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Original Research

Effects of Salinity on Species Diversity of Rotifers in Anthropogenic Water Bodies

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Abstract

This study investigated the influence of anthropogenic salinization on planktonic rotifer communities and traced changes in their diversity along a salinity gradient. The experiment was conducted in 14 ponds of varied anthropogenic origin located in Poland's Silesian Upland. On the basis of the mean concentration of total dissolved solids (TDS) and principal component analysis (PCA), the water bodies were divided into 4 groups in respect to salinity: freshwater ponds, TDS < 500 mg·dm^{-3}; subsaline ponds, TDS = 500-3,000 mg·dm^{-3}; hyposaline ponds, TDS = 3,000-20,000 mg·dm^{-3}; and mesosaline ponds, TDS = 20,000-50,000 mg·dm^{-3}. An increase in salinity resulted in a decrease of rotifer species richness and diversity. Salinity also had a negative effect on mean rotifer density. The highest densities were recorded in freshwater and hyposaline ponds, whereas the lowest were in subsaline and mesosaline waters. Rotifer species richness differed significantly at 2 salinity thresholds: TDS = 500 mg·dm^{-3} and 20,000 mg·dm^{-3}.

Keywords: rotifers, salinity, anthropogenic water bodies, ponds

Introduction

A major role in salinization of inland waters globally is played by climate change, which causes an excess of evaporation over precipitation, leading to secondary salinization of waters. This phenomenon is observed in semiarid and arid regions of Africa, Australia, and Asia, which expand as a result of global warming [1, 2]. In West Australia, salinization of waters also is partly due to gold and nickel mining [3, 4] and agriculture [2]. In Poland, a major cause of salinization of rivers and water bodies results from mining, mostly coal mines, especially in the Silesian Upland. This is so-called anthropogenic salinization (caused by human activity). Open-pit mining of coal or lignite in Germany and salt mining in England also have contributed to salinization of groundwater and surface waters in those regions [2, 5].

Salinization of surface waters changes the natural characteristics of aquatic ecosystems and decreases their productivity [2]. An excess of salt may be toxic to freshwater organisms, limiting their basic physiological and ecological functions. Salinity may affect the life history and fitness of species. Generally the major consequence of anthropogenic salinization of inland waters is a decrease in biodiversity [6-9]. Rotifers are very sensitive to salinity [10] and an increase induces changes in populations [11] by affecting their diversity and dynamics [12]. So far, in Polish literature only one study has dealt with the effects of anthropogenic salinization on zooplankton communities, including rotifers [13].

Preferences of individual rotifer species with respect to salinity are hardly studied [14]. Tolerance to changes in salinity is associated with the physiology of rotifers, which are classified as osmoconformers, although some of them are capable of osmoregulation [15].

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This study aimed to investigate the influence of anthropogenic salinization of ponds on rotifer communities and to trace changes in these communities along a salinity gradient.

Material and Methods

Study Area

This study was conducted in 14 water bodies of varied anthropogenic origin: 9 mining subsidence pools (StZac, Proz, StMoc, Go1, Go2, ZalBek, JFar, OsSzcz, ZbSzcz), 2 ponds formed in small subsidence basins as a result of flooding in 1997 (StPop1, StPop2), a water body formed in a sand pit mine (OsKn1), a water body formed in a clay pit mine (OsKn2), and another one formed by coal mining (OsMak). They are located within the administrative borders of the towns of Knurów and Zabrze and the village of Gierałtowice (Silesian Upland, South Poland). Detailed information on the studied ponds is presented in Tables 1 and 2.

Sampling

Material for biological research and analysis of physicochemical parameters was collected in the 14 anthropogenic water bodies from April till November 2008-10. Every two weeks, one qualitative plankton sample was collected, as well as 5 quantitative samples for biological research, and one water sample for analysis of physicochemical parameters. In total, 206 qualitative samples, 1,030 quantitative samples, and 206 water samples were taken. Classification of rotifer species followed Segers [16].

The physicochemical parameters were analyzed using the Merck kits for assessment of oxygen content and chloride concentration; and a Hanna portable meter (HI 9811-5) for measurements of pH, conductivity, and total dissolved solids (TDS), nitrates, and phosphates.

The number of species present in the studied samples (constancy) were counted. Where a species occurred in 75-100% of samples it was deemed to have high constancy.

The Shannon index of species diversity (H') was calculated by means of MVSP 3.1 software. To determine the major factors differentiating the water bodies studied, principal component analysis (PCA) was performed using CANOCO for Windows software. To assess the effect of environmental factors on rotifer communities, canonical correspondence analysis (CCA) was conducted using CANOCO for Windows 4.5 software. To check the significance of differences in rotifer density between the ponds, Kruskal-Wallis analysis of variance by ranks was performed (at $\alpha = 0.05$) by Statistica 8.0 software (StatSoft, PL).

Results and Discussion

The water bodies were ranked in respect of increasing salinity on the basis of TDS values (Fig. 1). Salinity was the lowest in Zacisze Pond (StZac) ($TDS_{śr} = 157.33$ mg·dm^{-3}), whereas the highest in the sedimentation ponds of coal mine Makoszowy (OsMak), and Knurów 2 (OsKn2).

Results of the principal component analysis (PCA) are shown in Fig. 2. The first axis (PCA1) explains as much as 93.1% of the total variation in physicochemical properties of the water bodies. The left-hand side of the ordination space includes ponds with low salinity, whereas the right-hand side shows the more saline water bodies. Thus the first PCA axis can be interpreted as salinity gradient. The second axis (PCA2) groups the ponds with respect to the other physicochemical parameters, but it explains only 4.9% of the total variation.

On the basis of PCA and mean TDS values, the water bodies could be divided into 4 groups (Table 1) with respect to salinity (based on the scale recommended by Hammer [7]: (FW) freshwater ponds, TDS < 500 mg·dm^{-3}; (S) sub-

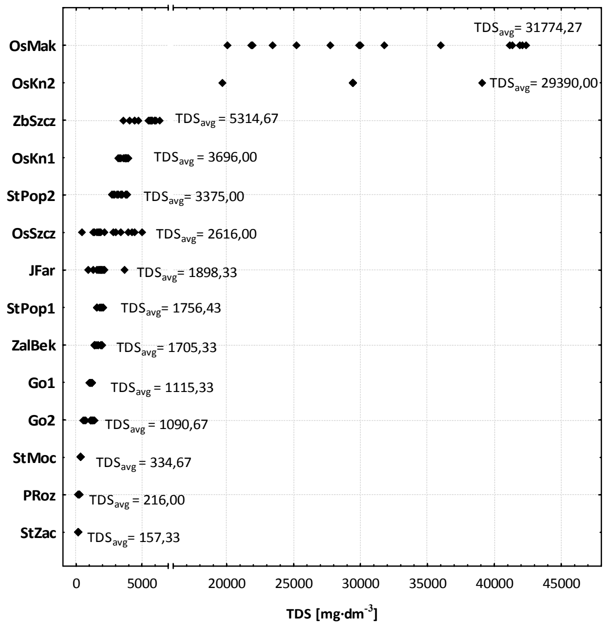

Fig. 1. Ranking of the studied ponds with respect to increasing salinity measured as total dissolved solids (TDS).

Table 1. Characteristics of reservoirs: origin, age, results of physico-chemical analisis of water, macrophytes.

Ponds	Freshwater			Subsaline					Hyposalins				Mezosalins		Kruskal-Wallis Test
	StZac	Proz	StMoc	Go1	Go2	ZalBek	StPop1	JFar	OsSzcz	StPop2	OsKn1	ZbSzcz	OsKn2	OsMak	
Latitude Langitude	50°12' 40"N 18°39' 27"E	50°11' 40"N 18°37' 37"E	50°13' 09"N 18°41' 20"E	50°12' 01"N 18°38' 12"E	50°12' 07"N 18°38' 03"E	50°12' 56"N 18°42' 03"E	50°11' 53"N 18°38' 28"E	50°15' 32"N 18°44' 45"E	50°11' 41"N 18°38' 05"E	50°11' 36"N 18°38' 46"E	50°13' 09"N 18°40' 08"E	50°11' 22"N 18°38' 50"E	50°13' 19"N 18°37' 18"E	50°16' 31"N 18°45' 51"E	
Origin ponds	Coal mine	Coal mine	Coal mine	Coal mine	Coal mine	Coal mine	After flooding	Coal mine	Coal mine	After flooding	Mine sand pit	Coal mine	Mine clay pit	Settler	
Year of creation	1974	1971	1974	1971	1971	1977	1997	1969	1964	1997	1974	1973	1974	1972	
T ºC (±SD)	18.60 (±5.64)	17.90 (±5.77)	17.20 (±5.39)	18.43 (±5.65)	17.53 (±5.61)	17.47 (±5.61)	18.61 (±5.39)	17.04 (±7.04)	18.67 (±6.17)	18.10 (±6.01)	17.87 (±5.19)	19.20 (±5.81)	22.50 (±4.82)	19.63 (±5.31)	–
pH (±SD)	7.0 (±0.46)	8.46 (±0.59)	7.95 (±0.49)	7.91 (±0.5)	7.85 (±0.33)	7.81 (±0.28)	7.96 (±0.3)	7.65 (±0.39)	8.24 (±0.53)	8.29 (±0.27)	8.25 (±0.28)	7.89 (±0.3)	7.23 (±0.11)	7.43 (±0.1)	H=109.316 $p<0.001$
Conductivity [$\mu S \cdot cm^{-1}$] (±SD)	320 (±25.3)	438.67 (±39.25)	680 (±45.67)	2199 (±494.7)	2261 (±128.8)	3414 (±453.7)	3521 (±365.8)	3782 (±1300)	5240 (±2738)	6750 (±758)	7408 (±395)	10650 (±1641)	58735 (±7319)	63456 (±16802)	H=194.269 $p<0.003$
Oxygen [$mg \cdot dm^{-3}$] (±SD)	8.85 (±1.5)	9.95 (±1.76)	10.84 (±1.72)	9.91 (±1.6)	8.27 (±1.48)	8.79 (±1.84)	8.80 (±1.55)	10.43 (±5.3	13.12 (±2.66)	9,83 (±2.83)	9.49 (±1.73)	11.15 (±3.76)	7.57 (±2.49)	5.73 (±1.7)	H=70.218 $p<0.002$
TDS [$mg \cdot dm^{-3}$] (±SD)	158.57 (±13.8)	216.0 (±18.05)	334.6 (±25.32)	1090.6 (±246.6	1115.3 (±77.9)	1705.3 (±236.4)	1756.4 (±190.1)	1898. (±657)	2616.00 (±1368)	3375.0 (±372.5)	3696.0 (±213.9)	5314.67 (±830.4)	29390 (±3670)	31774.27 (±8412)	H=194.307 $p<0.004$
Nitrates [$mg \cdot dm^{-3}$] (±SD)	0.93 (±1.07)	2.03 (±1.74)	0.42 (±0.6)	0.41 (±0.63)	0.31 (±0.84)	0.59 (±0.42)	0.27 (±0.44)	0.86 (±1.67)	0.75 (±0.89)	0.59 (±1.67)	0.69 (±0.89)	0.30 (±0.64)	3.83 (±0.72)	1.83 (±0.72)	H=89.402 $p<0.005$
Phosphates [$mg \cdot dm^{-3}$] (±SD)	0.51 (±0.45)	0.42 (±0.51)	0.60 (±0.46)	0.74 (±0.57)	0.62 (±0.6)	0.58 (±0.41)	0.59 (±0.49)	1.53 (±0.92)	0.46 (±0.26)	0.52 (±0.6)	0.73 (±0.79)	0.76 (±0.69)	0.72 (±0.72)	1.93 (±0.87)	H=46.532 $p<0.006$
Macrophyte	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	no	no	

StZac – pond Zacisze, PRoz – pond Pod Różą, StMoc – pond Moczury, Go1 – Goździk1, Go2 – Goździk2, ZalBek – pond Beksza, StPop1 – pond Powodziowy1, JFar – pond Farskie, OsSzcz – Osadnik Szczygłowice, StPop2 – pond Powodziowy2, OsKn1 – Osadnik Knurów1, ZbSzcz – pond Szczygłowice, OsKn2 – Osadnik Knurów2, OsMak – Osadnik Makoszowy

Table 2. List of rotifer species and abbreviations.

Anuraeopsis fissa Gosse	Anu.fis.
Ascomorpha ecaudis Perty	Asc.eca.
Ascomorpha ovalis (Berg.)	Asc.ova.
Ascomorpha saltans Bartsch	Asc.sal.
Asplanchna brightwelii Gosse	Asp.bri.
Asplanchna priodonta Gosse	Asp.pri.
Bdelloidea n. det.	Bdell.
Brachionus angularis Gosse	Bra.ang.
Brachionus bennini Leissling	Bra.ben.
Brachionus budapestinensis Daday	Bra.bud.
Brachionus calyciflorus Pallas	Bra.cal.
Brachionus diversicornis (Daday)	Bra.div.
Brachionus falcatus Zach.	Bra.fal.
Brachionus leydigii Cohn	Bra.ley.
Brachionus plicatilis Müller	Bra.pli.
Brachionus quadridentatus Her.	Bra.qua.
Brachionus rubens Her.	Bra.rub.
Brachionus urceolaris Müller	Bra.urc.
Cephalodella auriculata (Müller)	Cep.aur.
Cephalodella catellina (Müller)	Cep.cat.
Cephalodella forficula (Her.)	Cep.for.
Cephalodella gibba (Her.)	Cep.gib.
Cephalodella gracilis (Her.)	Cep.gra.
Cephalodella sterea (Gosse)	Cep.ste.
Cephalodella tenuior (Gosse)	Cep.ten.
Collotheca mutabilis (Hudson)	Col.mut.
Colurella adriatica Her.	Col.adr.
Colurella colurus (Her.)	Col.col.
Colurella hindenburgi Stein.	Col.hin.
Colurella obtusa (Gosse)	Col.obt.
Colurella uncinata (Müller)	Col.unc.
Conochilus natans (Seligo)	Con.nat.
Conochilus unicornis Rouss.	Con.uni.
Encentrum diglandula (Zaw.)	Enc.dig.
Encentrum marinum (Duj.)	Enc.mar.
Euchlanis deflexa (Gosse)	Euc.def.
Euchlanis dilatata Her.	Euc.dil.
Euchlanis lyra Hudson	Euc.lyr.
Filinia longiseta (Her.)	Fil.lon.
Filinia terminalis (Plate)	Fil.ter.
Gastropus stylifer (Imhof)	Gas.sty.
Hexarthra mira (Hudson)	Hex.mir.
Itura aurita (Her.)	Itu.aur.

Table 2. Continued.

Kellicottia longispina (Kell.)	Kel.lon.
Keratella cochlearis (Gosse)	Ker.coc.
Keratella quadrata (Müller)	Ker.qua.
Keratella tecta (Gosse)	Ker.tec.
Keratella testudo (Ehrenberg)	Ker.tes.
Keratella valga (Ehrenberg)	Ker.val.
Lecane bulla (Gosse)	Lec.bul.
Lecane closterocerca (Schm.)	Lec.clo.
Lecane flexilis (Gosse)	Lec.flex.
Lecane furcata (Murray)	Lec.fur.
Lecane hamata (Stokes)	Lec.ham.
Lecane ludwigii (Eckstein)	Lec.lud.
Lecane luna (Müller)	Lec.lun.
Lecane lunaris (Her.)	Lec.ris.
Lecane nana (Murray)	Lec.nan.
Lecane scutata (Har. & Myers)	Lec.scu.
Lecane stenroosi (Meissner)	Lec.ste.
Lecane tenuiseta Harring	Lec.ten.
Lecane ungulata (Gosse)	Lec.u
Lepadella acuminata (Ehr.)	Lep.acu.
Lepadella ovalis (Müller)	Lep.ova.
Lepadella patella (Müller)	Lep.pat.
Lophocharis oxysternon (Gosse)	Lop.oxy.
Monommata longiseta (Müller)	Mon.lon.
Monommata sp.	Mon.sp.
Mytilina mucronata (Müller)	Myt.muc.
Mytilina ventralis (Her.)	Myt.ven.
Notholca acuminata (Her.)	Not.acu.
Notholca labis Gosse	Not.lab.
Notholca salina Focke	Not.sal.
Notholca squamula (Müller)	Not.squ.
Ploesoma hudsoni (Imhof)	Plo.hud.
Polyarthra dolichoptera Idelson	Pol.dol.
Polyarthra major Burckhardt	Pol.maj.
Polyarthra minor Voigt	Pol.min.
Polyarthra remata Skorokov	Pol.rem.
Polyarthra vulgaris Carlin	Pol.vul.
Pompholyx complanata Gosse	Pom.com.
Pompholyx sulcata Hudson	Pom.sul.
Proales fallaciosa Wulfert	Pro.fal.
Squatinella rostrum (Schm.)	Squ.ros.
Synchaeta kitina Rousselet	Syn.kit.
Synchaeta oblonga Her.	Syn.obl.

Table 2. Continued.

Synchaeta pectinata Her.	Syn.pec.
Testudinella clypeata (Her.)	Tes.cly.
Testudinella elliptica (Ternetz)	Tes.ell.
Testudinella parva (Hermann)	Tes.par.
Testudinella patina (Müller)	Tes.pat.
Trichocerca capucina (Wierz. & Zach.)	Tri.cap.
Trichocerca cylindrica (Imhof)	Tri.cyl.
Trichocerca elongata (Gosse)	Tri.elo.
Trichocerca insignis (Herrick)	Tri.ins.
Trichocerca longiseta (Schrank)	Tri.lon.
Trichocerca pusilla (Jennings)	Tri.pus.
Trichocerca rattus (Müller)	Tri.rat.
Trichocerca similis (Wierz.)	Tri.sim.
Trichotria pocillum (Müller)	Tri.poc.
Trichotria tetractis (Her.)	Tri.tet.

saline ponds, TDS = 500-3000 mg·dm^{-3}; (H) hyposaline ponds, TDS = 3,000-20,000 mg·dm^{-3}; and (M) mesosaline ponds, TDS = 20,000-50,000 mg·dm^{-3}.

During the whole study period, 101 species and forms of rotifers were identified in the water bodies. Species diversity was the highest in freshwater (in accordance with the characteristics given in the site description) pond Zacisze (StZac), with 69 rotifer taxa, and the lowest in the most saline (mesosaline) ponds (OsKn, OsMak) with 8 and 15 taxa, respectively. The Shannon index of species diversity (H') and evenness index (J') were the highest in freshwater (in accordance with the characteristics given in the site description) Pod Różą Pond (PRoz, H' = 2.322, J' = 0.603). The Shannon index was the lowest in the most saline water body, i.e. the sedimentation pond of coal mine Makoszowy (OsMak, H' = 0.773) (Table 3).

Results of this study of anthropogenic water bodies in the Silesian Upland show a decrease in species richness and species diversity with increasing salinity. However, significant differences in species richness are observed at 2 salinity thresholds. The first one is at TDS of 500 mg·dm^{-3}, indicating that many freshwater (in accordance with the characteristics given in the site description) species are sensitive to increased salinity. The second one is at TDS of 20,000 mg·dm^{-3}. The range from 500 to 20,000 mg·dm^{-3} is tolerated by a relatively large number of rotifer species, whereas only a few are able to live in waters with TDS > 20,000 mg·dm^{-3} (Fig. 3).

In spite of the observed decline in rotifer species richness with increasing salinity, the number of recorded taxa was relatively high (Table 3). In most other studies of water bodies with both natural and secondary salinity (ponds, lakes, and rivers), the recorded number of rotifer species was markedly lower than in our study [7, 17-19]. The decrease in species richness with increasing salinity is a commonly observed trend in various types of saline waters all over the world [6, 7-9, 20, 21]. However, results on rotifer species richness and diversity in inland saline waters vary widely. Some authors reported a remarkable decrease

Table 3. Number of rotifer species, the Shannon index of species diversity (H') and evenness index (J'), and results of non-parametric ANOVA tests (for abbreviation see Table 1).

Ponds		Number of species	H'	J'
FW	StZac	69	1.178	0.278
	PRoz	47	2.322	0.603
	StMoc	53	1.996	0.503
S	Go2	43	1.992	0.530
	Go1	53	1.874	0.472
	ZalBek	26	1.406	0.432
	StPop1	34	1.477	0.419
	JFar	46	2.056	0.537
H	OsSzcz	40	1.624	0.440
	StPop2	33	1.170	0.335
	OsKn1	38	1.741	0.479
	ZbSzcz	33	1.051	0.301
M	OsKn2	15	1.465	0.541
	OsMak	8	0.773	0.372
Non-parametric ANOVA tests (Kruskal-Wallis)		H = 124.944 p < 0.001	H = 57.186 p < 0.001	H = 19.667 p = 0.104

Fig. 2. Similarity of physicochemical properties of the studied ponds based on principal component analysis (PCA).

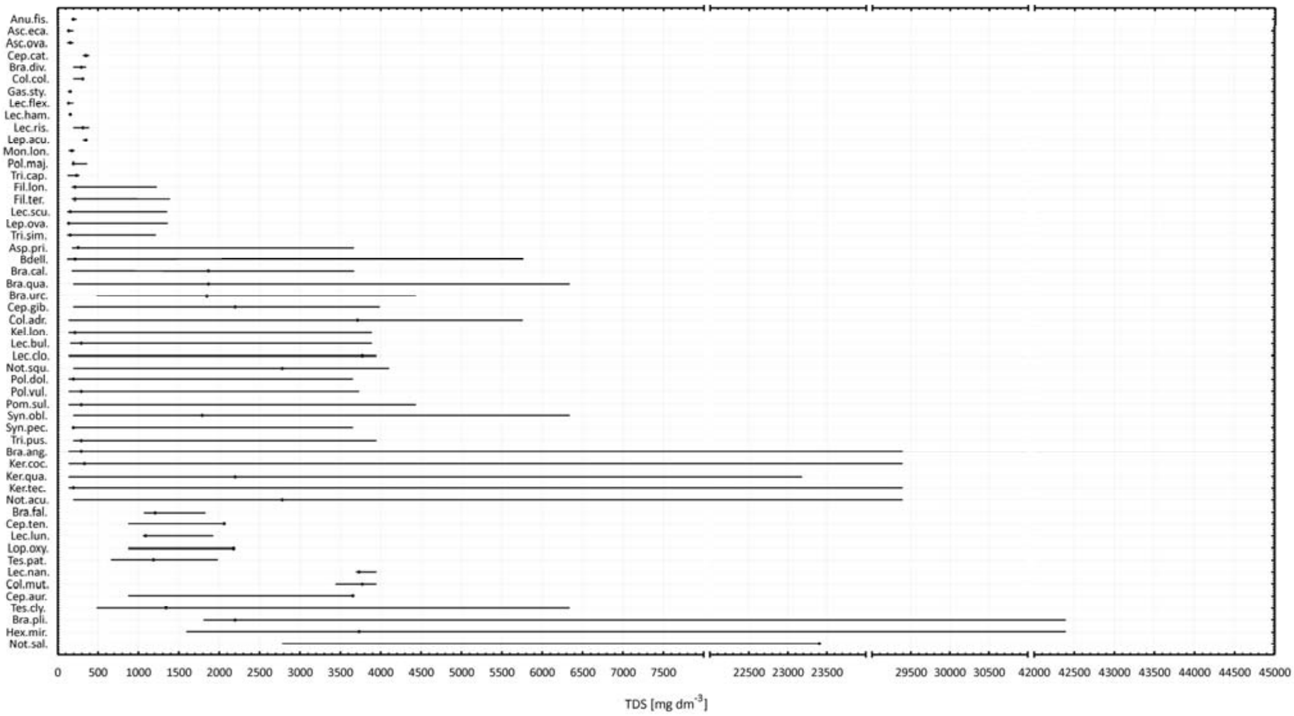

Fig. 3. Occurrence of select rotifer species in waters of different salinity (total dissolved solids, TDS). The analysis includes only samples where species constancy exceeds 30%. The point marks the TDS value for which the species reached the highest density.

in species richness with increasing salinity, whereas others recorded the highest rotifer species diversity in moderately saline waters. Swadling et al. [22] reported a significantly lower species diversity in waters with TDS of 350-750 mg·dm^{-3}, as compared to waters with TDS of < 350 mg·dm^{-3}. Kaya et al. [18] suggest that species diversity of rotifers is the highest in waters with TDS of 400-8,000 mg·dm^{-3}.

Research in Mexico showed that in inland saline waters, species richness and diversity are high, and in more saline water bodies, typical planktonic species are replaced by halophilous species [19].

In man-made ponds in Upper Silesia, salinity also had a negative effect on densities of rotifer communities. The mean density of rotifers was the highest in a group of freshwater ponds and in 2 hyposaline ponds. The lowest values of mean density were recorded in the most saline ponds. Differences in mean rotifer density between the studied water bodies were significant (Kruskal-Wallis analysis of variance by ranks: H' = 124.748, $p < 0.001$) (Fig. 4).

In waters of differrent salinity, various species find optimum living conditions that allow them to reach high densities and have a major effect on the total density of rotifers in the habitats. Simultaneously, it seems that subsaline and mesosaline waters are less favorable for the development of most rotifer species. Subsaline ponds are too saline for freshwater species to reach high densities, but simultaneously salinity is too low for halophilous species to thrive. Mesosaline ponds are characterized by a general deterioration of environmental conditions, e.g. a decrease in oxygen content, which is unfavorable also for halophilous species [2]. Most authors did not have any unambiguous influence of salinity on rotifer density [17]. However, experiments made by Toruan [23] on zooplankton from wetlands varying in salinity showed a marked decrease in rotifer densities when salinity reached 15,000 mg/dm^{-3}.

The CCA ordination diagram for species clearly indicates that some of them have their optimum at high salinity: *Brachionus plicatilis*, *Hexarthra mira*, and *Testudinella clypeata*. The location of many species in the left-hand part of the CCA plot indicates that they do not tolerate increased salinity, but are associated with waters with a higher concentration of nitrates. A distinct group is composed of *Ascomorpha ovalis*, *Conochilus natans*, and *Trichocerca similis*, whose occurrence depends on low salinity but may require other environmental conditions than the other species as well (Fig. 5).

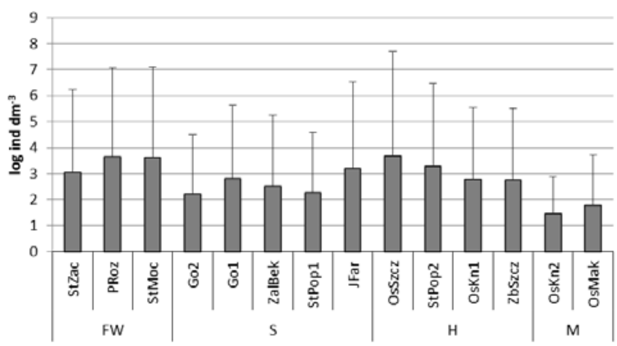

Fig. 4. Mean rotifer density and standard deviation (SD) in the studied ponds during the whole study period.

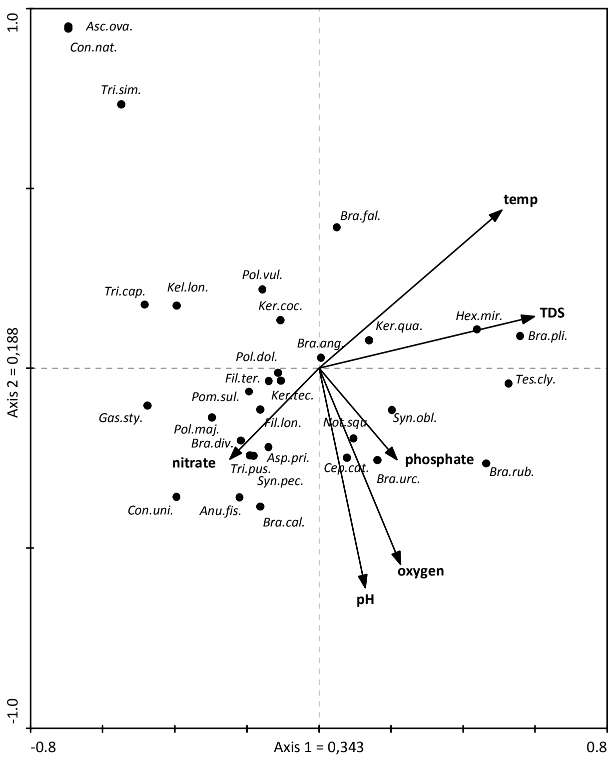

Fig. 5. Canonical correspondence analysis (CCA) diagram for select rotifer species.

Distribution of selected rotifer species in relation to salinity shows that many species do not tolerate high salinities. Eurytopic species, e.g. *Keratella cochlearis*, *Pompholyx sulcata*, *Kellicottia longispina*, *Polyarthra vulgaris*, and *Keratella tecta* reached the highest constancy in freshwater and subsaline ponds. Occurrence of these species was not limited only to waters with low salinity, but their constancy and density clearly decreased with increasing salinity (Fig. 3).

Halophilous species in this study, e.g. *Brachionus plicatilis* and *Hexarthra mira*, were observed regularly in hypo- to mesosaline waters. In earlier studies, *Brachionus plicatilis* was recorded from polluted water from mines in Upper Silesia [13]. This species is usually dominant in various inland saline ecosystems [17]. Temperature and salinity strongly affect its growth rate and reproduction [24]. Some authors suggest that in natural conditions it tolerates salinities of 2-65 mg·dm^{-3} [25].

A broad range of salinity tolerance of *H. mira* was confirmed by Fontaneto et al. [14]. This species has been recorded by many authors in various types of waters: fresh and subsaline, hyposaline, as well as mesosaline [6, 17].

In this study, *Notholca salina* was observed in hypo- and mesosaline ponds. It was recorded only in cold seasons and its density was low. This species, reported from saline anthropogenic water bodies, was not detected all the time because – like other *Notholca* species – it prefers low temperatures. Species of this genus are classified as halophilous. *N. salina* is rare in Poland, found e.g. in the Antarctic Lake Wujka, with salinity varying from 470 to 28,000 mg·dm^{-3} [26]. It is regarded as a typical halophilous species [14].

Conclusions

The major environmental factor affecting rotifer communities in this study is the level of salinity. An increase in salinity results in a decrease of species richness and diversity. Salinity also effects mean rotifer density. The highest densities were recorded in freshwater and hyposaline waters, whereas the lowest were in sub- and meso-saline waters. Rotifer species richness differs significantly at two salinity thresholds. The first one is at a TDS of 500 mg·dm^{-3}, indicating that many species are sensitive to increased salinity, while the second one is at a TDS of 20,000 mg·dm^{-3}. The range from 500 to 20,000 mg·dm^{-3} is tolerated by a relatively large group of species.

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