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ORIGINAL RESEARCH ARTICLE

Effect of physicochemical parameters on zooplankton in the brackish, coastal Vistula Lagoon

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Summary This paper analyzes whether physicochemical properties significantly influence the occurrence of zooplankton in a brackish reservoir. The studies were carried out on the Vistula Lagoon in August and September from 2006 to 2009 at 32 research sites. The environmental conditions in the Vistula Lagoon varied widely. At the time of the investigation, 17 species of rotifers, six species of Cladocera, and ten species of Copepoda were noted, and the total density of plankton fauna ranged from 145 to 765 ind. dm^{-3}. Statistical analysis demonstrated a significant correlation between the occurrence of some zooplankton species and certain environmental parameters, whereas the sampling sites were grouped according to study years. The zooplankton systems recorded at the research sites in 2006 constitute the most disparate group. Thus, it can be concluded that physicochemical properties might significantly impact both individual species (depending on their environmental demands) and entire zooplankton clusters.

1. Introduction

The instability of environmental conditions is a typical feature of brackish waters such as estuaries or lagoons (Cognetti and Maltagliati, 2000). Changes in abiotic factors are reflected in the biochemical activity of both vertebrates and invertebrates. These factors determine the rate of metabolic transformations, the efficacy of immune systems, and reaction patterns of bodies to stressors (Kinne, 1964; Roddie et al., 1984).

Studies to date of the Vistula Lagoon have focused on the physicochemical characters of the water (Nawrocka and Kobos, 2011; Paturej and Kruk, 2011; Witek et al., 2010), the biota composition of the pelagic zone (Dmitrieva and

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Semenova, 2012; Psuty and Wilkońska, 2009), or the bottom area of the lagoon (Rychter et al., 2011; Warzocha et al., 2016).

Zooplankton is one of the most important biotic elements that impact all functional aspects of aqueous ecosystems including food chains and trophic networks, energy flow, and the circulation of matter. They occupy a central position in pelagic zone food webs (Lampert, 1997). The occurrence and distribution of plankton fauna depend on a number of factors such as climate change, habitat physicochemical properties, and biotic factors (Ahmad et al., 2011; Alexander, 2012; Cottenie et al., 2001; Rajagopal et al., 2010; Richardson, 2008). Environmental factors are also important elements; for instance, water temperature impacts the growth and development of organisms and can influence their mortality (Hall and Burns, 2001). Different species show varied tolerances to increases or reductions in temperature ranges, and particularly sensitive individuals are eliminated by them (Andrulewicz et al., 2008; Tunowski, 2009). In addition, salinity has a significant impact on organisms, because it requires them to adjust the saline concentrations in their bodies to the surrounding environment. Changes in salinity are the direct cause of some species disappearing and others occurring (Ojaveer et al., 2010). Environmental factors can also prompt organisms to migrate in order to avoid unfavorable environmental conditions, i.e., excessively high or low salinity. Variations in salinity can also contribute indirectly to food shortages and, consequently, they impact zooplankton abundance (Perumal et al., 2009). Water pH can also have an impact on zooplankton; low pH causes reduced zooplankton abundance, as well as decreased biodiversity and the loss of some species (Dehui, 1995; Ivanova and Kazantseva, 2006; Yamada and Ikeda, 1999), whereas alkaline conditions that accompany high primary production favors the growth and abundance of zooplankton (Bednarz et al., 2002; Mustapha, 2009). The availability of light determines the distribution of producers, and this indirectly impacts the diversity and distribution of animals. It also influences the vertical migration of plankton that require a specific intensity of light for many physiological processes. Light also exerts an indirect impact on other physical factors such as temperature and water color (Andrulewicz et al., 2008). Oxygen dissolved in water, which is required for the survival of all aquatic organisms, is another important abiotic factor. Oxygen deficiencies can directly influence organism mortality. In addition, indirect influences are observed through predator—prey interactions since hypoxia influences mobile species to change their horizontal or vertical distribution (Decker et al., 2004). Many authors (Kudari and Kanadami, 2008; Paturej, 2005, 2006; Pinto-Coelho et al., 2005; Wang et al., 2007; Yildiz et al., 2007) claim that the trophic status of a reservoir, i.e., the availability of nutrients, significantly impacts the structure and abundance of zooplankton. When trophic conditions are modest, large, herbivorous forms (Calanoida copepods, large water fleas) dominate, while in fecund waters small detritivore forms and predatory organisms (Cyclopoida copepods, small water fleas, rotifers) occur abundantly (González et al., 2011).

The objective of the study was to determine whether physicochemical properties such as water temperature, salinity, pH, and water transparency, particulate matter, oxygen concentration, nutrient concentrations, and chlorophyll *a* significantly impacted zooplankton occurrence.

2. Material and methods

The study was conducted in the Polish part of the brackish Vistula Lagoon located in the southern part of the Baltic Sea. The lagoon is a broad, shallow reservoir with an average depth that does not exceed 2.6 m and a surface area of 328 km^2 (Chubarenko and Margoński, 2008). Salinity ranges from 0.5 to 6.0 PSU depending on the intensity of freshwater and brackish water inflows (Kruk et al., 2012). Samples were collected at the end of the summer season in August and September from 2006 to 2009 from 32 sampling sites (Fig. 1).

The zooplankton was collected either with a Ruttner sampler or a 10 dm^{-3} bucket at shallow, coastal sites. The biological material (30 dm^{-3}) was concentrated on an Apstein plankton mesh (with a 30 μm net size), fixed with Lugol solution, and preserved in 4% formalin. The zooplankton was examined microscopically and classified into one of three groups of planktonic animals: Rotifera, Cladocera, or Copepoda. The abundance of planktonic fauna was also determined. The zooplankton structure was estimated using the dominance and stability indicators proposed by Kasprzak and Niedbała (1981).

Measurements of physicochemical environmental factors were taken simultaneously with plankton sampling. Water transparency was determined with a Secchi disk and temperature, oxygen concentration, salinity, and pH were measured in situ with a HACH HQd Field Case oxygen probe (RUGGED) and a WTW Multi 350i probe. Particulate matter were determined with the direct weighing method (Hermanowicz et al., 1999). Chemical analyses were performed on unfiltered water samples to determine total phosphorus, orthophosphates, ammonium nitrogen, nitrate nitrogen, total nitrogen, and chlorophyll *a*. Pheophytin was determined in a laboratory as soon as possible after sampling. Ammonium nitrogen was determined spectrophotometrically with the indophenol method according to PN-C-04576-01:1976. Nitrate nitrogen (V) was measured colorimetrically with phenol disulphonic acid according to PN 73/C-04576/08-1973. The concentration of total nitrogen was determined as the sum of nitrate nitrogen and Kjeldahl's nitrogen measured with Kjeldahl's method (Golterman and Clymo, 1969). Total phosphorus and orthophosphates were determined with the

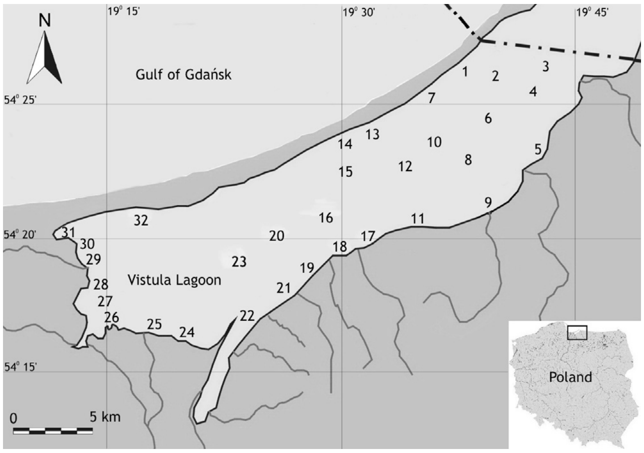

Figure 1 Location of the research sites on the Vistula Lagoon.

method using ammonium molybdenate based on Standard Methods (1999), whereas sampling and measurements of chlorophyll *a* were carried out according to ISO 10519:1997. Samples for chlorophyll *a* determinations were kept cool and in the dark until they were moved to the laboratory (within 4 h), where the water samples were filtered and immediately elaborated using a mechanical grinder and anhydrous ethanol (99.8%) as the extraction solvent. The chlorophyll *a* concentration was measured using a spectrophotometer (Shimadzu UV 1601) with an adjustment for pheopigments.

The results were processed with statistical methods using CANOCO version 4.52 (Ter Braak and Šmilauer, 2003). Before statistical analyses, zooplankton abundance was log $(x + 1)$ transformed to improve normality (Zar, 2010). All species and forms (*Keratella cochlearis f. tecta*) identified were included in the analyses. Nauplii and copepodites were excluded from the analyses since their identification to the species was impossible.

Environmental variables were analyzed for redundancy using Pearson's correlation. If two variables were highly correlated ($r > 0.6$ or $r < -0.6$), the variable which showed the higher overall mean correlation was excluded from further analyses. Except for pH, O_2, chlorophyll *a*, and N-NH_4, the environmental variables were log-transformed or log + 1 transformed (TN and N-NO_3) to approximate normal distribution.

Detrended Correspondence Analysis (DCA) was used to determine if RDA (Redundancy Analysis) or Canonical Correspondence Analysis (CCA) would be appropriate to evaluate associations between lagoon water physicochemistry and zooplankton abundance. The DCA ordination gradient was in the range of 3—4 standard deviations (3.33 SD), which implied that both linear and unimodal methods were appropriate for the data (Jongman et al., 1995). Thus, CCA was used to describe the relationships among the zooplankton species and the environmental variables selected for further analyses. The analyses were performed with focus scaling on inter-species distances (biplot scaling type). Environmental variables with variance inflation factors (VIF) <20 were selected for the following forward selection to avoid multicollinearity with other variables.

The automatic forward selection procedure (Ter Braak and Šmilauer, 2002) was used to select the contribution of environmental variables in the explanation of the species data set. This procedure computes the significance of a given variable and the stepwise cumulative variance explained with all the selected variables in the model. The statistical significance of eigenvalues and species-environment correlations for the axes generated by the CCA were tested with the Monte Carlo method based on 999 permutations including the unrestricted permutation. P values ≤ 0.05 were considered statistically significant.

3. Results

During the period studied, the Vistula Lagoon was characterized by extremely variable environmental conditions (Table 1). The water temperature was typical of the months in which the samples were collected and did not drop below 10°C. Water transparency was low at up to 0.5 m, which is

Table 1 Average values of the physicochemical parameters of the Vistula Lagoon in 2006—2009 (mean ± std. dev. (range)).

	2006	2007	2008	2009
T [°C]	20.5 ± 0.6 (19.7—22.1)	14.7 ± 2.4 (14.0—18.9)	18.7 ± 3.8 (10.9—20.7)	19.8 ± 2.0 (16.0—20.5)
SDV [m]	0.45 ± 0.04 (0.35—0.50)	0.35 ± 0.08 (0.25—0.45)	0.35 ± 0.06 (0.25—0.45)	0.27 ± 0.03 (0.20—0.30)
pH [—]	8.72 ± 0.18 (8.23—8.94)	8.67 ± 0.35 (8.22—9.25)	8.64 ± 0.13 (8.4—8.8)	7.69 ± 0.40 (7.0—8.4)
Particulate matter [mg dm^{-3}]	58 ± 12 (49—88)	56 ± 19 (12—84)	78.57 ± 22 (57—138)	95 ± 16 (68—120)
Salinity [PSU]	2.9 ± 0.7 (1.4—3.8)	3.43 ± 1.90 (1.2—9.3)	4.1 ± 0.4 (3.1—4.4)	3.5 ± 0.6 (2.3—4.5)
Oxygen [mg dm^{-3}]	7.9 ± 1.2 (6.8—11.4)	8.3 ± 2.0 (7.6—13.2)	10.0 ± 1.0 (8.7—12.9)	9.8 ± 0.6 (8.4—10.6)
Chl *a* [μg dm^{-3}]	32.77 ± 24.54 (13.11—101.57)	32.76 ± 11.71 (26.21—68.80)	81.91 ± 14.31 (38.23—102.39)	61.43 ± 25.98 (36.86—141.98)
Pheophytin [μg dm^{-3}]	132.4 ± 35.1 (29.29—167.14)	5.49 ± 6.02 (0.00—20.79)	8.61 ± 17.52 (0.00—92.82)	2.5 ± 0.56 (0.00—24.46)
TP [μg dm^{-3}]	191 ± 35 (163—261)	152 ± 39 (91—213)	210 ± 49 (104—284)	186.1 ± 36.23 (130—260)
SPR [μg dm^{-3}]	24 ± 10 (9—50)	16 ± 7 (0—65)	14 ± 10 (1—42)	14 ± 12 (1—50)
TN [mg dm^{-3}]	0.63 ± 0.11 (0.39—0.89)	1.25 ± 0.25 (0.88—1.74)	1.71 ± 0.27 (1.18—2.15)	1.62 ± 0.24 (1.03—2.12)
N-NO_3 [mg dm^{-3}]	0.01 ± 0.006 (0.01—0.03)	0.07 ± 0.02 (0.05—0.11)	0.04 ± 0.016 (0.02—0.08)	0.03 ± 0.013 (0.01—0.07)
N-NH_4 [mg dm^{-3}]	0.02 ± 0.01 (0.005—0.045)	0.02 ± 0.01 (0.012—0.064)	0.03 ± 0.007 (0.01—0.04)	0.03 ± 0.014 (0.01—0.07)

Table 2 Species composition, dominance and frequency of the zooplankton community in the Vistula Lagoon over the experimental period.

		Dominance [%][a]	Frequency [%][b]
Anureopsis fissa (Gosse, 1851)	Anu fis	0.0	6.3
Asplanchna priodonta Gosse, 1850	Asp pri	0.2	40.6
Brachionus angularis Gosse, 1851	Bra ang	2.3	53.1
Brachionus calyciflorus Pallas, 1766	Bra cal	0.9	31.3
Brachionus leydigii Cohn, 1862	Bra ley	0.1	3.1
Colurella colurus Ehrenberg, 1830	Col col	0.0	6.3
Euchlanis dilatata Ehrenberg, 1832	Euc dil	0.0	6.3
Filinia longiseta Ehrenberg, 1834	Fil lon	12.2	62.5
Keratella cochlearis f. tecta (Gosse, 1886)	Ker cot	10.8	96.9
Keratella cochlearis cochlearis (Gosse, 1851)	Ker coc	54.1	93.8
Keratella quadrata (Müller, 1786)	Ker qua	0.2	31.3
Polyarthra dolichoptera Idelson, 1925	Pol dol	0.1	12.5
Polyarthra platyptera Ehrenberg, 1838	Pol pla	1.8	18.8
Polyarthra vulgaris (Carlin, 1943)	Pol vul	0.5	25.0
Pompholyx sulcata Hudson, 1885	Pom sul	0.2	21.9
Synchaeta baltica Ehrenberg, 1834	Syn bal	0.1	15.6
Trichocerca pusilla (Lauterborn, 1898)	Tri pus	0.5	34.4
Trichocerca similis (Wierzejski, 1893)	Tri sim	0.5	12.5
Bosmina longirostris (Müller, 1785)	Bos lon	0.0	15.6
Ceriodaphnia quadrangula (Müller, 1785)	Cer qua	0.2	21.9
Chydorus sphaericus (Müller, 1776)	Chy sph	4.4	34.4
Diaphanosoma brachyurum (Liévin, 1848)	Dia bra	3.2	81.3
Leptodora kindtii (Focke, 1844)	Lep kin	0.0	6.3
Sida cristalina (Müller, 1776)	Sid cri	0.0	9.4
Acartia bifilosa (Giesbrecht, 1881)	Aca bif	0.1	21.9
Acartia longiremis (Dana, 1846)	Aca lon	1.7	81.3
Acartia tonsa (Dana, 1846)	Aca ton	1.1	75.0
Centropages hamatus (Lilljeborg, 1853)	Cen ham	0.0	3.1
Cyclops kolensis Lindberg, 1956	Cyc kol	0.2	25.0
Cyclops vicinus Ulyanin, 1875	Cyc vic	0.3	21.9
Eurytemora affinis (Poppe, 1880)	Eur aff	2.7	71.9
Eurytemora lacustris (Poppe, 1887)	Eur lac	1.1	28.1
Mesocyclops leuckarti (Claus, 1857)	Mes leu	0.1	6.3
Thermocyclops oithonoides (Sars, 1863)	The oit	0.2	25.0

[a] Dominance classes according to Kasprzak and Niedbała (1981): $>$10.0% eudominant species, 5.1—10.0% dominant species, 2.1—5.0% subdominant species, $\leq$1.0% sub-recedent species.

[b] Frequency criterion according to Tischler (1949) as cited in Trojan (1980): 100—76% (absolutely constant species), 75—51% (constant species), 50—26% (accesoric species), 25—0% (random species).

a characteristic phenomenon in vast, shallow brackish reservoirs that are estuary-like, such as the Vistula Lagoon. Water pH oscillated from neutral to slightly alkaline. The particulate matter concentration in the water did not drop below 50 mg dm^{-3}. Salinity, however, oscillated widely depending on the distance from sampling site to the open Baltic. Oxygen conditions were good in the years studied, and high levels of nutrients and chlorophyll *a* were recorded. Pheophytin concentrations, which were lower than chlorophyll *a* concentration except in 2006, indicated that conditions for zooplankton growth were good.

The Vistula Lagoon zooplankton included organisms from three taxonomic groups: Rotifera, Cladocera, and Copepoda. They were predominantly freshwater organisms that are highly tolerant of wide ranges of salinity. In addition, some brackish and marine taxa were observed. In total, 33 species were recorded, most of which belonged to Rotifera (17), followed by six Cladocera and ten copepod species. The species *K. cochlearis* was predominant in the qualitative structure of plankton fauna, while other commonly represented taxa included *Brachionus angularis*, *Filinia longiseta*, *Polyarthra platyptera*, *Chydorus sphaericus*, *Diaphanosoma brachyurum*, *Acartia longiremis* and *Eurytemora affinis* (Table 2).

The quantitative analysis of the samples indicated that the total density of zooplankton in the Vistula Lagoon ranged, on average, from 145 to 765 ind. dm^{-3} (Fig. 2). Among rotifers, the most abundant was *K. cochlearis* with the highest density at the stations sampled of 6059 ind. dm^{-3} and *F. longiseta* at 835 ind. dm^{-3}. Among plankton crustaceans, high numbers were recorded for *Ch. sphaericus* (1533 ind. dm^{-3}) and *D. brachyurum* (433 ind. dm^{-3}), while among copepods *A. longiremis* (162 ind. dm^{-3}) and *E. affinis* (208 ind. dm^{-3}) were numerous.

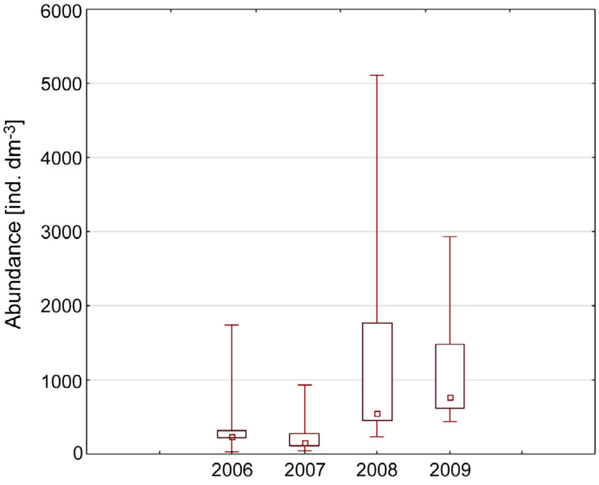

Figure 2 Average abundance of zooplankton in the Vistula Lagoon.

Canonical Correspondence Analysis was performed for 34 taxa and eleven environmental variables. Among all 13 variables (Table 1), Secchi Disc Visibility (SDV) and pheophytin were not included in the analyzed dataset since they were strongly correlated with the variables selected. The variance inflation factor (VIF) of environmental variables included in the analysis displayed very low values and did not exceed the threshold of $>$4. All 11 factors were included in the final CCA. Variables used in the ordination explained 35% of the total variability of the zooplankton. The first and second canonical axes explained 10.5% (eigenvalue 0.250) and 9.6% (eigenvalue 0.228), respectively, of the variance in the species data and 30.1% and 27.3%, respectively, of the variance in species-environment relationships (Table 3).

The species—environment correlation of all axes became significant in the Monte Carlo permutation test (F = 2.988, $P < 0.01$). The CCAs showed that six of the examined environmental variables related significantly with the zooplankton assemblages (Table 4). The assemblages correlated most strongly with the concentration of total nitrogen (TN), although pH also influenced zooplankton distribution heavily.

Along the gradient of the first axis, the largest correlation between environmental variables and sample location was for N-NO_3 concentration ($r = -0.48$), along the second axis this was negatively correlated with TN concentration ($r = -0.70$) and suspended solids ($r = -0.56$) and was positively correlated with pH (r = 0.63). The largest correlation with the third axis was associated with N-NH_4 concentration (r = 0.57), while the fourth axis was associated with O_2 concentration (r = 0.42).

Table 4 Environmental variables selected by the automatic forward procedure, in order of their inclusion in the model during the 'environmental' partial Canonical Correspondence Analysis of the species assemblages. The additional variance of each variable explains at the time of inclusion (i.e., conditional effect, lambda A) the marginal effect of each variable lambda (1), the statistics of the Monte Carlo significance test for the forward procedure (F) and the associated probability (P) for each variable.

Variable	λ_1	λ_A	P	F
TN[a]	0.20	0.20	0.002	6.42
pH[a]	0.20	0.18	0.002	6.45
T[a]	0.12	0.06	0.010	2.32
PM	0.12	0.03	0.292	1.14
N-NO_3	0.11	0.04	0.092	1.54
PSU	0.11	0.04	0.064	1.68
chl a [a]	0.09	0.05	0.026	1.99
N-NH_4 [a]	0.09	0.10	0.002	3.49
O_2	0.09	0.05	0.072	1.66
SPR[a]	0.07	0.06	0.006	2.30
TP	0.04	0.02	0.414	1.02

[a] Variable significant ($P < 0.05$).

The CCA biplot for species and environmental variables indicated that taxa such as *Ceriodaphnia quadrangula* were positively correlated with nitrates, *Leptodora kindtii* was positively correlated with temperature, and species such as *Synchaeta baltica*, *Anuraeopsis fissa*, and *Brachionus leydigii* were negatively correlated with pH (Fig. 3).

The sampling sites are grouped according to the years in which the experiments were conducted. The plankton clusters recorded at sampling sites in 2006 are the most disparate group (Fig. 4). The community structure of the zooplankton in the Vistula Lagoon in 2006 appears to be strongly affected by temperature, while nitrogen concentration was indicated as a negative influence. The zooplankton diversity in the lagoon in 2009 appeared to be strongly affected by low pH. The zooplankton assemblages observed in 2007 and 2008 were not close to any of the physicochemical arrows, indicating that more than one factor or unmeasured factors were likely to have been important controllers of taxonomic diversity in these years of the study.

Table 3 Summary of CCA results for the abundance of zooplankton taxa and 11 environmental variables. All axes were significant following Monte-Carlo permutation procedures.

Axes	1	2	3	4	Total inertia
Eigenvalues	0.250	0.228	0.101	0.074	2.380
Species—environment correlations	0.824	0.865	0.716	0.697	
Cumulative percentage variance					
of species data	10.5	20.1	24.3	27.5	
of species—environment relation	30.1	57.4	69.5	78.4	
Sum of all eigenvalues					2.380
Sum of all canonical eigenvalues					0.833

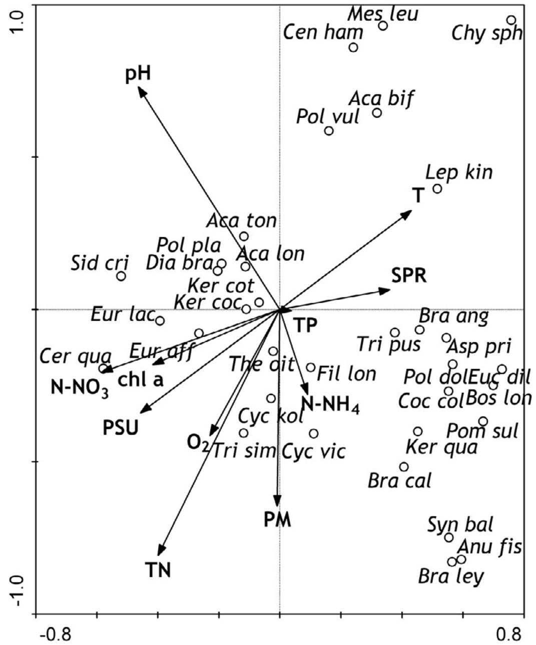

Figure 3 Canonical Correspondence Analysis (CCA) ordination plot for species composition and environmental variables (T, temperature; PSU, salinity; pH, water reaction; PM, particulate matter; chl a, chlorophyll *a*; O_2, dissolved oxygen; N-NO_3, nitrate nitrogen; N-NH_4, ammonium nitrogen; TN, total nitrogen; TP, total phosphorus; SPR, soluble reactive phosphorus). Code for species in Table 2.

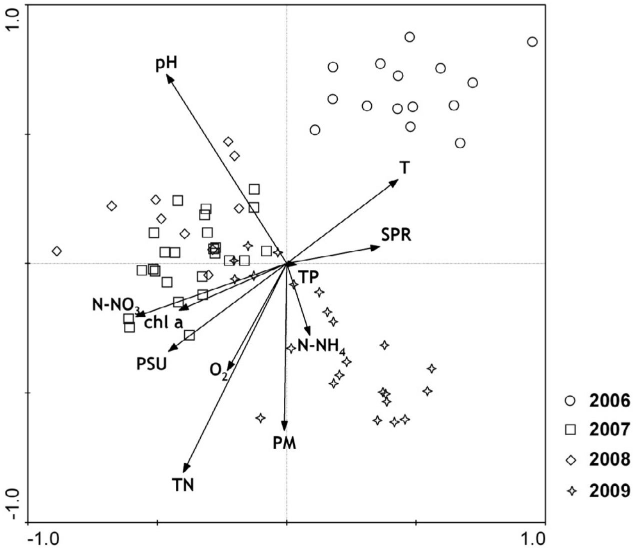

Figure 4 The CCA ordination diagram of samples and environmental variables (T, temperature; PSU, salinity; pH, water reaction; PM, particulate matter; chl a, chlorophyll *a*; O_2, dissolved oxygen; N-NO_3, nitrate nitrogen; N-NH_4, ammonium nitrogen; TN, total nitrogen; TP, total phosphorus; SPR, soluble reactive phosphorus).

4. Discussion

Variations in the physicochemical properties of water bring about changes in the composition and abundance of aquatic organisms. Different environmental factors play important roles in the development and abundance of zooplankton (Suresh et al., 2011). Plankton fauna are found across a wide range of environmental conditions, yet the presence of some species is limited by factors such as dissolved oxygen, pH, temperature, salinity, or other physical and/or chemical properties (Ahmad et al., 2011). In the study presented here, no distinct tendencies of zooplankton grouping depending on a given environmental parameter were observed. Some species showed a clear reaction to a given factor; *L. kindtii*, a water flea, was one of them with abundance increases at higher water temperatures. This regularity was confirmed under laboratory conditions by Vijverberg and Koelewijn (2004). These authors recorded growth rates that were comparable at 15°C, 17.5°C, and 20°C, but at higher temperatures (25°C) growth was distinctly faster. Bowersox et al. (2014) also observed the close relation between the occurrence of *Leptodora* and water temperature. Other species did not show any correlation with this parameter, which is surprising since many authors have proved that the abundance and species diversity of zooplankton depend on temperature (Cognetti and Maltagliati, 2000; Gophen, 2012; Kaya et al., 2010; Marques et al., 2006; Paturej, 2006; Sebastian et al., 2012; Stelzer, 1998). An analogical situation was observed for salinity. There were no significant relations between this parameter and the abundance of zooplankton, which contrasts with data in the literature that emphasize the impact of salinity on plankton fauna (Cognetti and Maltagliati, 2000; Dube et al., 2010; Gao et al., 2008; Laprise and Dodson, 1994; Marques et al., 2006; Paturej, 2005, 2009; Silva et al., 2009; Telesh and Khlebovich, 2010). This could be explained by the specificity of the lagoon studied, which is inhabited mainly by species with a high tolerance to wide salinity ranges. In the present study, these were euryhaline rotifers of freshwater origin such as the genera *Brachionus* and *Trichocerca* and the species of *K. cochlearis*, *F. longiseta*, and *Pompholyx sulcata* (Fontaneto et al., 2006). The copepods were represented by typically freshwater species, i.e., *E. affinis*, and marine species of *Acartia* genus — *A. tonsa* and *A. longiremis*. Water fleas were also found occasionally, because, as typically freshwater organisms, they do not tolerate high salinity (Boix et al., 2007, 2008; Brucet et al., 2009). Interestingly, there was a negative correlation between the abundance of *A. fissa*, *B. leydigii*, and *S. baltica* and water pH. These organisms demonstrate a high degree of tolerance to pH changes (Koste, 1978; Radwan et al., 2004); therefore, this must have resulted from the impact of another factor, for instance, predatory pressure or strong water currents. Rotifers play a very important role in estuarine environments (Holst et al., 1998; Margoński et al., 2006), and, in the present study, three dominant species comprised over 78% of the total numbers of zooplankton. Among them, only *F. longiseta* appears to have been affected mainly by ammonia concentrations, while influence of more than one of the measured environmental variables was noted with regard to the most abundant species of *K. cochlearis* (and its *tecta* form).

While analyzing the influence of physicochemical properties on the sampling sites, it was observed that the samples were grouped by years, which could have stemmed from a diversity of environmental variables that were noted in subsequent years of the study. In 2006, salinity was low and temperatures were high, whereas in 2009 pH was low. The results of CCA showed opposite directions in temperature and salinity gradients, which could suggest higher inflows of colder waters from the Baltic Sea in 2009 than in 2006. This could have had a marked influence on changes in zooplankton community structure between these two years. Different living conditions for plankton organisms form annually, which means that the clusters found in the lagoon do not have a fixed taxonomic "skeleton" and are formed and mixed depending on the abiotic factors in a given year that are, in turn, shaped by the varied impact of factors associated with the proximity of the open sea or freshwater inputs from rivers. Thus, the present study demonstrated that physicochemical properties played a major role in creating zooplankton species structure and could also significantly impact entire zooplankton clusters.

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References

Ahmad, U., Parveen, S., Khan, A.A., Kabir, H.A., Mola, H.R.A., Ganai, A.H., 2011. Zooplankton population in relation to physico-chemical factors of a sewage-fed pond of Aligarh (UP), India. BLM 3 (SI2), 336—341.

Alexander, R., (diss.) 2012. Interactions of zooplankton and phytoplankton with cyanobacteria. Univ. Nebraska, 69 pp.

Andrulewicz, E., Szymelfenig, M., Urbański, J., Węsławski, J.M., 2008. The Baltic Sea — What is Worth Knowing. Astra Print Shop, Gdynia, 113 pp., (in Polish).

Bednarz, T., Starzecka, A., Mazurkiewicz-Boroń, G., 2002. Microbiological processes accompanying the blooming of algae and cyanobacteria. Wiad. Botan. 46 (1—2), 45—55, (in Polish).

Boix, D., Gascón, S., Sala, J., Badosa, A., Brucet, S., López-Flores, R., Martinoy, M., Gifre, J., Quintana, X., 2008. Patterns of composition and species richness of crustaceans and aquatic insects along environmental gradients in Mediterranean water bodies. Hydrobiologia 597 (1), 53—69.

Boix, D., Sala, J., Gascón, S., Martinoy, M., Gifre, J., Brucet, S., Badosa, A., López-Flores, R., Quintana, X., 2007. Comparative diversity of crustaceans and aquatic insects from various water body types in coastal Mediterranean wetlands. Hydrobiologia 584 (1), 347—359.

Bowersox, B.J., Scarnecchia, D.L., Miller, S.E., 2014. Distribution, abundance and vertical migrations of *Leptodora kindtii* in a mainstream Missouri River reservoir, Montana, USA. J. Freshwater Ecol. 29 (2), 171—186.

Brucet, S., Boix, D., Gascón, S., Sala, J., Quintana, X.D., Badosa, A., Søndergaard, M., Lauridsen, T.L., Jeppesen, E., 2009. Species richness of crustacean zooplankton and trophic structure of brackish lagoons in contrasting climate zones: north temperate Denmark and Mediterranean Catalonia (Spain). Ecography 32 (4), 692—702.

Chubarenko, B., Margoński, P., 2008. The Vistula Lagoon. In: Schiewer, U. (Ed.), Ecology of Baltic Coastal Waters. Ecol. Stud. Springer-Verlag, Berlin-Heidelberg, 167—195.

Cognetti, G., Maltagliati, F., 2000. Biodiversity and adaptive mechanisms in brackish water fauna. Mar. Pollut. Bull. 40 (1), 7—14.

Cottenie, K., Nuytten, N., Michels, E., De Meester, L., 2001. Zooplankton community structure and environmental conditions in a set of interconnected ponds. Hydrobiologia 442 (1—3), 339—350.

Decker, M.B., Breitburg, D.L., Purcell, J.E., 2004. Effects of low dissolved oxygen on zooplankton predation by the ctenophore *Mnemiopsis leidyi*. Mar. Ecol.-Prog. Ser. 280, 163—172.

Dehui, Z., 1995. Effects of low pH on zooplankton in some suburban waterbodies of Chongqing City. J. Environ. Sci. 7 (1), 31—35.

Dmitrieva, O.A., Semenova, A.S., 2012. Seasonal dynamics and trophic interactions of phytoplankton and zooplankton in the Vistula Lagoon of the Baltic Sea. Oceanology 52 (6), 785—789.

Dube, A., Jayaraman, G., Rani, R., 2010. Modelling the effects of variable salinity on the temporal distribution of plankton in shallow coastal lagoons. J. Hydro-Environ. Res. 4 (3), 199—209.

Fontaneto, D., De Smet, W.H., Ricci, C., 2006. Rotifers in saltwater environments, re-evaluation of an inconspicuous taxon. J. Mar. Biol. Assoc. U.K. 86 (4), 623—656.

Gao, Q., Xu, Z., Zhuang, P., 2008. The relation between distribution of zooplankton and salinity in the Changjiang Estuary. Chin. J. Oceanol. Limnol. 26 (2), 178—185.

Golterman, H.L., Clymo, R.S., 1969. Methods for Chemical Analysis of Fresh Waters. Blackwell Scientific, Oxford, 172 pp.

González, E.J., Matos, M.L., Peñaherrera, C., Merayo, S., 2011. Zooplankton abundance, biomass and trophic state in some Venezuelan Reservoirs. In: Atazadeh, I. (Ed.), Biomass and Remote Sensing of Biomass. InTech, Rijeka, 57—74.

Gophen, M., 2012. The ecology of *Keratella cochlearis* in Lake Kinneret (Israel). Open J. Modern Hydrol. 2 (1), 1—6.

Hall, C.J., Burns, C.W., 2001. Effects of salinity and temperature on survival and reproduction of *Boeckella hamata* (Copepoda: Calanoida) from a periodically brackish lake. J. Plankton Res. 23 (1), 97—103.

Hermanowicz, W., Dojlido, J., Dożańska, W., Koziorowski, B., Zerbe, J., 1999. Physicochemical Analyses of Water and Sewage. Arkady, Warszawa, 556 pp., (in Polish).

Holst, H., Zimmermann, H., Kausch, H., Koste, W., 1998. Temporal and spatial dynamics of planktonic rotifers in the Elbe Estuary during spring. Estuar. Coast. Shelf Sci. 47 (3), 261—273.

ISO 10519:1997 (International Organization for Standardization), 1997. Determination of Chlorophyll Content. International Organization for Standardization, Switzerland, 24 pp.

Ivanova, M.B., Kazantseva, T.I., 2006. Effect of water pH and total dissolved solids on the species diversity of pelagic zooplankton in lakes: a statistical analysis. Russ. J. Ecol. 37 (4), 264—270.

Jongman, R.H.G., Ter Braak, C.J.F., Van Tongeren, O.F.R., 1995. Data Analysis in Community and Landscape Ecology. Cambridge Univ. Press, Cambridge, 324 pp.

Kasprzak, K., Niedbała, W., 1981. Biocenotic indicators in quantitative research. In: Górny, M., Grüm, L. (Eds.), Methods Applied in Soil Zoology, PWN, Warszawa, 397—416, (in Polish).

Kaya, M., Fontaneto, D., Segers, H., Altindağ, A., 2010. Temperature and salinity as interacting drivers of species richness of planktonic rotifers in Turkish continental waters. J. Limnol. 69 (2), 297—304.

Kinne, O., 1964. Physiologische und ökologische Aspekte des Lebens in Ästuarien. Helgoland. Wiss. Meer. 11 (3), 131—156.

Koste, W., 1978. Rotatoria. Die Rädertiere Mitteleuropas. Ein Bestimmungswerk, begründet von Max Voigt. Überordnung Monogononta. Gebrüder Borntraeger, Berlin-Stuttgart, 673 pp.

Kruk, M., Rychter, A., Mróz, M., 2012. The Vistula Lagoon. Environment and its Research in the VISLA Project. Wyd. PWSZ, Elbląg, 178 pp.

Kudari, V.A., Kanadami, R.D., 2008. Impact of changed trophic status on the zooplankton composition in six water bodies of Dharwad district, Karnataka state (South India). Environ. Monit. Assess. 144 (1—3), 301—313.

Lampert, U., 1997. Zooplankton research: the contribution of limnology to general ecological paradigms. Aquat. Ecol. 31 (1), 19—27.

Laprise, R., Dodson, J.J., 1994. Environmental variability as a factor controlling spatial patterns in distribution and species diversity of zooplankton in the St. Lawrence Estuary. Mar. Ecol.-Prog. Ser. 107, 67—81.

Margoński, P., Horbowa, K., Grzyb, A., Krajewska-Sołtys, A., Linkowski, T.B., 2006. Food composition of herring larvae in the Vistula Lagoon (southern Baltic Sea): impact of hydrological factors and changes in zooplankton community structure. ICES CM Documents 2006/F 03, 17 pp., http://www.ices.dk/sites/pub/CM%20Doccuments/2006/F/F0306.pdf.

Marques, S.C., Azeiteiro, U.M., Marques, J.C., Neto, J.M., Pardal, M. A., 2006. Zooplankton and ichthyoplankton communities in a temperate estuary: spatial and temporal patterns. J. Plankton Res. 28 (3), 297—312.

Mustapha, M.K., 2009. Zooplankton assemblage of Oyun Reservoir, Offa, Nigeria. Rev. Biol. Trop. 57 (4), 1027—1047.

Nawrocka, L., Kobos, J., 2011. The trophic state of the Vistula Lagoon: an assessment based on selected biotic and abiotic parameters according to the Water Framework. Oceanologia 53 (3), 881—894, http://dx.doi.org/10.5697/oc.53-3.881.

Ojaveer, H., Jaanus, A., MacKenzie, B., Martin, G., Olenin, S., Radziejewska, T., Telesh, I., Zettler, M.L., Zaiko, A., 2010. Status of biodiversity in the Baltic Sea. PLoS One 5 (9), http://dx.doi.org/10.1371/journal.pone.0012467.

Paturej, E., 2005. Zooplankton of seaside lakes in the coastal region of the Baltic Sea. Wyd. UWM, Olsztyn, 129 pp., (in Polish).

Paturej, E., 2006. Assessment of the trophic state of the coastal Lake Gardno based on community structure and zooplankton-related indices. Electr. J. Polish Agricult. Univ. 9 (2), http://www.ejpau.media.pl/volume9/issue2/art-17.html.

Paturej, E., 2009. A zooplankton-based study of coastal lakes. Baltic Coast. Zone 13 (2), 25—32.

Paturej, E., Kruk, M., 2011. The impact of environmental factors on zooplankton communities in the Vistula Lagoon. Oceanol. Hydrobiol. St. 40 (2), 37—48.

Perumal, V., Rajkumar, M., Perumal, P., Rajasekar, T.K., 2009. Seasonal variations of plankton diversity in the Kaduviyar estuary, Nagapattinam, southeast coast of India. J. Environ. Biol. 30 (6), 1035—1046.

Pinto-Coelho, R., Pinel-Alloul, B., Méthot, G., Havens, K.E., 2005. Crustacean zooplankton in lakes and reservoirs of temperate and tropical regions: variation with trophic status. Can. J. Fish. Aquat. Sci. 62 (2), 348—361.

PN 73/C-04576/08-1973, 1973. Water and sewage. Studies on the content of nitrogen compounds. Measuring nitrate nitrogen. Colorimetric method with phenol-disulphonic acid, 4 pp.

PN-C-04576-01:1976, 1976. Water and sewage. Studies on the content of nitrogen compounds. Measuring ammonium nitrogen with a colorimetric indol-phenolic method, 3 pp.

Psuty, I., Wilkońska, H., 2009. The stability of fish assemblages under unstable conditions: a ten year series from the Polish part of the Vistula Lagoon. Arch. Polish Fish. 17 (2), 65—76.

Radwan, S., Bielańska-Grajner, I., Ejsmont-Karabin, J., 2004. Rotifers (Rotifera). Wyd. Uniw. Łódz., Łódź, 447 pp., (in Polish).

Rajagopal, T., Thangamani, A., Sevarkodiyone, S.P., Sekar, M., Archunan, G., 2010. Zooplankton diversity and physico-chemical conditions in three perennial ponds of Virudhunagar district, Tamilnadu. J. Environ. Biol. 31 (3), 265—272.

Richardson, A.J., 2008. In hot water: zooplankton and climate change. ICES J. Mar. Sci. 65 (3), 279—295.

Roddie, B.D., Leakey, R.J.G., Berry, A.J., 1984. Salinity-temperature tolerance and osmoregulation in *Eurytemora affinis* (Poppe) (Copepoda: Calanoida) in relation to its distribution in the zooplankton of the upper reaches of the Forth estuary. J. Exp. Mar. Biol. Ecol. 79 (2), 191—211.

Rychter, A., Paturej, E., Jabłońska-Barna, I., 2011. Animals of the Vistula Lagoon. In: Kruk, M., Rychter, A., Mróz, M. (Eds.), Vistula Lagoon, 67—90, (in Polish).

Sebastian, P., Stibor, H., Berger, S., Diehl, S., 2012. Effects of water temperature and mixed layer depth on zooplankton body size. Mar. Biol. 159 (11), 2431—2440.

Silva, A.M.A., Barbosa, J.E.L., Medeiros, P.R., Rocha, R.M., Lucena-Filho, M.A., Silva, D.F., 2009. Zooplankton (Cladocera and Rotifera) variations along a horizontal salinity gradient and during two seasons (dry and rainy) in a tropical inverse estuary (Northeast Brazil). Pan-Am. J. Aquat. Sci. 4 (2), 226—238.

APHA, AWWA, WEF, Washington, D.C., 1496 pp.

Stelzer, C.P., 1998. Population growth in planktonic rotifers. Does temperature shift the competitive advantage for different species? Hydrobiologia 387—388, 349—353.

Suresh, S., Thirumala, S., Ravind, H.B., 2011. Zooplankton diversity and its relationship with physicochemical parameters in Kundavada Lake, of Davangere District, Karnataka, India. ProEnvironment 4 (7), 56—59.

Telesh, I.V., Khlebovich, V.V., 2010. Principal processes within the estuarine salinity gradient: a review. Mar. Pollut. Bull. 61 (4—6), 149—155.

Ter Braak, C.J.F., Šmilauer, P., 2002. CANOCO Reference Manual and User's Guide to Canoco for Windows: Software for Canonical Community Ordination (Version 4.5). Microcomputer Power, Ithaca, 500 pp.

Ter Braak, C.J.F., Šmilauer, P., 2003. Program CANOCO, Version 4.52. Biometris — Quantitative Methods in the Life and Earth Sciences. Plant Research International, Wageningen Univ. & Res. Centre, Wageningen.

Tischler, W., 1949. Grundzüge der terrestrischen Tierökologie. F. Vieweg & Sohn, Braunscheig, 220 pp.

Trojan, P., 1980. General Ecology. PWN, Warszawa, 419 pp., (in Polish).

Tunowski, J., 2009. Zooplankton structure in heated lakes with differing thermal regimes and water retention. Arch. Polish Fish. 17 (4), 291—303.

Vijverberg, J., Koelewijn, H.P., 2004. Effect of temperature on development and growth of the raptorial cladoceran *Leptodora kindtii* under laboratory conditions. Freshwater Biol. 49 (11), 1415—1422.

Wang, S., Xie, P., Wu, S., Wu, A., 2007. Crustacea zooplankton distribution patterns and their biomass as related to trophic indicators of 29 shallow subtropical lakes. Limnologica 37 (3), 242—249.

Warzocha, J., Szymanek, L., Witalis, B., Wodzinowski, T., 2016. The first report on the establishment and spread of the alien clam *Rangia cuneata* (Mactridae) in the Polish part of the Vistula Lagoon (southern Baltic). Oceanologia 58 (1), 54—58, http://dx.doi.org/10.1016/j.oceano.2015.10.001.

Witek, Z., Zalewski, M., Wielgat-Rychert, M., 2010. Nutrient stocks and fluxes in the Vistula Lagoon at the end of the twentieth century. Wyd. Nauk. Akad. Pom., Słupsk-Gdynia, 186 pp.

Yamada, Y., Ikeda, T., 1999. Acute toxicity of lowered pH to some oceanic zooplankton. Plankton Biol. Ecol. 46 (1), 62—67.

Yildiz, Ş., Altindağ, A., Ergönül, M.B., 2007. Seasonal fluctuations in the zooplankton composition of a eutrophic lake: Lake Marmara (Manisa, Turkey). Turk. J. Zool. 31 (2), 121—126.

Zar, J.H., 2010. Biostatistical Analysis. Prentice-Hall, New York, 944 pp.