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RESEARCH ARTICLE

Effects of salinity on species composition of zooplankton on Hau River, Mekong Delta, Vietnam

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Abstract – The area surrounding the Hau River is one of the most important aquaculture and fisheries areas in the Mekong Delta, Vietnam. Fish, shrimp farms and fishers rely of the natural zooplankton production in the incoming water to sustain production. Zooplankton samples were collected from July 2017 to June 2018 using a zooplankton net with mesh size of 60 μm at 3 sites on Hau river at Tran De (river mouth), Dai Ngai (midpoint) and Cai Con (farthest salt intrusion area on Hau river). Qualitative and quantitative samples of zooplankton together with salinity level were determined monthly at each sites. The salinity was found to fluctuate from 0 to 20‰ in the study area. A total of 137 zooplankton species were recorded including 26 species of Protozoa (19%), 47 species of Rotifera (34%), 12 species of Cladocera (9%), 44 species of Copepoda (32%) and 8 other taxon (6%). Copepod and rotifer prevailed with high densities (19.9×10^3 ind m^{-3} and 19.7×10^3 ind m^{-3}, respectively), whereas protozoa and cladocera were less abundant with 6.8×10^3 ind m^{-3} and 4.9×10^3 ind m^{-3}, respectively. When salinity increased to more than 5, protozoa and copepods were more abundant and reached a peak at 20 with 25.0×10^{36} ind m^{-3} and 53.0×10^3 ind m^{-3}, respectively. Regression analysis indicated that the density of zooplankton was significantly correlated to salinity variation. Protozoa and copepod were positively correlated with salinity, whereas cladocera and rotifer were negatively correlated with salinity. The impacts of climate change could exacerbate the seasonal fluctuations in salinity and zooplankton composition.

Keywords: Hau River / Mekong Delta / salinity changes / zooplankton composition / zooplankton structure

1 Introduction

Zooplankton communities are of the first important links of the food webs in aquatic ecosystems. Their functions also help balance the ecosystem, maintain and enhance biological productivity of a water body. In aquaculture, zooplankton are the primary food source with high nutritional value, which are indispensable during the larval rearing period of aquatic animals (Lavens and Sorgeloos, 1996; Das *et al.*, 2012) and in aquaculture ponds (Porchas-Cornejo *et al.*, 2013; Anton-Pardo and Adámek, 2015). Zooplankton, however are very sensitive to environmental changes. Any factor impacting on water body will affect the structure and abundance of zooplankton. Therefore changes in zooplankton structure or composition can be an indicator of changes of the environment. Many studies have showed that saline intrusion and salinity are important factors controlling species composition and biomass of zooplankton communities in coastal estuarine ecology (Valdes and Moral, 1998; Nielsen *et al.*, 2003; Anton-Pardo and Armengol, 2011; Steinberg *et al.*, 2015). Changes in zooplankton structure may result in changes in food webs which could affect the productivity of the ecosystems. Importance roles of zooplankton on fish and fisheries production both in natural and farmed conditions have been noticed by a quite number of researches. Fernando (1994) emphasized the importance of zooplankton to fish yields and fisheries in the tropic freshwater areas. Ludwig (1999) described the succession of zooplankton in a freshwater pond and stressed the improtance of rotifers as initially small prey of the young fish. Recently, Rajashree *et al.* (2017) mentioned the structure and important role of zooplankton in the rice fields as the natural food sources, especially cladocerans for fishes concurrently in this habitat. Amian (2018) also confirmed the indispensable role of zooplankton in which rotifers play as food source for fish larvae in the extensive fish ponds where

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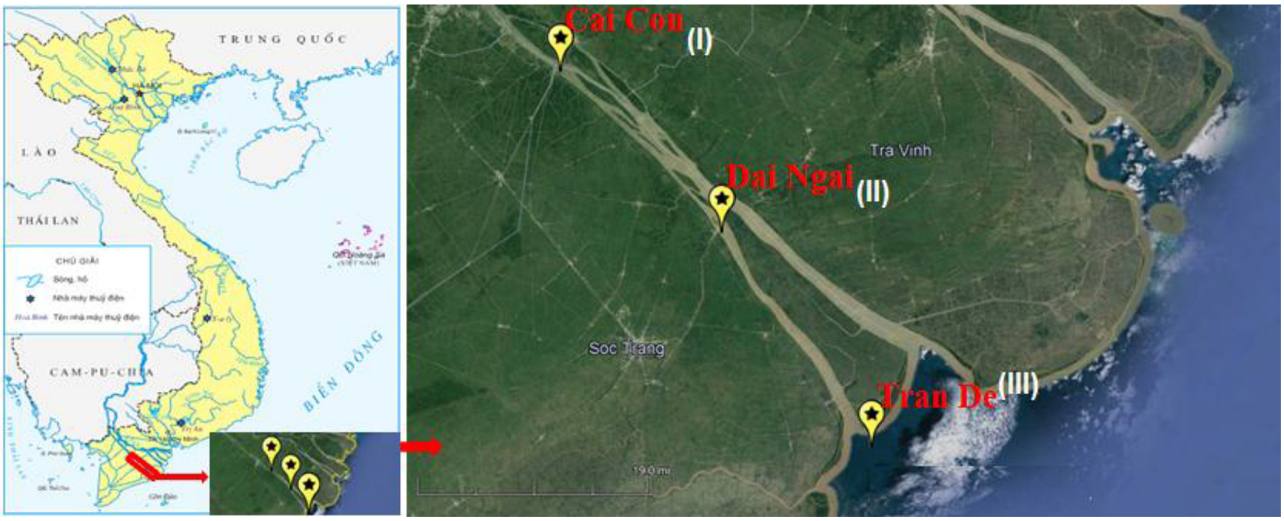

Fig. 1. Hau River and 3 sites (I, II, III) for zooplankton sampling.

they present with highest richness and abundance. In shrimp ponds, zooplankton were determined as the crucial natural food for the postlarvae immediately after stocking (Coman *et al.*, 2003; Anton-Pardo and Adámek, 2015).

Hau River is one of the two large tributaries of the Mekong River. It provides important ecosystem services to local people and it is crucial for the development of aquaculture in the Mekong Delta (Quyen and Amararatne, 2016). In recent years, saline intrusion has increased in the Mekong Delta in general and in Hau River basin in particularly. Severed intrusion of salinity in the Mekong Delta due to climate change, sea level rise and reduction of freshwater from the upstream in the dry season was projected by many studies (Hoanh *et al.*, 2003; Tuan *et al.*, 2007; Nhan *et al.*, 2007; Sunada, 2009). Recent report has confirmed the serious salt intrusion thriven not only by the above mentioned causes but also by other anthropogenic activities that exacerbate the circumstances in the Mekong Delta (Eslami *et al.*, 2019). It has caused substantial damage to agriculture and aquaculture in the region (Duyen *et al.*, 2012; Tri, 2016). Salinization may have a strong impact on the fisheries productivity as it changes the structure of zooplankton community and food webs. Productivity of freshwater fish farming systems such as rice-fish, fish pond culture along Hau River may be impacted. With a similar trend, fisheries production on this important river may also be affected. Little is known about the zooplankton composition on Hau River, especially in the estuary (Cho *et al.*, 2012; Lien *et al.*, 2014). Moreover, these studies focused mainly on species diversity and composition rather than structure variation under salinity changes. The aim of this study was therefore to provide data of changes in plankon in general and zooplankton in specific under salinity alterations especially severed salt intrusion by climate change impact in the Mekong Delta, Vietnam. Changes of zooplankton composition under salinity changes can reflect changes in zooplankton composition and food web structure and ultimately fish productivity. This discovery would for the first time provide important database for prediction of productivity due to zooplankton composition and abundance changes in the surrounding areas of Hau River, especially areas affected by salinity intrusion in the Mekong Delta.

2 Methods

2.1 Time and site of study

The study was conducted from July, 2017 to June, 2018 in the lower reaches of the Hau River belonging to Soc Trang province. As mentioned earlier, Hau River is the largest tributary of Mekong River and running through 4 provinces in the Vietnamese territory including An Giang (upper reach), Can Tho and Hau Giang (middle reach) and Soc Trang (lower reach) provinces which are parts of the Mekong Delta. The weather in the Mekong Delta is characterized by two distinct seasons, a rainy season (from May to October) and a dry season (from November to April). In the study area, zooplankton samples were collected monthly throughout the two seasons at 3 sites on Hau River: (I) Cai Con (9°55′48.9″- 105°54′02.6″) is the most upstream point of the river (about 60 km from the river mouth) that is reached by the saline intrusion that occurs during the dry season); (II) Dai Ngai (9°43′47.2″–106°04′52.4″) the middle site; and (III) Tran De river mouth (9°28′0.90″ – 106°14′35.5″) (Fig. 1).

2.2 Sample collection

Quantitative and qualitative zooplankton samples were collected at a depth of 30 cm at both at high tide and low tide as Hau River is featured with semi-tidal regime. The quantitative samples were taken by using a 20 L bucket to scoop water from different points within the sampling site and filtering through a 60 μm mesh size zooplankton net with a total volume of 400 L. The qualitative samples were collected by dragging the net along the sampling site for about 5 minutes. Both samples were preserved in 110 mL plastic bottles with formalin (38%) at 4-6% and transported to be analysed at the laboratories of

College of Aquaculture and Fisheries, Can Tho University. With each sample, salinity was also recorded using a refractometer at all sites and periods.

2.3 Sample analysis

Qualitative samples were analysed by identifying all zooplankton species using the published taxonomy keys including Shirota (1966), Chen (1980) and Dang *et al.* (2015). Densities (ind m^{-3}) of zooplankton were determined on the species basis using Sedgewick-Rafter and Bogorov counting chambers. Before counting the samples were screened through a 200 µm mesh size net. Large specimens were counted thoroughly by the Bogorov chamber and the rest was counted by the Sedgewick-Rafter chamber. Densities of each species of the four main zooplankton groups (Protozoa, Rotifera, Cladocera and Copepoda) were determined based on the following formula for the Sedgewick-Rafter chamber:

$$X = \frac{T * 1000 * V_{cd} * 10^6}{A * N * V_M}$$

where X density of zooplankton species (ind m^{-3}); T: number of individuals of each species counted, A: area of a counting square (1 mm^2); N: number of counting squares = 180; V_{cd}: sample concentrated volume (mL); V_M: sampling sample volume in the field.

Those counted by Bogorov chamber were determined with the following formula:

$$D = \frac{X}{V_M} \times 10^3$$

where D: density of zooplankton species (ind m^{-3}); X: number of individuals of each species counted; V_M: sampling sample volume in the field.

Total density of a species or group was a sum determined from the above two formulas.

Bio-indices including Margalef species richness (d), Shannon diversity index (H'), Simpson dominant species (λ) and Pielou similarity index (J') were applied to assess the structure of zooplankton community.

2.4 Data analysis

Data were analysed using different specialized software including SPSS 16.0, Primer 7.0.13, R 3.6 and R. studio. In order to fully assess the impact of salinity on the structure of the zooplankton community which is composed of only 4 main groups including Protozoa, Rotifera, Cladocera and Copepoda, analysis and assessment were carried out in two ways. Firstly, (i) the zooplankton composition was assessed at different salinity ranges based on species number (SN), percentage of appearance (%) of species which is the proportion of each zooplankton group to total species of zooplankton, population density (ind m^{-3}) of each group of zooplankton. Secondly, (ii) the distribution of species and community density of zooplankton was assessed at different salinity using correlation and regression analysis. The structure of zooplankton community at different salinities was analysed by PCA correlation and Discriminant function analysis. PCA analysis was used to assess the similarity of distribution of zooplankton species under the effect of different salinities. The purpose of Discriminant function analysis is to determine the relationship between salinity and density of 4 main zooplankton groups (not for other taxa). Positive or negative correlation of salinity to 4 zooplankton group densities (Protozoa, Rotifera, Cladocera and Copepoda) is expected. Densities (ind m^{-3}) of 4 zooplankton groups including Prorozoa (X_1), Rotifera (X_2), Cladocera (X_3) and Copepoda (X_4) are dependent factors and affected by fluctuation of salinity. Salinity range is the independent factor. Discriminant function analysis was started by computing the data of 4 plankton group densities as the independent variables (internal independence between 4 groups of zooplankton) and salinity data as the grouping variables. This analysis was completed by Fisher's test with a within group correlation to predict group of membership. From the results of Discriminant function analysis, an equation (Z) was built to predict the fluctuation of total zooplankton density based on 4 zooplankton groups which had been affected by salinity. The result of the output "Standardized Canonical Discriminant Function Coefficients" was used to calculate the equation (Z). In addition, the "Percent of variance of Eigenvalues" was used to explain the predictive power of the equation (Z). The predicted model result of total zooplankton density (ind m^{-3}) is expressed by equation (Z) as follow:

$$Z = \alpha_1 * X_1 + \alpha_2 * X_2 + \alpha_3 * X_3 + \alpha_4 * X_4$$

where Z: total zooplankton density (ind m^{-3}). Z is the predicted value when X_1, X_2, X_3, X_4 are fluctuated by salinities. X_1, X_2, X_3 and X_4: density (ind m^{-3}) of Protozoa, Rotifera, Cladocera and Copepoda, respectively. α_1, α_2, α_3 and α_4: coefficients of Protozoa, Rotifera, Cladocera and Copepoda, respectively which were outputted from the Discriminant function analysis.

3 Results

3.1 Fluctuation of salinity

Throughout the year, salinity recorded at 3 different sampling sites on Hau River revealed a strong seasonal fluctuation (Fig. 2).

From Figure 2, the actual salinity recorded at all sampling sites varied from 0 to 20. Salinity at Tran De was higher than that in Dai Ngai and salinity in Dai Ngai was higher than that in Cai Con. Salinity at high tide was higher than that at low tide.

In the rainy season which is from August to October, salinity was 0 at all sites and at both high and low tide (Fig. 2). However, in the early dry season in November salt intrusion started with 2 salinity detected at Tran De (river mouth). Increases in salinity were observed further landward from January onward. Strong saline intrusion occurred in the dry season from December to April. Highest salinity was recorded in March with 6 at Dai Ngai (ii) and 20 at Tran De (iii). At Cai Con, the farthest site from river mouth salinity reached a maximum of 1 at low tide and 2 at high tide in January is considered the most upstream point in the Hau River reached by the salinity intrusion. Salinity dropped sharply to 0 at three sampling sites at the beginning of the rainy season in June.

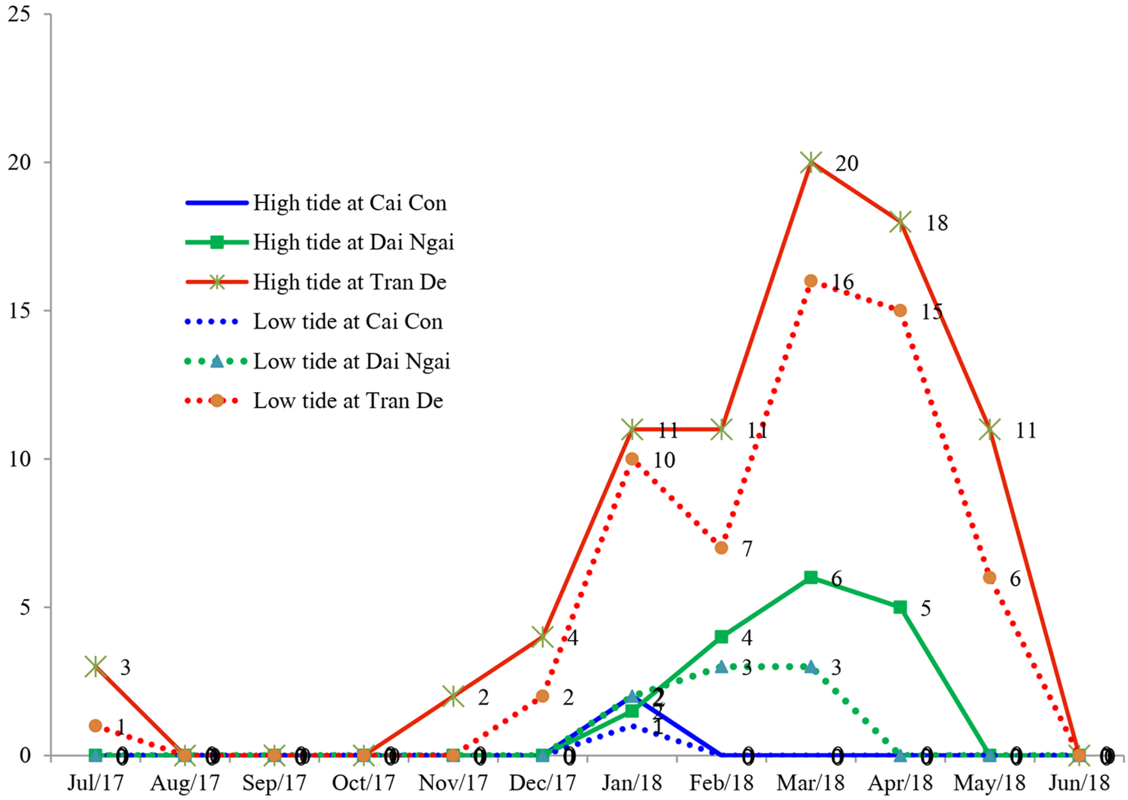

Fig. 2. Fluctuation of salinity on Hau River throughout sampling periods.

3.2 Composition of zooplankton on Hau River

3.2.1 Species composition and abundance

A total of 137 zooplankton species was recorded on Hau River in which 128 of them are holoplankton (see Appendix) including Rotifera accounting for highest number with 47 species (34%), followed by Copepoda with 44 species (32%), Protozoa, 26 species (19%) and Cladocera, 12 species (9%). In addition to the 4 main zooplankton groups, 8 other taxon (6%) were also noted as meroplankton including mollusc larvae, aquatic insects, Polychaeta, Nematoda and Chaetonagtha. Copepods and rotifers were the most abundant groups with the highest densities (19.9×10^3 ind m^{-3} and 19.7×10^3 ind m^{-3}, respectively), followed by protozoans (6.8×10^3 ind m^{-3}) and cladocerans (4.9×10^3 ind m^{-3}) (Fig. 3).

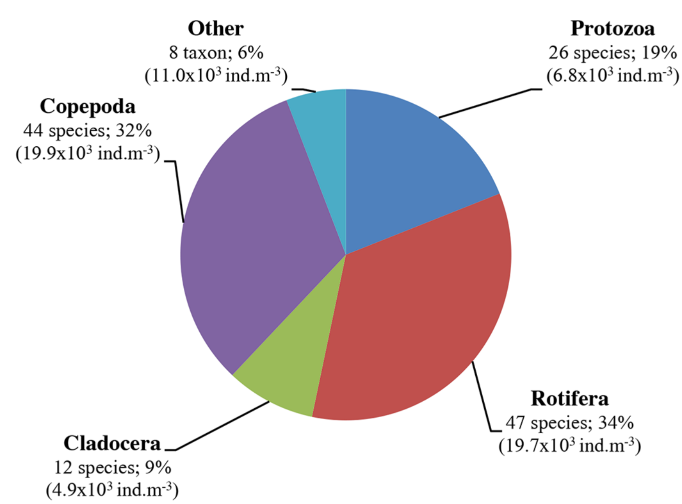

Fig. 3. Species composition and density (figures in the bracket) of zooplankton on Hau River.

3.2.2 Diversity and bio-indices

Figure 4 shows a difference in Cumulative Dominance and Species rank between cladocera and other groups (protozoa, rotifer and copepod) on the Hau River. Cumulative Dominance increased fastest with Species Rank for the cladocera, with relative increase more similar for other 3 groups. This relationship indicates that the impact of salinity by tide and by time has a different effect on the relationship between Cumulative Dominance and Species rank of zooplankton community.

Diversity of zooplankton community on Hau River was assessed through different biodiversity indices including *d*, J′, H′, λ and presented in Table 1.

The results from biodiversity index analysis show that the Magalef species richness (d) of Protozoa, Rotifera, Cladocera and Copepoda was always >5.0 and ranged from 5.0 to 5.85 (Tab. 1). This indicates that zooplankton composition on Hau River was quite diverse. Species richness of cladocera was highest among 4 zooplankton groups with a value of 5.85 indicating that Hau River is a typical freshwater ecosystem. Similar to *d*, the Shannon diversity index (*H*′) of 4 zooplankton groups was quite high ranging from 3.59 to 4.02.

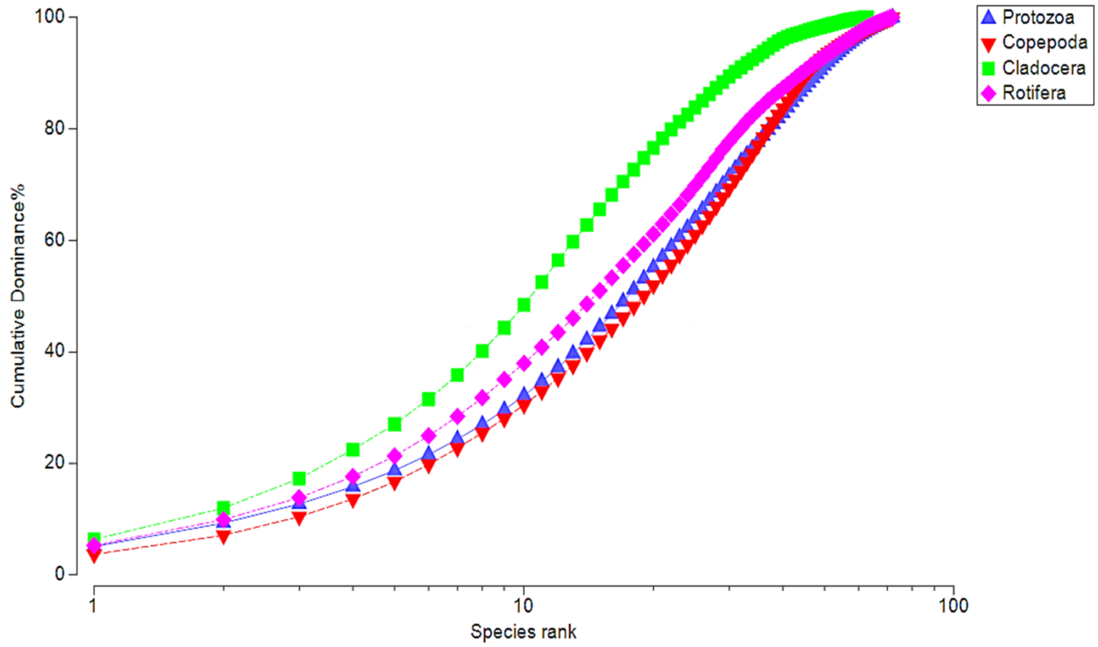

Fig. 4. Cumulative Dominance (%) and Species rank of 4 zooplankton groups on Hau River.

Table 1. Bio-indices of zooplankton on the Hau River.

Zooplankton	Bio-indices			
	d	*J′*	*H′*	λ
Protozoa	5.41	0.940	4.022	0.021
Rotifera	5.01	0.917	3.921	0.024
Cladocera	5.85	0.867	3.593	0.034
Copepoda	5.00	0.942	4.029	0.020

Highest *H′* was found for copepod, up to 4.03 (Tab. 1) indicating that copepod was a dominant zooplankton group in the river. In contrast, the *H′* of cladocera was lowest indicating that cladocera is less diverse compared to the other groups. The Pieloud similarity index (*J′*) presented in Table 1 shows that the *J′* index of zooplankton was in a range of 0.867 to 0.942. Highest *J′* index was found for copepod, reaching a peak of 0.942. This indicates that copepod has a highest similarity in the community. The similarity of cladocera was lowest with 0.867 (Tab. 1). Population structures of protozoa and rotifer were quite high in similarity as their *H′* index were high (0.940 and 0.917, respectively). The Simpson dominant species indices (λ) of zooplankton were quite low ranging from 0.20 to 0.43. It is clearly seen that copepod got a highest diversity among 4 groups of zooplankton and therefore obtained lowest λ of 0.020. In contrast, cladocera presented with lowest *J′* leading to a highest λ of 0.34. This proved that dominant species richness in cladocera population was lowest. The dominant species richness of protozoa and rotifer populations were relatively high with λ index of 0.021 and 0.024, respectively (Tab.1).

3.3 Zooplankton with salinity changes

3.3.1 Species composition structure

As salinity changed gradually with a range of 0 to 20, effects of salinity on zooplankton species structure were assessed. At different salinities, the species composition of zooplankton on Hau River was remarkably different indicating that the fluctuation of salinity resulted in a strong effect on zooplankton species composition (species number and occurrence percentage) on Hau River (Fig. 5). The number of rotifer and cladocera species varied with changes in salinity and tended to decrease with increasing salinity (0–20). At 0, rotifers were the most abundant group with 12 species (Fig. 5a) accounting for 49% of total zooplankton at all sampling sites. When salinity increased to 20 at the river mouth (Tran De) at high tide in March (Fig. 2), only one species of rotifer was recorded accounting for 5%. Cladocera was also found in most of the sites at 0 but a lower number of 3 species and only 12% by composition (Fig. 5a and 5b). However, when salinity increased to 10 at Tran De during low tide in January (Fig. 2), no species of cladocera was recorded.

Species number of protozoa and copepod also varied sharply with salinity changes. However, the fluctuation of these two groups was completely opposite to that of rotifer and cladocera as the number of species increased with increased salinity. Three species of protozoa were recorded at 3 in Dai Ngai (midpoint) at low tide in February to March and increased to 9 species at 20 in Tran De at high tide in March. Similarly, only 6 species of copepod were found at 0 but increased to 11 at 4, 10 at 11 and 10 species at 20 (Fig. 5).

The species structure of zooplankton on the Hau River was influenced by the changes in salinity as salt water intruded up the river. In freshwater rotifers were the most abundant group (49%). However, when salinity increased to the number of

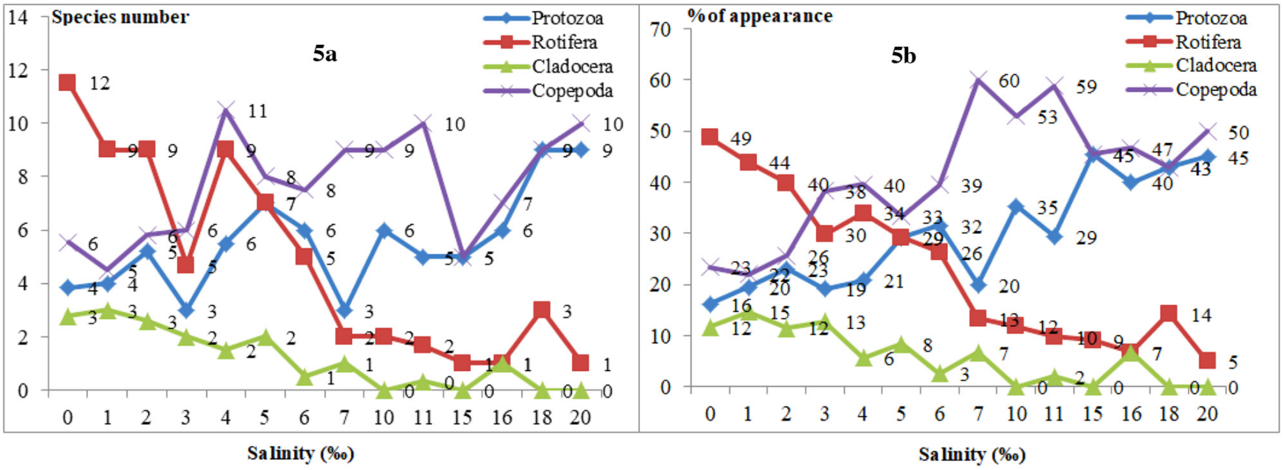

Fig. 5. Number of zooplankton species (5a), and % of appearance (5b) at different salinities

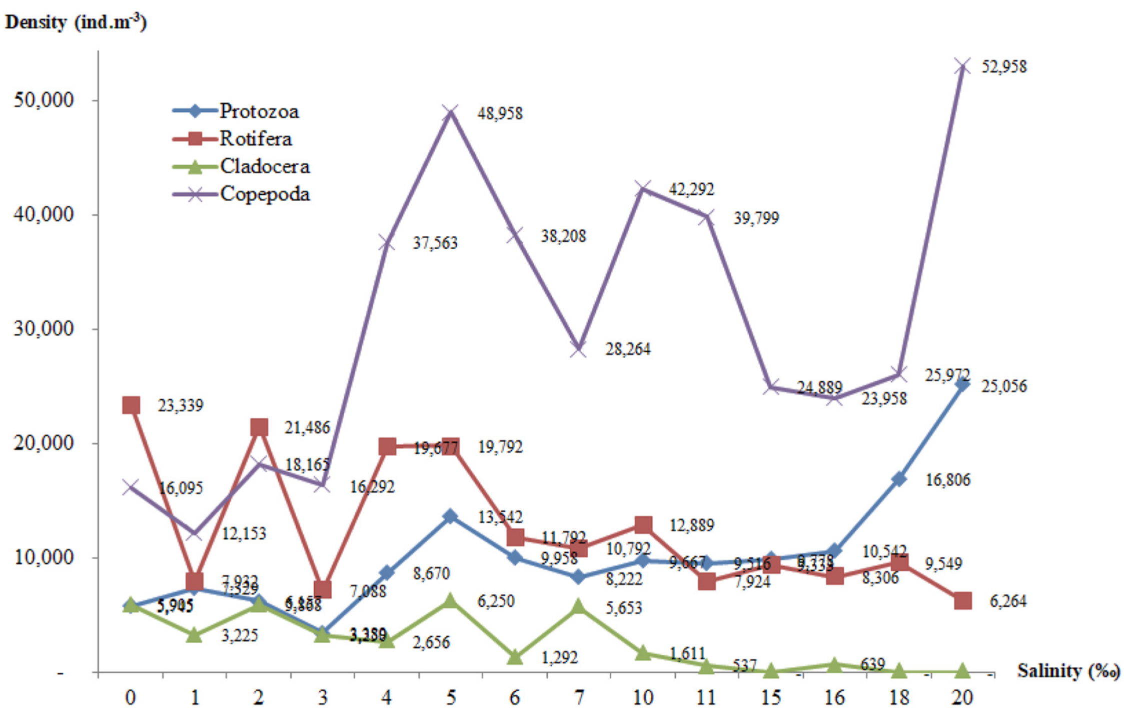

Fig. 6. Fluctuation of zooplankton densities at different salinities.

species and abundance of rotifers and cladocerans decreased. In contrast both species numbers and the species composition of copepods and protozoans increased with salinity (Fig. 5a,b).

3.3.2 Abundance

Similar to species composition structure, effects of salinity on abundance of zooplankton was also noticed (Fig. 6). Increased densities of protozoans and copepods were recorded as salinities increased from 0 to 20. However, the opposite was observed for rotifers and cladocerans. Protozoa densities ranged 3.4×10^3–25.0×10^3 ind m^{-3} in which lowest density (3.4×10^3 ind m^{-3}) was found at 3‰ in Dai Ngai at low tide from February to March (Fig. 2) and highest density (25.0×10^3 ind m^{-3}) recorded in Tran De at high tide in March when salinity reached 20. Rotifers were found more abundant (23.3×10^3 ind m^{-3}) at 0 than at 20 (6.3×10^3 ind m^{-3}). Density of cladocera was highest (6.2×10^3 ind m^{-3}) at 5 in Dai Ngai at high tide in April and reduced significantly at higher salinity (10) and were not present in the samples at salinities greater than 15. Copepods were the most abundant group in the river. When salinity was greater than 4, the density of copepod increased significantly and reached a peak of 53.0×10^3 ind m^{-3} at 20 at Tran De in March. However, when salinity decreased to less than 3, a substantial reduction in density of copepod was observed at 1 (12.1×10^3 ind m^{-3}) in Tran De at low tide in July.

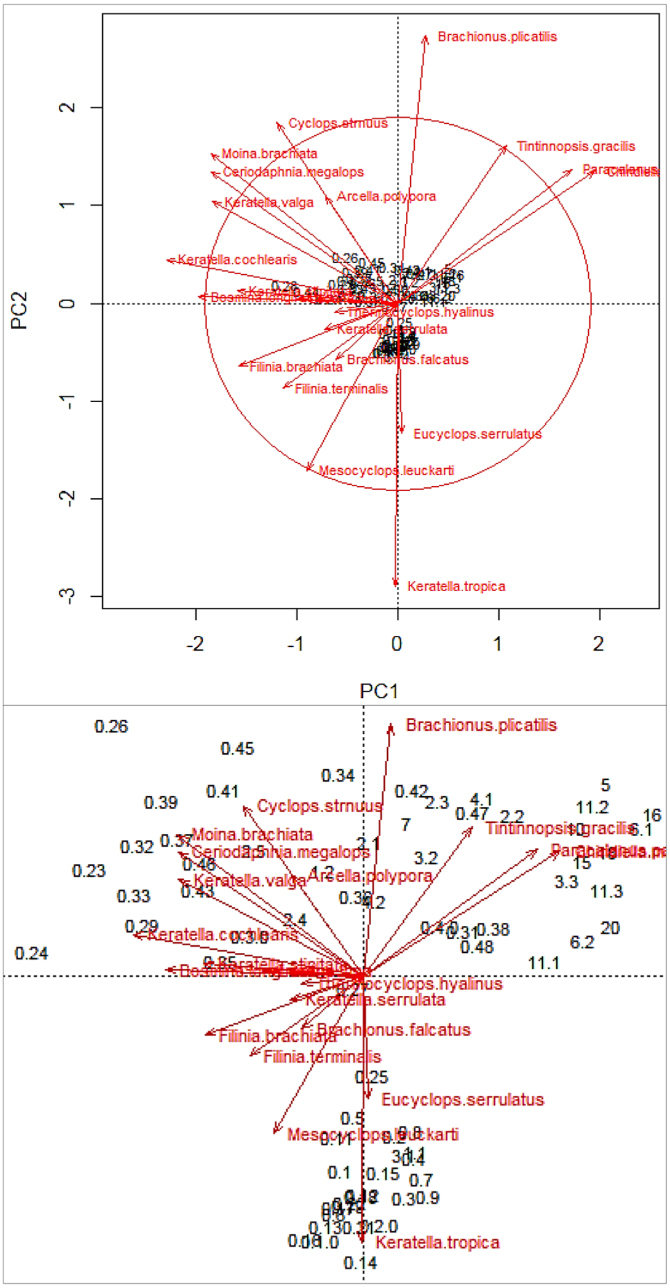

Fig. 7. PCA biplot of the Hellinger-transformed 21 zooplankton species under different salinities on Hau River (PC1 explained 24.8% var., PC2 explained 37.7% var.).

3.4 Correlation between salinity and distribution of zooplankton

3.4.1 Similarity in distribution at different salinities

Twenty one zooplankton species with high occurrence percentage and density (including 2 of protozoa, 10 of rotifer, 3 of cladocera and 6 of copepod) were selected for PCA analysis to assess the correlation between salinity and distribution of zooplankton.

The PCA results indicate that salinity was significantly correlated with distribution of zooplankton (Fig. 7) and when added together PC1 and PC2 explained 62.5% of all the variability in the data. Salinity was the main factor influencing the distribution of rotifer species (*Brachionus plicatilis* Muller, 1786, *Keratella tropica* Apstein, 1907 and *Keratella cochlearis* Gosse, 1851), copepods (*Paracalanus parvus* Claus, 1863, *Cyclops strenuus* Fischer, 1851, *Mesocyclops leuckarti* Claus, 1857, *Eucyclops serrulatus* Fischer, 1851), protozoans (*Tintinnopsis gracilis* Kofoid and Campbell, 1929) and cladoceans (*Moina brachiata* Jurine, 1820, *Ceriodaphnia megalops* Sars, 1890). In addition, *B. plicatilis* (rotifer) and *T. gracilis* (protozoa) were found to have similar distribution and broad expansion with sites and times at low salinities of 0–4. *P. parvus* and *Chiridiella macrodactyla* Sars, 1907 (calanoid copepods) were strongly associated with higher salinities (10–20). In contrast, *Eucyclops serrulatus* Fischer, 1851, *Mesocyclops leuckarti* Claus, 1857 (cyclopoid copepods) and *K. tropica* (rotifer) were more associated with lower salinity, especially 0. Similarly, *C. strenuus* (copepod), *M. brachiata, C. megalops* (cladocera), *Keratella valga* Ehrenberg, 1834 (rotifer), *Arcella polypora* Penard, 1890 (protozoa) were also associated with low salinity (0–2).

3.4.2 Regression model of zooplankton density under salinity changes

The Discriminant function analysis result showed that when salinity fluctuated from 0–20, density of Protozoa and Copepoda had a positive correlation with salinity whereas density of Rotifera and Cladocera was negatively correlated with salinity. Hence, total density (ind m^{-3}) of zooplankton was predicted by the following equation:

$$Z = 0.441 * X_1 - 0.784 * X_2 - 0.334 * X_3 + 0.889 * X_4 \quad (1)$$

($P < 0.001$, % of variance = 83.0%).

As salinity rises zooplankton abundance increases, Equation (1) indicated that this increase is driven by copepods and protozoans with corresponding declines in the numbers of rotifers and cladoceans.

4 Discussion

4.1 Fluctuation of salinity on Hau River

Salinity on the Hau river was found to vary seasonally becoming freshwater even in the river mouth during the rainy season in August and October. Highest salinities were noted in the dry season, where small increases in salinity were even noticed at the upper most sampling point (Cai Con) and more strongly at the river mouth (Tran De). Similar trend was also found by Binh *et al.* (2018) who concluded that salinity is regularly diminished upstream-ward on Hau River due to the dilution of freshwater flowing down from the upstream. In Tien River (another branch of Mekong River in MD), Hung *et al.* (2018) also reported that salinity of surface water decreased significantly from river mouth to upstream during July to October annually. However, salinity increases during the dry season from December to April as sea water intruded further landward. This increased salinity occurred stronger at high tide than low tide. This phenomenon was also observed by Binh *et al.* (2018) on Hau River where saline intrusion was recorded much further at high tide. Salinization is reported to be an increasing problem in the Mekong Delta (Dat *et al.*, 2012; CCAFS-SEA, 2016; Anh *et al.*, 2018) having significant impact on crop production, freshwater supplies and freshwater ecosystems. Reduction of flow caused by climate change and anthropogenic activities, especially upstream dam construction may exacerbate problem of saline intrusion in the Mekong Delta. Although water flow and hydrological regimes are dependent upon many factors and complicated to predict (Dat and Likitdecharote, 2010 and Dat *et al.*, 2012), the flow can be described mathematically and modelled by using computer simulation (MRC, 2009) which is commonly useful tool to predict salt intrusion under flow reduction, sea level rise or climate changes (Dat *et al.*, 2012; Long *et al.*, 2016; Li *et al.*, 2017).

4.2 Effects of salinity on composition structure of zooplankton on Hau River

Ecologically, salinization or increased salinity would change the composition and densities of zooplankton (Zorina-Sakharova *et al.*, 2014; Paturej and Gutkowska, 2015; Tavsanoglu *et al.*, 2015). Gao *et al.* (2008) indicated that variation of salinity in the estuary resulting in regional and seasonal alteration of dominant species. This is true for the fact that zooplankton composition changed obviously from the river mouth to landward areas along Hau River with variable salinity. At low salinity range of 0–2, rotifers were most abundant with highest number of species. This record is consistent with results found by Zakaria *et al.* (2007) and Zorina-Sakharova *et al.* (2014) that in low-salinity water, rotifers are dominated in zooplankton communities. In addition, Bielanska-Grajner and Cudak (2014) also emphasized that in low-salinity water environments (less than 0.5), diversity of zooplankton depends on species of rotifers as low salinity or light-saline intrusion is the optimum conditions for rotifer populations to expand. Herzig (1987) also stated that rotifers were suitable for thriving in freshwater or low salinity. Another study in the estuary of north-eastern Brazil by Silva *et al.* (2009) also confirmed a rich species composition of rotifers recorded in the rainy season, when freshwater from inland areas flowed out and reduced salinity in the estuary. Similar to rotifers, cladocera was a zooplankton group that thrived at most of the sampling sites with low salinity (less than 5) on Hau River. This phenomenon was also recorded in the study of Spoljar *et al.* (2018) that cladocera was a typical group growing in freshwater or low salinity. When salinity in the estuary decreased due to rain, the species composition of cladocera became richer (Silva *et al.*, 2009).

When saline intrusion occurred in the dry season, salinity increased to more than 7. The composition of zooplankton community changed remarkably from Dai Ngai to Tran De (from medium salinity to high salinity). Number of species and densities of protozoa and copepods consequently became richer whilst abundance (both species number and densities) of rotifers and clacocera decreased sharply. This explains positive and negative correlation to salinity of 2 distinct groups including protozoa and copepods, and rotifers and cladocera, respectively on Hau River. This trend was also described by Zakaria *et al.* (2007) and Spoljar *et al.* (2018) that rotifers and clacocera had a negative correlation with salinity while protozoa and copepods displayed a positive correlation with salinity. At 9, zooplankton composition structure was most stable and copepods were dominant with calanoids and harpactoids (Werba, 2016). In this study both calanoids and cyclopoids were found and the PCA analysis revealed clearly the distribution of these groups related to salinity. *Paracalanus parvus* and *Chiridiella macrodactyla* are calanoids and found at higher salinity (>10) while *Eucyclops serrulatus, Mesocyclops leuckarti, Cylops strennus* are cyclopoids and characterized with freshwater. Zakaria *et al.* (2007) also confirmed *Paracalanus parvus* grew strongly in high salinity water environments around more than 38.5. Other species of calanoids such as *Arcatia tonsa* Dana, 1849 was also recorded to well adapt to salinity from 15 to 20 (Cervetto *et al.*, 1999). Abundance of copepods was also observed increasing with salinity increasing (Qian *et al.*, 2008; Raybaud *et al.*, 2008; Toruan, 2012; He, 2012; Prado *et al.*, 2017). However, increasing of salinity lead to decrease or disappear of cladocera species (Anton-Pardo and Armengol, 2011). Another study had also emphasized that increased salinity would reduce species richness of cladocera, especially within 7–9 (Zorina-Sakharova *et al.*, 2014). Similar to copepods, abundance of protozoa on Hau River was also positively increasing with increased salinity. When studying on the effects of salinity on structure of zooplankton community in Cu Lao Dung mangrove in Soc Trang province (in Mekong Delta), Lien *et al.* (2013) found that in the rainy season with low salinity (2–5), protozoa occurred with a proportion of 25% of zooplankton composition, but in the dry season when salinity decreased, the percentage of occurrence of protozoa increased to 50%.

In general, at higher salinity conditions, especially at Tran De estuary in the dry season, copepods were more abundant both in species number and density on Hau River. This finding is consistent to previous studies in different areas in the world as well as in Vietnam. For example copepods also increased with increasing salinity in Mondego estuary of Portugal (Vieira *et al.*, 2003), in Aiguamolls de l'Emporda wetland of Spain (Balmana, 2004) and in the coastal area of the Mekong Delta, Vietnam from Soc Trang to Bac Lieu (Van *et al.*, 2012).

Changing in zooplankton community in freshwater area leads to reduction of cultured fish production as the preferred preys (rotifers and cladocera) are replaced by unsuitable copepods or protozoa. Whereas, in the brackishwaters copepods are more preferably consumed by brackishwater fish or shrimp (Anton-Pardo and Adámek, 2015). Thus, there could be some advantages to marine or brackishwater fish species but more disadvantages to freshwater ones under salinization. Regardless of the direct impacts, an ecosystem must have been significantly altered ecologically as a whole. In the ecosystem, not only changes in zooplankton composition but more importantly in phytoplankton which are the food source of zooplankton. Changes in species composition of phytoplankton could negatively impact on the ecosystem and its surrounding environment as more dinoflagellates may invade with higher salinity into the estuaries. Dinoflagellates are also classified as protists (Ruppert and Barnes, 1994) more abundant in the coastal marine waters and many of them can produce toxins (Graham and Wilcox, 2000). Larsen and Nguyen (2004) described 70 species of potentially harmful microalgae from Vietnamese coastal waters including the Mekong estuary. Among these species, 75% are dinoflagellates. In addition to alteration of food web structure, effects of harmful dinoflagellates to aquaculture, especially shellfish culture are of much concern along the coastal areas (Matsuyama, 1999).

In conclusion, the structure of zooplankton species on lower reach of Hau River was typical of freshwater or oligohaline community in the rainy season. However, the composition structure changed with the saline intrusion during the dry season. As stronger saline intrusion are predicted to occur under impacts of upstream dam construction and climate change (less rain, drought, sea level rises) the zooplankton community might one day be characterised as brackish water. Only a small increase in salinity can cause significant upheavals in the zooplankton community as rotifers and cladocera were predominant in water of less than 5, while copepods dominated in all salinities of more than 5. These changes in zooplankton community could have significant impacts on Mekong Delta ecosystem including the fish populations in the Mekong Delta and the livelihoods of stakeholders.

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Appendix

List of 128 species belonging to four main zooplankton groups including Protozoa, Rotifera, Cladocera and Copepoda found in the estuarine areas of Hau River, Mekong Delta, Vietnam.

Protozoa	
1	*Arcella polypora* Penard, 1890
2	*Arcella vulgaris* Ehrenberg, 1830
3	*Centropyxis aculeata* (Ehrenberg, 1838)
4	*Centropyxis ecornis* Leidy, 1879
5	*Codonella amphorella* Biedermann, 1893
6	*Codonella aspera* Kofoid and Campbell, 1929
7	*Codonella morchella* Cleve, 1900
8	*Difflugia acuminata* Ehrenberg, 1838
9	*Difflugia corona* Wallich, 1864
10	*Difflugia oblonga* Ehrenberg, 1838
11	*Favella azorica* (Cleve, 1900)
12	*Favella fistulicauda* Jorgensen, 1924
13	*Tintinnidium fluviatile* Stein, 1863
14	*Tintinnidium neapolitanum* Daday, 1887
15	*Tintinnopsis cylindrata* Kofoid and Campbell, 1892
16	*Tintinnopsis gracilis* Kofoid and Campbell, 1929
17	*Tintinnopsis lacustris* Brandt, 1906
18	*Tintinnopsis lobiancoi* Daday, 1887
19	*Tintinnopsis nucula* (Fol, 1884)
20	*Tintinnopsis parvula* Jorgensen, 1912
21	*Tintinnopsis radix* (Imhof, 1886)
22	*Tintinnopsis tocantinensis* Kofoid and Campbell, 1929
23	*Xystonella longicauda* (Brandt, 1906)
24	*Difflugia* sp.
25	*Tintinnopsis* sp.
26	*Zoothamnium* sp.
Rotifera	
27	*Asplanchnopus myrmeleo* (Ehrenberg, 1834)
28	*Asplanchna priodonta* Gosse, 1850
29	*Asplanchnopus multiceps* (Schrank, 1793)
30	*Brachionus angularis* (Gosse, 1851)
31	*Brachionus bakeri* Ehrenberg, 1907
32	*Brachionus bidentata* (Anderson, 1889)
33	*Brachionus budapestinensis* Daday, 1885
34	*Brachionus calyciflorus* Pallas, 1766
35	*Brachionus caudatus* Barrois and Daday, 1894
36	*Brachionus diversicornis* (Daday, 1883)
37	*Brachionus falcatus* Zacharias, 1898
38	*Brachionus forficula* (Wierzejski, 1891)
39	*Brachionus pala* Ehrenberg, 1907
40	*Brachionus plicatilis* Muller, 1786
41	*Brachionus quadridentatus* Hermann, 1783
42	*Brachionus rubens* (Ehrenberg, 1838)
43	*Elosa woralli* Lord, 1891
44	*Filinia brachiata* (Rousselet, 1901)
45	*Filina longiseta (*Ehrenberg, 1834)
46	*Filinia opoliensis* (Zacharias,1898)
47	*Filinia terminalis* (Plate, 1886)
48	*Keratella cochlearis* (Gosse, 1851)
49	*Keratella hiemalis* (Carlin, 1943)
50	*Keratella quadrata* (Muller, 1786)
51	*Keratella serrulata* (Ehrenberg, 1838)
52	*Keratella stipitata* Ehrenberg, 1838
53	*Keratella tropica* (Apstein, 1907)
54	*Keratella valga* (Ehrenberg, 1834)
55	*Lecane bulla* (Gosse, 1851)
56	*Lecane crenata* (Harring, 1913)
57	*Lecane elasma* Harring and Myers, 1926
58	*Lecane hastata* (Murray, 1913)
59	*Lecane leontina (*Turner, 1892)
60	*Lecane luna* (Muller, 1776)
61	*Monostyla lunaris* (Ehrenberg, 1832)
62	*Philodina roseola* Ehrenberg, 1832
63	*Platyias patulus* (Muller, 1786)
64	*Platyias quadricornis* (Ehrenberg, 1832)
65	*Ploesoma lenticulare* Herrick, 1885
66	*Ploesoma truncatum* (Levander, 1894)
67	*Polyarthra vulgaris* Carlin, 1943
68	*Testudinella patina* (Hermann, 1783)
69	*Trichocerca cylindrica* (Imhof, 1891)
70	*Trichocerca longiseta* (Schrank, 1802)
71	*Ploesoma* sp.
72	*Polyarthra* sp.
73	*Trichocerca* sp.
Cladocera	
74	*Bosmina coregoni* Lilljeborg, 1900
75	*Bosmina longirostris* (Muller, 1785)
76	*Ceriodaphnia lacustris* Birge, 1893
77	*Ceriodaphnia megalops* Sars, 1890
78	*Ceriodaphnia rigaudi* Richard, 1984
79	*Diaphanosoma brachyurum* (Lievin, 1848)
80	*Moina brachiata* (Jurine, 1820)
81	*Moina rectirostris* var. *casani* Arevalo, 1920
82	*Penilia schmackeri* Richard, 1895
83	*Pseudosida bidentata* Herrick, 1884
84	*Macrothrix* sp.
85	*Moina* sp.
Copepoda	
86	*Acartia discaudata* (Giesbrecht, 1882)
87	*Acartia tonsa* Dana, 1849
88	*Calanus minor* (Claus, 1863)
89	*Calanus vulgaris* (Dana, 1849)
90	*Candacia pachydactyla* (Dana, 1849)
91	*Canthocamptus staphylinus* (Jurine, 1820)
92	*Centropages violaceus* (Claus, 1863)
93	*Chiridiella macrodactyla* Sars, 1907
94	*Cyclops magnus* Marsh, 1920
95	*Cyclops strnuus* (Fischer, 1851)
96	*Cyclops vicinus* Uljanin, 1875
97	*Diaptomus connexus* Light, 1938
98	*Diaptomus kenai* Wilson, 1953
99	*Diaptomus siciloides* Lilljeborg, 1889
100	*Eodiaptomus japonicus* (Burckhardt, 1913)
101	*Euaugaptilus gibbus* (Wolfenden, 1904)
102	*Euaugaptilus oblongus* (Sars, 1905)
103	*Euchirella maxima* Wolfenden, 1905
104	*Eucyclops agilis* Koch, 1838)
105	*Eucyclops macrurus* (Sars, 1863)
106	*Eucyclops serrulatus* (Fischer, 1851)
107	*Hemicyclops japonicus* Itoh and Nishida, 1993
108	*Lucicutia atlantica* Wolfenden, 1904
109	*Macrocyclops fuscus* (Jurine, 1820)
110	*Macrosetella gracilis* (Dana, 1846)
111	*Megacalanus princeps* Wolfenden, 1904
112	*Mesocyclops leuckarti* (Claus, 1857)
113	*Mesocyclops oithonoides* (Sars, 1863)
114	*Oithona nana* Giesbrecht, 1892
115	*Oithona robusta* Giesbrecht, 1891
116	*Paracalanus aculeatus* Giesbrecht, 1888
117	*Paracalanus parvus* (Claus, 1863)
118	*Scaphocalanus magnus* (Scott, 1894)
119	*Sinodiaptomus chaffanjoni* (Richard, 1897)
120	*Sinodiaptomus sarsi* (Rylov, 1923)
121	*Temora turbinata* (Dana, 1849)
122	*Thermocyclops hyalinus* (Rehberg, 1880)
123	*Tortanus gracilis* (Brady, 1883)
124	*Tropocyclops parasinus* Fischer, 1860
125	*Acartia* sp.
126	*Calanus* sp.
127	*Diaptomus* sp.
128	*Oithona* sp.