultaneously in one direction. The constant movement of water in a waterway results from the inclination (slope) of its bed and is the basic difference between stagnant and flowing waters. Stagnant waters predominantly provide lentic habitats (calm, with slow movements) prevail, and flowing waters predominantly provide lotic habitats (mobile, dynamic). Each watercourse has its beginning (source), upper, middle and lower parts, ending with an outlet to a larger watercourse, lake or sea. The upper sections of rivers with the highest flow velocity are called "streams", and the middle and lower sections, usually carrying more water but flowing slowly, are called "rivers".

Many different classifications of rivers have been created. Depending on the length and size of the basin, Z. Mikulski (1963) distinguishes:

- small rivers (length 100–200 km with a basin area of 1000–10,000 km^2)

- medium rivers (length 200–500 km with a basin area of 10,000–100,000 km^2)

- large rivers (length 500–2500 km with a basin area of 0.1–1 million km^2)

- great rivers (length over 2,500 km with a basin area of over 1 million km^2)

Taking into account the location of the river, it is divided into: mountain and lowland (plain).

Flowing waters form a river system in a given area. In this system, one of the watercourses is considered the main river. The main river with its tributaries forms a river network.

Starmach et al. (1976) suppose that rivers, although occupying a much smaller area on the Earth's surface than lakes (1% of land area), play very important natural and economic roles. Rivers account for 2% of the earth's surface freshwater resources (Gleick, 1996). The network of rivers intersects all continents and supplies vast areas of the Earth with fresh water, creating living conditions for organisms.

4.2.2. General characteristics and classification of canals

Artificial canals are important junctions connecting natural rivers of various sizes, structures and functions into a large-scale inland water system (Gorączko, 2015).

According to Segovia et al. (2019), there are two broad types of canal:

Waterways: canals and navigational channels usually constructed to allow the passage of boats or vessels between rivers of different catchments (i.e., crossing a watershed) used for transporting goods and people. These can be subdivided into two kinds:

Those connecting existing lakes, such as the Welland, which connects Lake Ontario to Lake Erie; those connecting rivers, such as the Rhine-Main-Danube Canal; and those connecting seas and oceans, such as the Suez Canal connecting the Gulf of Suez to the Mediterranean Sea and separating Asia from Africa, and the Panama Canal connecting the Pacific and Atlantic oceans.

Those connected in a city network, such as the Canal Grande and others of Venice, the Grachten of Amsterdam or Utrecht, and the waterways of Bangkok.

Aqueducts: water supply canals that are used for the conveyance and delivery of potable water, municipal uses, hydro power canals, agriculture irrigation and flood protection.

Such an artificial waterway is divided into places with different levels of the water table 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 a navigational role, making it important to guarantee navigability by using weirs and dams to ensure appropriate water depths and locks to allow boats to ascend and descend between stretches that differ in elevation (Segovia et al., 2019).

Locks are essential structures whose main function is to enable vessels to sail in both directions by overcoming the difference in water level from lower to higher and *vice versa*. The most common are chamber locks consisting of basic elements such as a higher and lower valve, a chamber, a lock gate, a closing chamber gate (upper and lower) and bypass canals (Tołkacz, 2010).

Activities performed as part of the ship lock cycle include:
- phase I: after opening the valve on the gate through which the vessel is to enter, the water levels in the chamber will equalize by gravity with the water level on the side (upper or lower) from which the vessel is to enter; the gate is then opened and the vessel enters the lock chamber;
- phase II: the lock gate is closed behind the vessel, effectively sealing it within the chamber; the valve at the gate through which the vessel intends to depart is opened, and the water level in the chamber equalizes by gravity with the water level in the "destination" stretch of canal; thus, the ship is transported vertically;
- phase III: the gate to the "destination" stretch of the canal is opened and the ship sails to the other side of the lock.

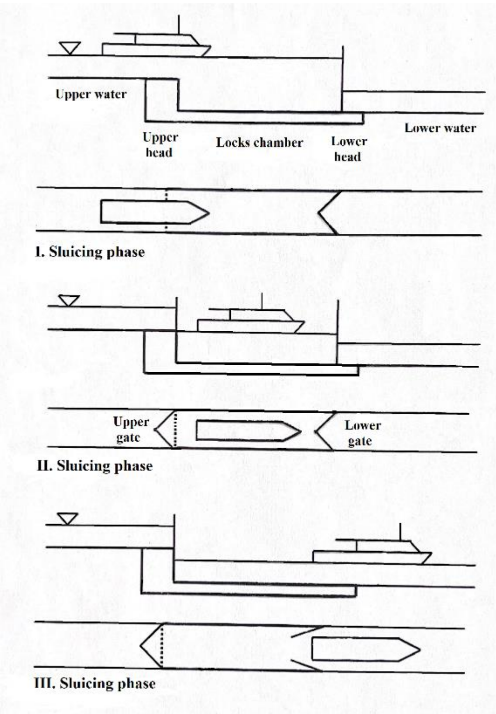

Figure 1. Phases of the ship lock cycle, (Tołkacz, 2010).

During the sluicing process carried out in a lock with intermediate gates, a pair of gates is always used; the third gate is open at this time. The lengths of locks are usually adapted to the size of ships. The construction of these "parallel locks" saves the water moving from the upper to the lower level. This is important not only for the length of the current locking, but also for the issue of water supply. These sluice gates often use artificial flows supplied by pumps and pipelines to fill the chamber. This solution allows the use of locks, but at the same time increases their operation costs.

The purpose of canal bypassing is to allow water to flow into the chamber space after opening the upper gate and to flow out of this space after opening the lower gate.

The building of locks was essential in order for inland transport water connections to be developed via the construction of artificial canals and the regulation of rivers (Muszyńska-Jeleszyńska and Marciniak, 2016).

4.2.3. Physical and chemical parameters of flowing waters

The directional movement of water is a feature that distinguishes waterways and canals from other water environments. Studies of the distribution and anatomical and behavioral adaptations of organisms provide evidence that it is flow velocity (V) that is fundamental to the organisms that inhabit these environments. Flow velocity (V) is the speed of the water stream, expressed in centimeters or meters per second (cm/s, m/s). The flow velocity depends on the angle of inclination of the bed and the depth of the river (Bajkiewicz-Grabowska and Mikulski, 1993). The speed of water velocity and the physical forces associated with this movement create one of the most important environmental factors affecting organisms living in waterways and canals. Water flowing in a river is constantly mixed, so there are no vertical gradients except for the light gradient.

The water flow velocity determines the quality of the conveyed substrate and its ability to sediment (settling possibilities). The flow velocity in the watercourse decreases with decreasing slope of the bed. Therefore, the bottom in the upper course of the river is stony and gravelly, while in the lower course of large, slow-flowing rivers it is rich in clay and sand.

Flowing waters exhibit a large range of thermal conditions. Temperature changes are observed along the course of the river. The temperature fluctuation of the source is not great; it is around 8 °C. As the distance from the sources increases, the temperature of the flowing waters approaches the average air temperature. Therefore, the water temperature along the river rises in summer and falls in winter. Large daily temperature changes of up to 6 °C can be observed in small rivers, while these changes are small in large rivers (Lampert and Sommer, 1996; Allan, 1998). In canals, the water temperature is close to the average air temperature, and in small canals significant daily fluctuations in water temperature are observed.

The concentration of oxygen is usually higher in flowing waters than in lake water, which is mainly caused by turbulent movements. The oxygen content varies between 6 and 8 mg $O_2 \cdot dm^{-3}$ in the summer and between 8 and 12 mg $O_2 \cdot dm^{-3}$ in winter (Starmach, 1976).

In many canals (e.g. the Bydgoszcz Canal) and in the lower sections of rivers, where photosynthesis is an important source of oxygen, oxygen depletion can be observed at night, when the consumption of oxygen in the respiratory process is not compensated by its production during photosynthesis.

A considerable amount of oxygen is used for oxidation and decomposition of organic substances dissolved and suspended in the water column or contained in bottom sediments (Górniak and Kajak, 2019). The impact of high oxygen demand due to pollution can be more severe at high summer temperatures, which reduce the solubility of oxygen in water, and at low water levels in summer, e.g. in the Oder river and Gliwicki canal (Napiórkowska-Krzebietke et al., 2020).

4.2.4. Groups of organisms in rivers and canals

The following four groups of organisms can be distinguished in rivers:

1. bottom-inhabiting organisms, i.e. benthos,
2. organisms inhabiting a solid substrate protruding above the bottom, i.e. periphyton (definition according to Giziński and Falkowska, 2003),
3. organisms inhabiting the surface layer of water in contact with air, i.e. neuston and pleuston,
4. organisms living in the water mass, of which:

- plankton: a group of organisms "passively floating in the water column", according to the definition of Hensen (1887, cited after Mikulski, 1982), or according to the definition of Giziński and Falkowska (2003) - "a group of organisms with limited ability to resist stronger water movements",
- nekton: differing from plankton in size and with efficient apparatus system enabling nekton organisms to move actively, independent of water movements; in rivers, nekton is formed almost exclusively by fish and lampreys.

Benthos of rivers and canals

There are various types of habitats at the bottom of watercourses and canals. The bottom can be rocky, gravelly (fast water flow); sandy or muddy (medium and slow water flow). It is the nature of the bottom that determines the benthic biocenosis. In the lower sections of rivers and canals, where there is an adequate flow of water, macrophytes may occur, especially from the order *Potametalia* (*Potamogeton fluitans*, *Potamogeton perfoliatus*, *Batrachium fluitans*). The diversity of plants in European rivers is low (about 50 species). The sandy bottom typical of the middle and lower reaches of rivers, as well as some canals, is not a very favorable habitat for the zoobenthos. It has a very unstable character, which is why it is dominated by organisms either so small that they can fit between grains of sand, or so large and strong that being covered with sand is not dangerous for them. The first group includes small protozoa, rotifers (*Proales*, *Monostyla*, *Phylodina*) and small chironomid larvae (*Pomodrilus stephensoni*). The second group consists of large, active animals that can burrow in the sand (Gammagus, large dragonfly and mayfly larvae). There may also be large mollusks belonging to the families Unionidae and Dreissenidae. The taxonomic diversity of the benthos of the sandy bottom is quite high, but the biomass is small (Żbikowski, 2000). Muddy bottom communities in the lower courses of rivers and in canals are, according to Mikulski (1982), much richer in quality than stony and sandy bottom communities. There can occur many pond and lake species. Diatoms and cyanobacteria develop well on a muddy substrate. The microfauna is abundant and diverse in river muds. Numerous protozoa, rotifers, various species of crustaceans belonging to the order of Cladocera (*Chydorus*, *Leydigia*, *Disparalona*) and ostracods can be found. Among the macrofauna of the muddy bottom there are many species of oligochaetes, chironomid larvae, mayflies and dragonflies. The biomass of the zoobenthos of the muddy bottom is higher than that biomass of the benthos living on the sandy bottom (Żbikowski, 2000). Water flow regime fundamentally structures benthic communities through its effects on near-bed hydraulics. Changes in flow velocity can determine distribution and density of benthic invertebrates (Bruno et al., 2016). Some studies report that the use of benthic macro-invertebrates as indicators in water bodies is an effective approach for water quality assessment (Rodrigues et al., 2021; Vitecek et al., 2021; Zhang et al., 2021). Biological establishment of benthos in rivers and canals determined the ecological change due alteration in substratum and hydrology of rivers (Saxena and Tyagi, 2021).

Periphyton of rivers

Periphyton are, according to Starmach et al. (1976), Górniak and Kajak (2019), plant and animal organisms forming a group on a living or dead substrate in the water above the bottom. In fact, periphyton is found only on objects floating on water or artificially placed in it, and on higher plants (fouling algae, small animals, entangled planktonic forms). In the canals, periphyton is found on elements of hydrotechnical structures and on macrophytes.

An association similar to the periphyton in lakes is formed, but it is species-poor. In periphyton studies of rivers, an artificial substrate has increasingly been introduced into the water. For example, B. Szlauer and L. Szlauer (1998) used a polyethylene film suspended in the water column in the Oder River. In the periphyton on such a substrate, the following species dominated: *Dreissena polymorpha*, *Bithynia tentaculate*, *Hirudinea*, *Acroluxus lacustris*, and representatives of Oligochaeta and *Asellus sp*.

Neuston and pleuston of rivers and canals

Neuston is a group of tiny, microscopic organisms associated with the surface film of water. Unlike pleuston, it occurs not only in secluded places (Giziński and Falkowska, 2003). It consists of bacteria, fungi, small algae and protozoa. Neuston organisms use wind-blown organic matter and planktonic organisms trapped in the surface film.

Pleuston is a group of larger organisms visible to the naked eye that use the surface film of water in secluded, stagnant parts of rivers. The pleuston, according to Giziński (l.c.), consists mainly of both spore-bearing plants (e.g. *Salvinia natans*) and flowering plants, primarily various species of duckweed (*Lemna sp*.). The pleuston also includes bugs – water striders (*Hydrometra spp*.) and beetles – and snails (*Gyrinus sp*.). Both Neuston and Pleuston in rivers are very poor (Starmach et al., 1976). However, in canals, the abundance of neustonic and pleustonic organisms depends on the prevailing hydrological conditions.

Plankton of rivers and canals

The plankton of rivers is called "potamoplankton". This concept was introduced by Zacharias in 1898 (Starmach et al., 1976). The plankton of rivers and canals consists of species that are also found in stagnant waters, i.e. there are not only river or canal species. In the plankton of rivers and canals, phytoplankton predominates over zooplankton. The greatest quality and quantity of plankton in rivers and canals is observed during spring and summer. Places of plankton formation are, in smaller rivers, calm bays or lakes through which the river flows and, in canals, in front of the locks. The main factors determining good conditions for the reproduction and development of plankton in rivers and canals are weak water flow and a sufficiently long time of water movement. According to Kawecka and Eloranta (1994), the flow velocity cannot exceed 0.4 m/s and according to Starmach et al. (1976) 0.5–0.8 m/s.

The plankton of rivers and most canals is usually lesser in quality and quantity than that of standing waters, although this is not always the case. B. Szlauer and L. Szlauer (1994), during a zooplankton study of the river Oder near Szczecin, found that the number of species and abundance were similar to those recorded in moderately eutrophic lakes.

An important feature of plankton in rivers and canals is that it is not uniform in origin. Only a certain part of it is formed in the mother watercourse – it is autochthonous. The rest is made up of allochthonous components flowing from tributaries and reservoirs in contact with the watercourse or canal. Large rivers have more native plankton. As in canals with very slow water flow, the plankton of rivers and canals may contain, in addition to typical planktonic species, numerous species from the bottom or edges disturbed by the water current.

Diatoms predominate in phytoplankton (algae) communities in the water column of rivers and canals. We meet representatives of the genera *Cyclotella*, *Melosira*, *Stephanodiscus*, *Asterionella*, *Tabellaria* and *Fragillaria*. Many species of green algae of the genera *Scenedesmus*, *Pediastrum* and *Closterium* are also observed. Sometimes, under favorable physical and chemical conditions, we also see the development of blue-green algae, such as: *Anabena flos-aquae*, *Aphanizomenon flos-aquae* or *Microcystis aeruginosa* (Kawecka and Eloranta, 1994; Dembowska and Napiórkowski, 2000).

The study of phytoplankton has mainly focused on large river systems and lakes. In human-impacted rivers, local environmental variables and hydrological changes are responsible for shaping phytoplankton behavior (Waylett et al., 2013; Gómez and O'Farrell, 2014). The authors of most studies have pointed out the importance of river flow velocity and retention time as factors regulating the development of this assemblage (Dembowska, 2021; Kentzer et al., 2010; Descy et al., 2017). Water velocity is considered to be the controlling factor and to significantly affect the depletion or acquisition of phytoplankton in regulated rivers (Kim et al., 2019). Recent work has reported several environmental predictors determining phytoplankton bloom ecology in UK canals (Kelly and Hassall, 2018).

In the zooplankton of watercourses (rivers and flowing canals), the main role is played by small organisms belonging to rotifers and, from the crustaceans, small cladocerans and larval stages of copepods (i.e., nauplii). The organisms that dominate in the zooplankton of rivers are adapted to changing environmental conditions. Smaller animals, e.g. rotifers, are less exposed to mechanical damage at high water flow velocities. Both rotifers (which account for more than 90% of the total number of zooplankton in rivers) and small cladocerans reproduce parthenogenetically (i.e., there is no need to look for a partner to maintain the species). Among rotifers, species characteristic of European rivers from the Brachionidae family dominate, such as: *Brachionus angularis*, *Brachionus calyciflorus*, *Keratella cochlearis*, *Keratella tecta*, *Keratella quadrata* (Giziński et al., 1989; B. Szlauer and L. Szlauer, 1994; van Dijk and Van Zanten, 1995; Marneffe et al., 1996; Kentzer et al., 2010; Napiórkowski and Napiórkowska, 2013; Napiórkowski and Napiórkowska, 2014). On the other hand, among the small cladocerans, the most common are *Bosmina longirostris* and *Chydorus sphaericus*. Copepods in potamoplankton, especially in the flow section, are represented mainly by the smallest larvae (nauplii). Larger larvae (copepodites) and adults are less common. The most frequently recorded species of copepods in rivers are *Acanthocyclops robustus*, *Thermocyclops crassus* and *Acanthocyclops vernalis* (Heiler et al., 1994; B. Szlauer and L. Szlauer, 1994; Balogh et al., 1994; Caramujo et al., 1998; Kentzer et al., 2010).

Nekton of rivers and canals

Nekton is a group of larger pelagic organisms that have a well-developed ability to actively move independently of water current. Fish are the most biodiverse and numerous nekton.

Fish communities in large rivers are characterized by a high diversity, which reflects the structural diversity and habitat richness of inshore zones and the various but interconnected habitats (Schiemer, 2000). In intermittent rivers, fish can be structured by local abiotic conditions. Hydrological variations and extremes in water flow (periodical floods and droughts) influence spatial and temporal distribution of fish species (Matthews et al., 2013). Rapid increases and decreases in flow velocity are often associated with declines in abundance and species richness (Davey and Kelly, 2007). Environmental changes may alter the species composition of a fish community. Temperature is considered a potential driver of fish growth. Warm waters positively affect larval growth. Rising temperatures speed up the metabolism of fish – and thus demand for oxygen – while oxygen solubility decreases (Teubner et al., 2019). Typical fish of European rivers are *Rhinichthys atratulus*, *Etheostoma flabellare*, *Cottus gobio*, *Salmo trutta* and *Salvelinus alpinus*.

Canals are important shelter ecosystem for native fish (Billman, 2013). Some intermittent canals (drained streams and ditches) may also provide suitable habitats for the reproduction of endemic fish species and resources for their juveniles. Some fish survive in highly managed water bodies – including both native and exotic species. Cowley et al. (2007) recorded high densities of these species in an agriculture irrigation canal system along the middle Rio Grande of New Mexico. However, some authors agree that hydrological changes and human manipulation determine the fish species composition in artificial waterways and large rivers (Waltham and Connolly, 2007; Zajicek et al., 2018; Rolls and Arthington, 2014). For example, concrete lining of the canal, extreme water level variation and regular vegetation clearance to enhance water flow substantially limited shelter resources for fishes (Kloskowski et al., 2013). The water flow velocity and conductivity influence fish density and number of their species (Colvin et al., 2009).

5. MATERIALS AND METHODOLOGY

5.1. Area of studies. History of the Bydgoszcz Canal

The Bydgoszcz Canal is the unique hydrotechnical monument. This magnificent monument linked the tributaries of the Oder River and the Vistula River. The idea of linking waterways of the East Europe and the West Europe was exceptional. While the city became an important economic centrum in the 19th century, the canal, due to its connection with colonization influenced the demographic relations of the region (Mincer, 1991).

The construction project of the Bydgoszcz Canal was created in the pre-partition period and was submitted by the royal cartographer Franciszek Florian Czaki in the form of a memorial in 1766 at the meeting of the Crown Treasury Commission. According to this design, the canal was the subject of construction idea and should have linked the Noteć River from the area of Rynarzewo with the Brda River on the area of Bydgoszcz at that time (Midzio, 1978). However, plan was not realized due to events connected with the First Partition of Poland. But, less than a year after the partition, in the spring of 1773, work began on the construction of the canal according to Frederick the Great, the ruler of Prussia who with regard to annexation process took over the land of Royal Prussia, as a result of partition, Bydgoszcz joined his country together with surrounding areas. The construction was completed in September 1774. The built Nakło Wschód sluice and the built dams on the Brda River contributed to a significant improvement of navigation conditions on the canal. In the years 1812 – 1815, the dam in Dębinko (allowing water to be dammed on the upper Noteć), the Nakło Wschód lock and the dam on the Brda River were built, which contributed to a significant improvement of the navigation conditions on the canal. The existing waters of the wet and swampy area were used for the construction. Soon, however, due to silting (peaty bottom), dredging and reconstruction of the locks had to be resumed (Winid, 1928). Despite these undertakings, until the next reconstruction in the times of the Duchy of Warsaw, the canal was not a fully operational waterway.

At the turn of the 18th to the 19th century the works of deepening, strengthening of the canal and planting trees took place. At the beginning of the 19th century the conditions for floating on the canal and on the Noteć River were improved. The reconstruction process,

despite huge costs assigned on making the vision of bricks applications real, was profitable in the long perspective, because wooden locks required changing for every 15 – 20 years.
In the middle of 19th century all the wooden locks on the canal were eliminated. In Prądy and Osowa Góra were built new massive locks made of bricks and granite (Izajasz et al., 2017).

Figure 2. Plan of the Bydgoszcz Canal from 1894, (Izajasz et al., 2017).

5.2. Meanings and functions of the Bydgoszcz Canal

The Bydgoszcz Canal is important part of the International Waterway E70. This route connects the water systems of Western, Central and Eastern Europe. It leads to Antwerp and Rotterdam via Netherlands, Germany (the Berlin water junction of inland waterways), Northern Poland (Gorzów, Bydgoszcz, Gdańsk) up to Kaliningrad and further via the system of waterways of the Neman to Klaipeda (The International Waterway E70, 2014).

The Bydgoszcz Canal is located in north-west Poland between the cities of Bydgoszcz and Nakło. It connects two largest rivers in Poland – The Vistula River and the Oder River, through their tributaries. From the East it is the biggest artificial tributary of the lower section of estuary of the Brda River and from the West is the tributary of the Noteć River (Izajasz and Dziedzic, 2014).

The total canal length is 24.5 km, of which 15.7 km is located in the catchment of Noteć (tributary of Oder River) and 9.0 km in the Brda (tributary of Vistula River) catchment. The canal is supplied with water from the Upper Noteć and with water from small watercourses and streams in the Bydgoszcz and in the Bydgoszcz-Nakło valley (including the Kruszyński stream, Młyńska stream, and Prądy stream) (Babiński et al., 2008).

The Bydgoszcz Canal with its hydrotechnical structures, e.g. locks, is important section of the inland waterway (water connection). There are six single chamber locks regulating the water level made of concreate with the same size of chambers 57.4 x 9.6 m. The four locks are located on the arid side in an industrial area near the city of Bydgoszcz. The four locks are located in the East section in industrial area near the city of Bydgoszcz – Okole, Czyżkówko, Prądy and Osowa Góra. The two other locks are located in the West section in agriculture area – Józefinki and Nakło Wschód. The height of fall of the locks ranges from 1.83 m (Józefinki) to 7.58 m (Okole). The units were equipped to overcome the differences of water level in the canal. Locks enable vertical transportation of vessels between upper and lower part of particular locks. Hydrotechnical structures on the Bydgoszcz Canal include historic locks excluded from using. These locks enable only impoundments of water and they do not allow vertical transportation of vessels (Inland navigation guide,1936).

The Bydgoszcz Canal is classified as the 2nd class waterways. The width of the navigable route ranges from 28 to 30 m. The depth of water in the canal ranges from 1.6 to 2.0 m, depending on the level of impoundment. The main elements conditioning the classification of the Bydgoszcz Canal as a waterway are the existing hydrotechnical structures, which were characterized on the basis of their water permits (Izajasz et al., 2017).

5.3. Description of studied sites

The study was performed at six sampling sites in three areas: Area 1: the Bydgoszcz Canal: (site 1) Jozefinki 53°07'49.7''N 17°38'23.9''E, (site 2) Osowa Góra 53°08'48.9''N 17°52'49.2''E, (site 3) Prądy 53°08'38.6''N 17°53'37.8''E, (site 4) Okole 53°08'11.9''N 17°58'06.1''E, Area 2: (site 5) the Noteć Canal – Łochowo 53°07'56.5''N 17°51'18.1''E and Area 3: (site 6) the Brda River 53°08'16.0''N 17°58'20.8''E.

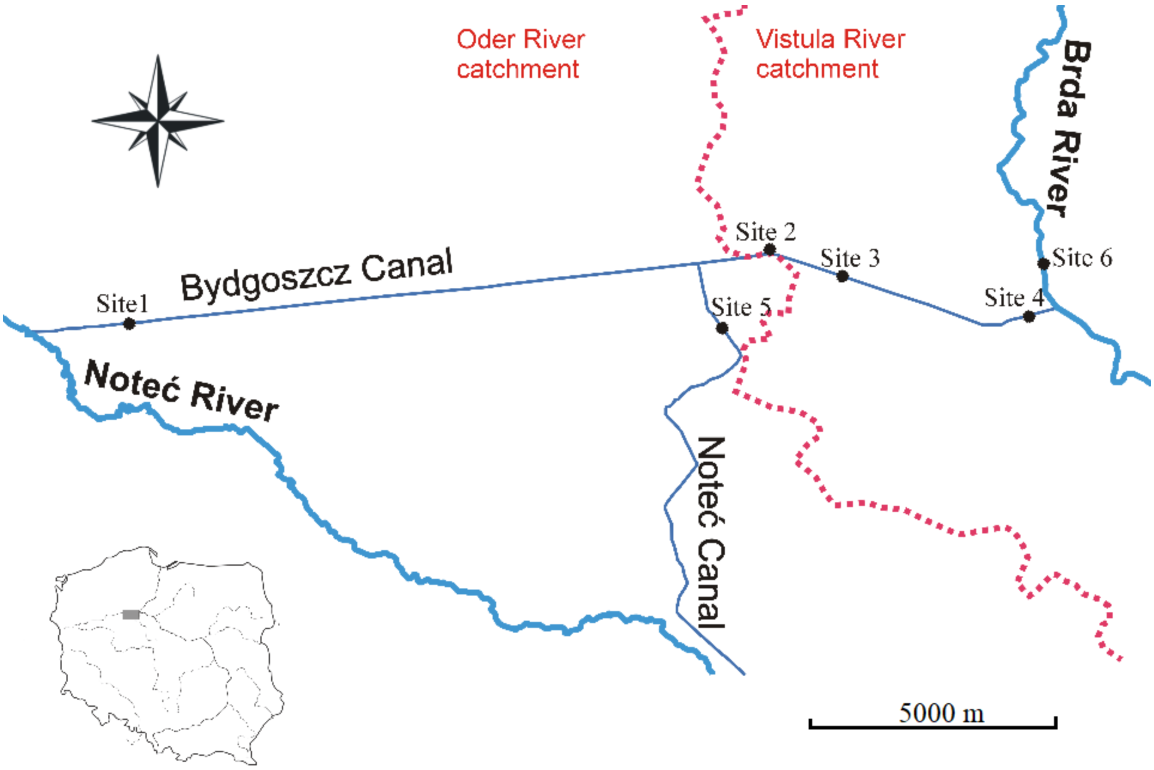

Figure 3. The map of investigated area. Bydgoszcz Canal: site 1– Józefinki; site 2 – Osowa Góra; site 3 – Prądy; site 4 – Okole. Site 5 – Noteć Canal – Łochowo. Site 6 – Brda River.

Józefinki Site 1 - is located at 37.2 km of the Vistula-Oder waterway. The amount of water used for one crossing of the vessel is 1176 m^3. The filling time is 3 minutes, but the actual time for one lock is approximately 25 minutes. The minimum water flow directed to the upper position of the waterway Vistula-Oder is Q =1.5 m^3/s, including in the direction of the Józefinki hydroelectric plant Q = 1.014 m^3/s. This flow uses to lock objects towards the Vistula River, Osowa Góra lock and in the direction of the Oder River. The maximum water flow directed to the upper station is Q = 1.1 m^3/s. The chamber is filled and emptied through circulation canals in the lock heads. The supports of the lower head are simultaneously used as supports for the road bridge. The lock is used to maintain the water level for navigation and operation of water intakes. In addition, it allows the discharge of surplus water in the flow range 1.0 to 7.0 m/s.
The Józefinki lock is a single-chamber lock built between 1912 and 1925. Technical parameters of the lock are: length 57.4 m, width 9.6 m. The relief dike was rebuilt in the 1960s. The heavy lock construction is made of concrete with brick and stone lining. The upper water level is maintained by steel cantilever double-leaf sluice gates which are moved manually.

The structure is made of concrete while the abutments are made of brick. The gates are wooden, lifted by manually operated mechanisms. The banks of the relief canal are reinforced with stone (Water law operation of the damming stage Józefinki, 1971).

Figure 4. Site 1 Józefinki. A view to upstream of the lock (own picture).

Osowa Góra Site 2 - is located at 21.0 km waterway Vistula-Oder. Water consumption per sluicing is 2270 m³. The practical time for one sluicing is about 25 minutes, with a sluice chamber filling time of about 6 minutes. The practical closing time of the gates are 3 minutes, while the closing time of the circulating canal gates are 4 minutes. This lock serves to maintain the navigability of the section of the Bydgoszcz Canal between km 37.2 and km 21.0.

The upper water level is maintained by the upper flap gates and the lower water level by the supported gates. The lock is filled and emptied by means of circulation canals located on both sides of the lock head. The gates and gates of the circulation canals are operated by manually operated mechanisms. The hydrotechnical structure was built in 1910 – 1914. Technical parameters of the locks are: length 57.4 m, width 9.6 m, height 6.9 m (above and below the water). The upper gate is a steel-framed flap gate with a manual drive. The lower double steel gates are manually operated. The walls of the lock and gates are made of concrete with brick lining (Water law operation of the damming stage Osowa Góra, 1999).

Figure 5. Site 2 Osowa Góra. A view to upstream of the lock (own picture).

Figure 6. Site 2 Osowa Góra. A view to downstream of the lock (own picture).

Prądy Site 3 - is located 20.0 km of the Vistula-Oder waterway. The maximum throughput of the lock is 4.0 m/s and water consumption is 2300 m^3 per one sluicing in approximately 25 minutes. This lock serves to maintain the navigability of the section of the Bydgoszcz Canal between 21.0 km and 20.0 km and to lock floating objects in both directions on this waterway. The upper water level is maintained by the upper flap gates, the lower water level by the support gates. The chamber is filled and emptied by means of circulation canal located in the heads of the lock gates. The gates and gates of the circulation canals are operated by manually operated mechanisms. The practical closing time of the gates are 2 to 5 minutes.

It is a single-chamber lock built between 1910 and 1914. The basic technical parameters are: length 57.4 m, width 9.6 m, height of the chamber wall 6.85 m (above and below the water). The upper door is a steel flap door with a manually operated mechanism. The lower cantilever steel double-leaf doors are manually operated. The lock has a siphon culvert in the right (south) wall to allow water to pass from the upper station to the lower station. The walls and bottom of lock are made of concrete with brick lining. The bank fortification consists of a slope pier with wooden sheet piling and a stone slope. Below the lock on the right-hand side is an outfall from the now non-operational municipal sewage treatment plant with a large accumulation of sediment (Water law operation of the damming stage Prądy, 1999).

Figure 7. Site 3 Prądy. A view to upstream of the lock (own picture).

Figure 8. Site 3 Prądy. A view to downstream of the lock (own picture).

Okole Site 4 - is located at 14.8 km of the Vistula-Oder waterway. The maximum water throughput through the stage (relief canal) is 4.2 m/s. Water consumption per sluicing without the use of saving reservoirs is 4560 m^3. The practical time for one sluicing is about 20 minutes, including the time for filling the chamber of 6 minutes. The operation time for closing the gates is 3 minutes. The filling and emptying of savings reservoirs is carried out by steel cylindrical closures, either electrically or manually driven. The practical time for closing them is 2 minutes. The sluice has in the right (south) wall a siphon inlet. The maximum capacity of the lock is 4.2 m/s. The savings reservoirs of concrete construction, have a bottom area of 1.400 m^2. The saving reservoirs are designed to carry out economical water management for filling and emptying the lock chamber and to speed up these operations.

The lock is used to maintain the navigability of the section of the Bydgoszcz Canal between 16.0 km and 14.8 km, as well as to lock floating objects in both directions. The lock is located 400 m above the connection of the Bydgoszcz Canal with the Brda River. The upper water level is maintained by flap gates, the lower level - by cantilever gates. Filling and emptying of the lock chamber is carried out by circulation canals, located on both sides of the chamber along its entire length. Control of the closures and gates of the circulation canals is carried out from the central control station. It is a single chamber lock with electric and emergency manual drive. The hydrotechnical structure was built in 1910 – 1914. The basic technical parameters are: chamber length 57.4 m, chamber width 9.6 m, chamber wall height 10.6 m (above and below the water). The upper gate is a steel flap gate with a height of 3.5 m (above water level). Its practical closing time is 2 minutes. The chamber walls are made of concrete with brick lining. The bottom and sills are reinforced concrete construction. Water levels at the lower stage are shaped according to flows in the Brda River (Water law operation of the damming stage Okole, 1999).

Figure 9. Site 4 Okole. A view to downstream of the lock (own picture).

Noteć Canal – Łochowo Site 5 – Noteć Canal connects the Warta River with the Bydgoszcz Canal at km 23.2 of the Vistula - Oder waterway.

The Upper Noteć Canal was built in 1774 to provide additional water to the Bydgoszcz Canal. Since 1882, it has also been a part of the navigable canal connecting Lake Gopło with the Vistula-Oder waterway. The Upper Noteć Canal is the last section of the Warta-Bydgoszcz Canal waterway (from 121.6 to 146.6 km) with length of 25 km and width of 16 m. It has six (plus two on the Noteć River) single-chamber navigation locks with chamber dimensions of 42.0 x 5.0 m made of concrete, clinker bricks and stone blocks.

Łochowo lock is located on the Upper Noteć Canal near the mouth into the Bydgoszcz Canal. The chamber dimension is 44.3 x 5.1 m and height is 3.0 (above the water level).

http://www.odznaka.kuj-pom.bydgoszcz.pttk.pl/opisy/1f/lisiogon.htm

Figure 10. Site 5 Noteć Canal – Łochowo. A view to upstream of the lock (own picture).

Figure 11. Site 5 Noteć Canal – Łochowo. A view to downstream of the lock (own picture).

Figure 12. Site 5 Noteć Canal – Łochowo. A view to downstream of the lock, where water samples were collected (own picture).

Brda River Site 6 - is one of the left-bank tributary of the Vistula River, the longest river of Poland which belongs to the catchment area of the Baltic Sea. The Brda River flows out from Lake Smołowskie, part of the Bytowskie Lake District. It is 238 km in length and the surface area of the river basin is about 4634 km^2.

This river flows into Bydgoszcz city from the north and is a natural watercourse about 20-30 m in width until the point where it joins the Bydgoszcz Canal (Babiński et al. 2014). Our research was focus at site located near the mouth of the Bydgoszcz Canal to the Brda River with width about 45 m and the depth, *c.*2.5 m. The water flow velocity at studied site was *c.*0.8 m/s.

Figure 13. Site 6 Brda River. A view, where water samples were collected (own picture).

5.4. The purpose and history of zooplankton research in the Bydgoszcz and the Noteć Canals

So far, hydrobiological research of the above-mentioned canals has not been carried out on such a large scale.

The first goal, if the research covers a new area, was the cognitive goal. I wanted to assess the variability of zooplankton depending on the locations of the designated sites.
The observed variability motivated to further research to determine what causes zooplankton variability in artificial canals.

I tried to determine the impact of human pressure on the canal waters. One of the symptoms of anthropopressure is an increase in water trophy, therefore it seemed logical to use zooplankton indicators. The indicators based on the knowledge of the species composition, abundance and biomass of rotifers were selected, because rotifers were the most numerous group of zooplankton both in terms of quality and quantity.

During the study so far, I have observed that there is also variability in small sections of the canal near the locks, so the next stage of research was to determine how hydrotechnical structures can affect the zooplankton of the canal. I assessed the variability of environmental conditions and zooplankton downstream and upstream the locks.

The next step, which could be implemented in the future, seems to be to assess whether the closed locks can be nurseries of life for the canal's zooplankton.

5.5. Sampling methods

Water samples were collected once a month during vegetation season in 2019, 2021 and 2022 at 6 studied sites. In addition, in 2021 and 2022 samples were taken from sites downstream of the locks (site 2,3 and 5). A total of 144 samples were taken.

Water samples were taken with 1-L Patalas bucket at different depths. Water was filtrated using a special plankton net, mesh size 25 μm. In order to obtain one sample of zooplankton, 20 L water was filtered. In total 144 both qualitative and quantitative samples were collected.

All zooplankton samples were preserved in Lugol's solution (Wallace et al., 1993; Harris et al., 2000). The identification and count 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 sample volume (20 dm^3) was adjusted to 10 ml, a 1 ml aliquot of well-mixed concentrate pipetted into a Sedgewick-Rafter chamber. The zooplankton was counted under a microscope in a Sedgewick-Rafter chamber by the sub-sample method (McCauley, 1984). The abundance was presented as the number of individuals per L (N, ind/L).

The taxonomical identification of zooplankton was made according to the commonly available studies and keys (Kiefer, 1978; Wallace et al., 1993; Einsle, 1996; Radwan et al., 2004; Błędzki and Rybak, 2016). To characterize the density-dominance relationship, the Shannon-Weaver diversity index (H') and Pielou evenness index (J') were used. The collection of samples was measured alongside with the physical and chemical parameters of water, such as: flow velocity (v, m/s), Secchi disc visibility (SD, m), temperature (WT, °C), oxygen concentration (DO, mg/L), saturation (%), conductivity (EC, μS cm^{-1}), chlorophyll (chl-a, μg/L), nitrates (NNO_3^-, mg/L), phosphates (PPO_4^{2-}, mg/L) and pH. Measurements of physical and chemical parameters 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).

5.6. Statistical analyses

The environmental variables responsible for variations in the zooplankton taxonomic composition, density and biomass were determined by Canonical Correspondence Analysis (CCA) (Ter Braak and Verdonschot, 1995). Statistically significant correlations between environmental and biological parameters were tested by Spearman's rho using Past 4.03 software (Hammer et al., 2001). Two-way cluster analysis was performed to group sites on their similarity within environmental and biological data in the investigated months. Ward's clustering method and Euclidean distance in PC-ORD 6.08 (McCune and Mefford, 2011) were used to compare spatial and seasonal similarity of environmental and biological parameters during the study period. These statistical analyses were used in Kolarova and Napiórkowski, 2022.

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) (6) contribution of species that indicate a high trophic state in the indicatory group's number.

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 and Haldna, 2014; Heddam, 2016; Ochocka and Pasztaleniec, 2016).

The relationship between the rotifer index TSI_{ROT} and the index based on the Secchi disk TSI_{SD} was analyzed with using the scatterplot with linear regression line. Statistical analysis was performed using Statistica 14.0.0.15. software (TIBCO Software Inc., Palo Alto, CA, USA). Pearson simple correlation coefficient was calculated to compare the rotifers indices ($TSI_{ROT1\text{-}ROT6}$) and TSI_{SD}. The normality of data distribution was tested by the Shapiro–Wilk W test (Shapiro and Wilk, 1965). These statistical analyses were used in Kolarova and Napiórkowski, 2023.

The spatial changes of zooplankton community structure were determined based on different hydrological and environmental conditions. 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 the Euclidean similarity index and between biological parameters by the Bray-Curtis similarity index. 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 presented results were processed statistically by using Canoco 5.0 software (Ter Braak and Smilauer, 2002). Pearson simple coefficient was tested to analyze statistically significant correlations between environmental and biological parameters by Past 4.03 software (Hammer et al., 2001). These statistical analyses were used in Kolarova and Napiórkowski, 2023 in prep..

6. VERIFICATION OBJECTIVES AND HYPHOTHESES

How do specific environmental conditions in canals affect the structure and variability of zooplankton community? [A1]

The specific objective was as follow: comparing the zooplankton species composition in natural river and two artificial waterways.

I assumed that:
a. Spatial community structure during the growing season would depend on differences in hydrological, environmental and biological conditions and their influence on food availability (algal growth) and on the creation of ecological niches for zooplankton (macrophytes growth).
b. Crustacean diversity (species number and density) would be lower because their development could be disturbed by excessively high water flow or they could be carried away by the water flow.
c. Crustacean density would also be limited as a result of their competition with rotifers for algal food.

The results of the research presented in article [A1] led to the following conclusions:

a. Environmental conditions shaped the zooplankton community in waters of studied canals. A temperature rise led to an increase in zooplankton biomass; the temperature accelerated the growth of crustaceans more than the growth of rotifers.
Similar results were obtained by Hansson et al., (2007) in a lake in southern Sweden. Authors suggesting that that the spring period, with strong alterations in temperature-driven processes such as predation and resource supply, is important in shaping the summer zooplankton community. The results of my research showed that water temperature is the main factor affecting the abundance and biomass of crustacean zooplankton in the Bydgoszcz Canal. A similar relationship was observed on the Danube (Vadadi-Fülöp and Hufnagel, 2014). Contrary,

moderate temperatures in May accelerated the growth and feeding rate of many small feeders (rotifers) (Edmondson, 1965).

b. In stagnant Bydgoszcz Canal turbid water and high chlorophyll concentration (in spring) favored the development of small rotifer zooplankton; a clear water and low chlorophyll concentration (in summer) promoted the development of crustacean zooplankton and large rotifers. During the growing season in the Bydgoszcz Canal, the abundance and biomass of rotifers changed similarly to chlorophyll. According some authors (Demetraki-Paleolog, 2004; Dembowska, 2021) small algae that appear in spring provide excellent food for rotifers, and this favors the development of rotifer zooplankton.

c. In the Bydgoszcz Canal was the greatest occurrence of zooplankton (density, biomass and number of species) compared with sites in the Brda River or the Noteć Canal.

The reason may be different tolerance to water flow rate and different levels of macrophyte vegetation. For example, lower water flow (in Bydgoszcz Canal sites) may directly influence the development of zooplankton organisms by creating more stable growth conditions (Baranyi et al., 2002; Napiórkowski and Napiórkowska, 2014; Balkić et al., 2018) or indirectly by allowing macrophytes to create ecological niches supporting zooplankton development, especially crustaceans (Kuczyńska-Kippen et al., 2009; Chaparro et al., 2015). Both direct and indirect effects of hydrological conditions on zooplankton life were observed in the studied watercourses.

Are rotifers indices suitable for assessing the trophic status in slow-flowing waters of canals? [A2]

The specific objective was as follow: applying the zooplankton indicators (TSI_{Rot}) to assess the trophic level in canals.

I assumed that:

a. The rotifers index (TSI_{ROT}) would reflect trophic changes in artificial, slow-flowing and stagnant canal waters, similarly as for lakes.

b. The 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.

The results of the research presented in article [A2] led to the following conclusions:

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

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). It was found that the dominant species (*Keratella cochlearis*, *Keratella tecta*, *Brachionus calyciflorus* and *Anuraeopsis fissa)* prefer high trophic states (Figure 14). The species found during our research were typical of eutrophic waters (Ejsmont-Karabin, 2012; Pociecha et al., 2018).

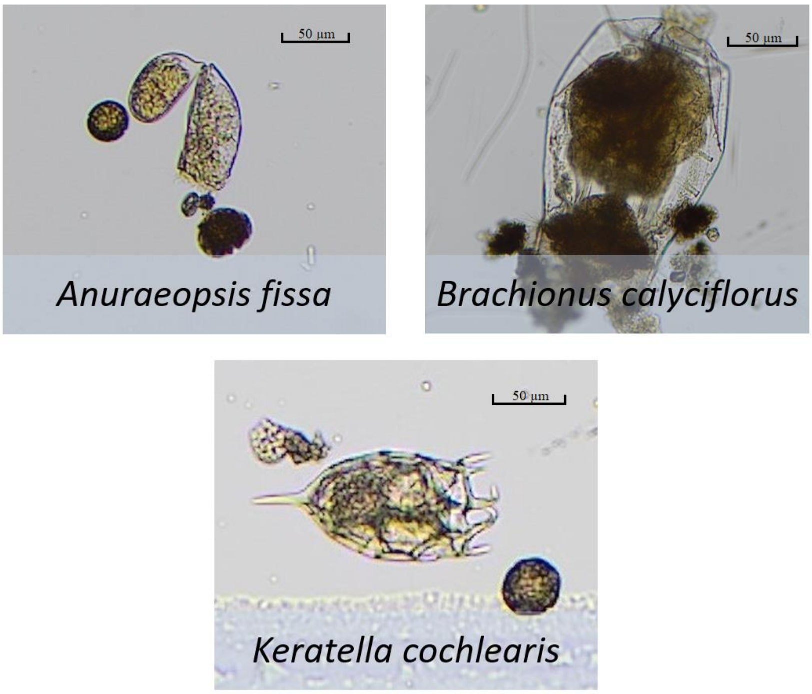

Figure 14. Dominant group of rotifers identified at studied sites. Pictures were taken by light microscope and soft imaging camera at 10× magnification (own picture).

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, small bacterivorous rotifers, which occur during the summer blooms, indicate high trophy (Ejsmont-Karabin and Hillbricht-Ilkowska, 1994; Ejsmont-Karabin, 2012). A similar regularity was observed in the trophic gradient on the studied canals.

b. My 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. 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.

c. It was 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.

Based on TSI_{SD}, most of the sites were classified as meso-eutrophic, while 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 and Czerniawski, 2018). Based on TSI_{ROT}, the studied canals were characteristized by low meso-eutrophy to high meso-eutrophy. TSI_{ROT} increased towards the city in the Bydgoszcz Canal. The part of the Bydgoszcz Canal catchment (Site 4) exposed to the city showed greater trophic pollution (Table 2 and Table 3).

Table 2. Mean values of Trophic State Indexes of rotifers ($TSI_{ROT,\ ROT1\text{-}6}$) (Ejsmont-Karabin, 2012) and Carlson's Trophic State Indexes (TSI_{SD}) (Carlson, 1977) in the summers of 2019, 2021, and 2022 (July–August) in the Bydgoszcz Canal and the Noteć Canal sites.

	Site 1	Site 2	Site 3	Site 4	Site 5
TSI_{ROT1}	40	36	38	48	38
TSI_{ROT2}	39	38	39	51	39
TSI_{ROT3}	45	47	46	51	48
TSI_{ROT4}	57	60	63	64	63
TSI_{ROT5}	54	48	50	48	50
TSI_{ROT6}	42	43	44	51	45
TSI_{ROT}	45	45	45	52	47
TSI_{SD}	55	51	52	62	52

Table 3. Following values with corresponding Trophic states (Ejsmont-Karabin, 2013).

Value TSI_{ROT}	Trophic state
35-45	High mesotrophy
45-50	Meso-eutrophy I. stage
50-55	Meso-eutrophy II. stage
55-60	Low eutrophy
60-65	High eutrophy
>65	Polytrophy

d. It was 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.

The *European Water Framework Directive* (WFD) requires the ecological quality of waters 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.

The influence of locks on canals zooplankton (Bydgoszcz canal and Noteć canal – Poland). [A3]

The specific objective was as follow:

- comparing the zooplankton species composition between the sites upstream and downstream the locks in two artificial waterways,
- comparing the environmental conditions upstream and downstream the locks and their impact on the zooplankton community.

I assumed that:

a. Zooplankton community would differ in diversity, density and biomass between the two sides of the locks based on the differences in hydrological and environmental conditions.

b. The canal waters upstream the locks will stagnate, thereby creating better conditions for the development of zooplankton.

c. The water flowing down from the lock would temporarily increase the water flow velocity, resulting in a decrease in zooplankton diversity and density.

The results of the research presented in article [A3] led to the following conclusions:

a. Density and biomass of rotifers changed similarly to chlorophyll at sites upstream the locks. Our results support the theory that rotifer communities are defined by bottom-up effects linked to food supply, such as small phytoplankton (probably Cryptophyta) (Yoshida et al., 2003; Felpeto et al., 2013; Dembowska, 2021; Wang et al., 2022). The increased availability of food resources can contribute to higher densities and biomass of rotifers (Shayestehfar et al., 2008; Kolarova and Napiórkowski, 2022).

b. Zooplankton diversity was higher at sites upstream of locks. During the study rotifers were dominated over crustaceans in density and diversity. The number of rotifer species upstream slightly prevailed of the number downstream. Rotifers represented 80 % of all zooplankton species. The most dominant were *Keratella cochlearis*, *Keratella quadrata* and *Keratella tecta*. Crustaceans represented 20 % of all zooplankton species. The most dominant among crustaceans were Cladocera - *Bosmina longirostris*, *Ceriodaphnia pulchella*, *Chydorus sphaericus* and nauplii (copepod larval forms). 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.

c. Low flow velocity and macrophytes as habitat favored high diversity and density of zooplankton upstream the lock.

The zooplankton biomass, including rotifer biomass, was also higher upstream the locks than downstream (site 2 and site 3). This happened because the zooplankton density increased at these sites. According to some authors zooplankton biomass in turbulent waters is much lower (e.g., downstream the locks) than in calm waters (e.g., upstream the 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.

Kuczyńska-Kippen et al. (2021) suggested high rotifers density 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 the locks (low flow velocity and macrophytes vegetation) favored high density and diversity of rotifers. Several authors have reported that rotifers are less susceptible to changes in environmental and hydrological conditions than crustaceans (Marneffe et al., 1996; Demetraki-Paleolog, 2004; Špoljar et al., 2012).

d. Water temperature stimulated the growth of crustacean (density and biomass) and the total zooplankton biomass at sites downstream the lock. Similarly, study by Wei et al. (2017) crustacean zooplankton was positively correlated with water temperature in 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.

e. Only site 1 showed higher zooplankton density (rotifers and crustaceans), zooplankton biomass and crustacean biomass to be higher downstream 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. Similar changes have been reported by Jeppesen et al. (2014). The sediment deposition downstream 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., 2014). The increased availability of food resources can contribute to higher densities and biomass of rotifers and crustaceans (Kolarova and Napiórkowski, 2022).

7. SUMMARY

- The studied canals are a good place for development of zooplankton community.
- Rotifers dominate over crustaceans.
- In the Bydgoszcz Canal was found more zooplankton than in the Noteć Canal and the Brda River. It follows from hydrological conditions.
- Zooplankton in the canal is affected by human activity, which is reflected by an increase in the trophic level of the water, which has been measured using rotifers indicators.
- Zooplankton is also affected, albeit ambiguously, by hydrotechnical structures in the form of locks. It is probably also the influence of hydrological conditions on environmental conditions and on the structure of zooplankton.
- Despite the ongoing research summarized in this dissertation, many questions about zooplankton in canals remain unanswered. This should encourage further research on these objects.

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9. APPENDICES

A collection of articles comprising in the doctoral thesis conducted at the Faculty of Biological Sciences of Kazimierz Wielki University in Bydgoszcz, Poland

A-1

Kolarova, N., Napiórkowski, P. (2022). How Do Specific Environmental Conditions in Canals Affect the Structure and Variability of the Zooplankton Community? WATER, 14(6), 979. doi:10.3390/w14060979

A-2

Kolarova, N., Napiórkowski, P. (2023). Are rotifer indices suitable for assessing the trophic status in slow-flowing waters of canals? HYDROBIOLOGIA, 1-11. doi:10.1007/s10750-023-05275-7

A-3

Kolarova, N., Napiórkowski, P. (under review). The influence of locks on canals zooplankton (Bydgoszcz canal and Noteć canal – Poland). ECOHYDROLOGY & HYDROBIOLOGY, 000-000

10. ACKNOWLEDGEMENTS

First and foremost, I am grateful to my supervisor prof. Paweł Napiórkowski for the plenty of time he devoted to answering my professional and practical questions related to my PhD thesis, for his expert guidance, comments, suggestions and patience during my PhD study. His immense knowledge and wide experiences have encouraged me throughout my academic research and daily life. I need to thank prof. Ewa Dembowska and MSc Marta Ciechacka for valuable help and assistance during field work. I thank to Prof. Obolewski and MSc Mikołaj Matela who helped me with statistical analyses. I thank to Tim Brombley for checking and proofreading the manuscripts. I am also very thankful to Prof. dr. Lisette de Senerpont Domis for mentoring and MSc Suzanne Wiezer for care and technical help in laboratory during my internship in Netherlands Institute of Ecology (NIOO-KNAW). I owe special thanks to prof. Sławomir Cierbin, who helped me to manage the internship in Netherlands. I also thank all members of the team of Department of Hydrobiology for help and practical advices during my study. It was wonderful five years. Last but not least, I would like to express my gratitude to my parents and boyfriend for understanding, constant encouragement and believing in me. It would be impossible for me to complete my study.