Seasonal fluctuation of water quality parameters and zooplankton composition in the Hau River and its tributaries, Vietnam

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Abstract. The objective of this study was to determine the seasonal fluctuation of water quality elements and zooplankton composition in the Hau river, Vietnam. The study was conducted four times a year in An Giang, Can Tho, and Soc Trang provinces. Sampling was conducted at 29 sites, including 14 sites on the main river and 15 sites on its tributaries. The mean temperature, pH, dissolved oxygen (DO) and biological oxygen demand (BOD) concentrations at sampling locations did not change significantly between the dry and rainy seasons. Nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations in the dry season were higher than those in the rainy season. A total of 148 zooplankton species was recorded. Among them, Rotifera was the most abundant group, with 52 species, followed by Protozoa with 48 species, and the others ranging from 10 to 22 species. The species composition of zooplankton in the tributaries was higher than in the main river. At the same time, species composition in the rainy season was higher than in the dry season. The densities of Copepoda, Rotifera, Cladocera, and Copepod's nauplii were found to have significant negative correlations with NO_3^- concentrations ($p < 0.05$). However, close correlations were not recorded between these organisms and concentrations of chemical oxygen demand (COD) and total phosphorus (TP) in the Hau River. The Shannon-Wiener diversity index (H') fluctuated from 1.6 to 3.2 and Margalef's richness index (D) fluctuated from 0.9 to 4.6 indicating that the pollution level of the study area was from light to β-moderate pollution. The results of this study provided a reference for studying the composition and distribution of seasonal zooplankton communities, water quality characteristics, and pollution levels in the Hau River.
Key Words: biodiversity, Hau River, species composition, water quality parameters, zooplankton.

Introduction. The Mekong Delta is well known for its dense system of rivers and canals, which provides the most favorable conditions for the growth and evolution of aquatic fauna and flora. This also results in diversity of these communities. The delta is currently facing many water-related challenges and opportunities. External challenges consist of water regulation and land use changes in riparian countries, which could alter the flow of the Mekong's branches in the delta. The delta is also seriously threatened by climate change-induced sea level rise (Wassmann et al 2004), which negatively impacts some of the existing production systems in coastal areas and further inland. Serious pollution problems, induced by agricultural, industrial, and urban activities, are also emerging in the delta. The main agricultural activities linked to water pollution in the Mekong Delta are land preparation (e.g., puddling), fertilizer and pesticide use, waste water release from animal production (mainly pigs and poultry) and aquaculture (mainly fish and shrimp) (Renaud & Kuenzer 2012). The Hau River is the biggest branch of the Mekong River in the lower basin, with a length of 226 km. The Hau River flows through different areas of the Mekong Delta (MD), including An Giang, Can Tho, Hau Giang, and Soc Trang, carrying substantial aquatic resources that contribute significantly to the freshwater fishery production of the region, in which fish is the main and vital component (Vu et al 2015). Consequently, the Hau River (the last part of the Mekong River before emptying into the East Sea) is polluted by organic, chemical, and microbiological substances (Renaud & Kuenzer 2012). The above activities affect water quality and aquatic organisms like zooplankton and phytoplankton, in which zooplankton plays an important role in aquaculture, including being an indicator that determines water quality, pollution, and the state of eutrophication (Saler 2004). Zooplankton communities often vary in composition as certain species are highly sensitive to changes in nutrient cycling, temperature, and variable environmental conditions (Primo et al 2015). According to Dorche et al (2018), zooplankton communities generally change in response to the quality of water. Zooplankton are microscopic animals that are represented mostly by crustaceans, rotifers, and protozoans. They include both primary consumers that feed on phytoplankton and secondary consumers that feed on other zooplankton. Freshwater zooplankton are an important biological component in aquatic ecosystems, whose main function is to act as a primary and secondary link in the food chain, and play a vital role in the energy transfer of aquatic ecosystems (Altaff 2004). They are assumed to be a vital part in indicating water quality, eutrophication, and production of a freshwater body. In order to determine the status of a freshwater body, it is necessary to measure seasonal variations and the presence of zooplankton (Zannatul & Muktadir 2009). Therefore, the main objective of this research was to determine the seasonal fluctuation of water quality elements and zooplankton composition in the Hau River, Vietnam. This study provides crucial theoretical support for water quality assessment and long-term watershed management in the Hau River and other similar rivers.

Material and Method

Description of the study area. The study was conducted on the Hau River which is the most important tributary of the Mekong River in the lower basin. With a length of 226 km, Hau River flows through different areas of the Mekong Delta including An Giang (AG), Can Tho (CT), and Soc Trang (ST) provinces. The river also serves as the main line of drainage for rainwater and flood. Recently, Hau River has received many different effluents from industrial, agricultural, and domestic activities of human beings. The weather in the Mekong Delta is characterized by two distinct seasons: rainy season (RS) (from May to October) and dry season (DS) (from November to April). In the study area, zooplankton and water samples were collected from three provinces along the Hau River, starting from An Giang (upstream) with ten sites (1-10), Can Tho (middle stream) with nine sites (11-19), and Soc Trang (downstream) with ten sites (20-29) (Figure 1). A total of 29 sampling sites were selected including 14 locations on the main river (MR) and 15 locations on its tributaries (TR). Selection of the sampling sites was based on the influences of effluents coming from various activities including residential, aquaculture, agriculture, and industrial zones.

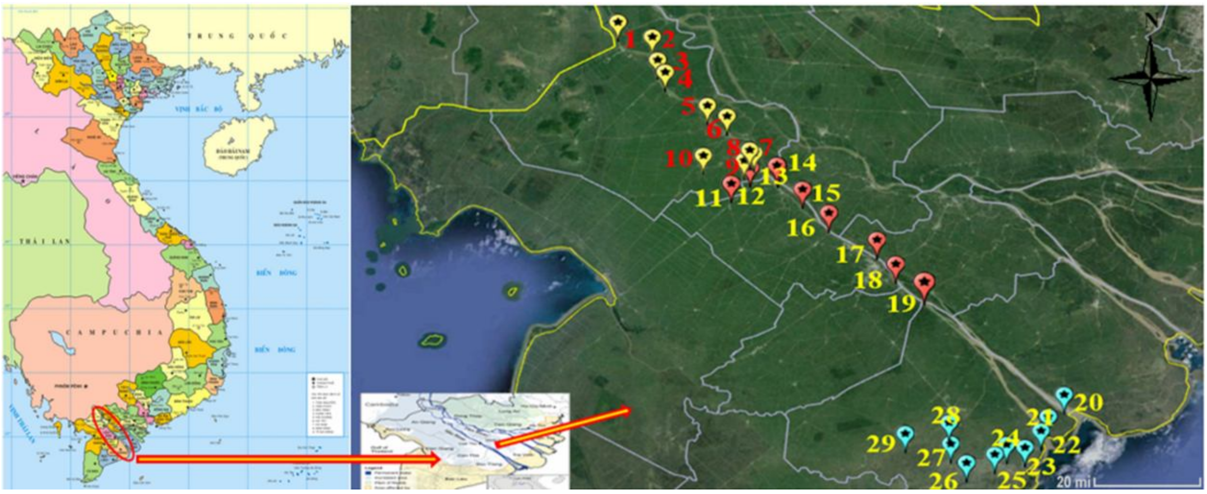


Figure 1. Sampling sites on the Hau River.

Samples were taken four times a year in March, June, September, and December of 2019 and interpreted seasonally, like dry season (March–December) and rainy season (June-September). At each sampling site, samples were collected at two inshore points and one point in the middle of the river. For the mainstream (Hau River), samples were collected at one inshore point and one point in the middle at a depth of 30-40 cm.

Analysis and sampling methods. Water quality parameters were collected at the same time with zooplankton samples. Temperature, pH, salinity, and dissolved oxygen (DO) concentrations were directly measured at the sampling locations by the Hana Multiparameter HI9828. Biological oxygen demand (BOD), total suspended solids (TSS), total ammonia nitrogen (TAN), nitrate (NO_3^-), total phosphorus (TP), total nitrogen (TN), and PO_4^{3-} concentrations were collected and stored at 4°C in a 1-L plastic bottle and analyzed in the laboratory (Table 1).

Table 1

Sampling and analysis methods of some water quality parameters

No.	*Parameters (mg L^{-1})*	*Analytical methods*
1	TSS	Samples were filtered through a glass fiber filter paper (diameter of 47mm) with a filter size of 0.45 µm and dried at 105°C (2540-D) (APHA 2017)
2	BOD	APHA (2017)
3	TAN	Indo-phenol Bluemethod (APHA 2017)
4	NO_3^-	Sulfosalicylic acid method (ISO 7890-3:1988 (E))
5	TN	Sample digestion by the Macro-Kjeldahl method (4500-N_{org} B), then colorimetric by the Indo-phenol Blue method (APHA 2017)
6	PO_4^{3-}	$SnCl_2$ method (4500-P-D) (APHA 2017)
7	TP	Sample digestion by the Kjeldahl method (Patton & Truitt 1992), then colorimetric by the $SnCl_2$ method (4500-P-D) (APHA 2017)

Qualitative samples of zooplankton were collected using a zooplankton net with a mesh size of 60 µm. The net was pulled below the water surface to intake water along the water body as long as possible. For quantitative sampling, samples were taken directly from the water surface. A 20-liter plastic bucket was used to collect water at ten different points along the sampling sites and was poured into the net with a total volume of 200 L. The sample was stored in a 110 mL plastic bottle and fixed with formalin at a concentration of 4%.

The qualitative samples were analyzed under an Olympus CX 23 microscope (with an objective length of 40 X) and based on the taxonomic keys developed by Shirota (1966), Dang et al (1979), Boltovskoy (1999), Nguyen (2001) and Phan et al (2015) to identify zooplankton species. Density of zooplankton was determined by counting a single individual using the Sedgewick-Rafter counting chamber under an Olympus Cx23 binocular microscope (Boyd & Tucker 1992). The number of individuals or abundance of zooplankton was determined using the following formula:

$$X\ (\text{ind m}^{-3}) = (T*1{,}000*V_{con.}*10^6)/(A*N*V_{sam.})$$

where: X = density of zooplankton species (ind m^{-3}); T = number of individuals counted; $V_{con.}$ = volume of concentrated sample; A = the area of one square (1 mm^2); N = number of counting cells counted; and $V_{sam.}$ = volume of water filtered through the plankton net.

Biological indices

(1) Shannon-Wiener diversity index (H’): the H’ index was calculated for each sample (Shannon-Wiener 1949). This is a commonly used mean for calculating biological diversity in aquatic and terrestrial environment and estimated as:

$$H' = -\Sigma Pi.\ln Pi$$

where: Pi = ni/N (n_i = number of individuals of the species *i* and N = total number of individuals of all species in the samples).

(2) Margalef diversity index (D):

$$D = (S-1)/\ln(N)$$

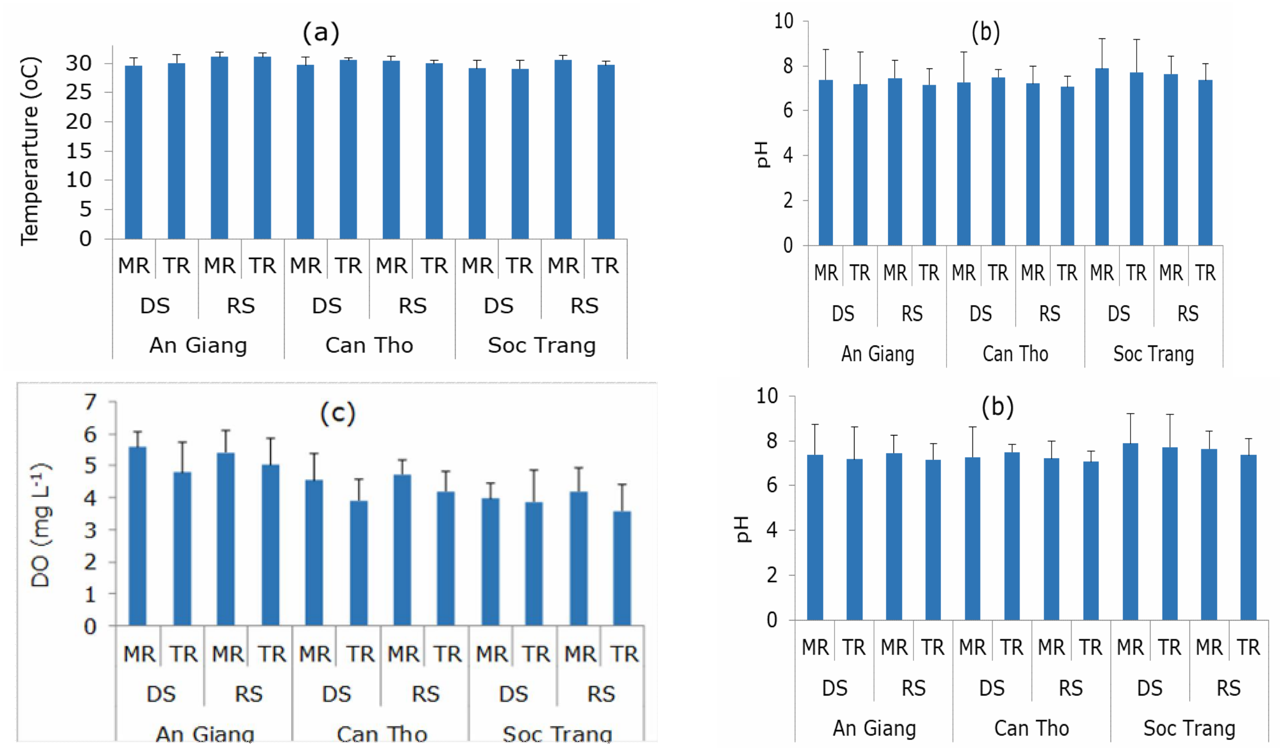
where: S = number of species, and N = total number of individuals in the collected sample.

Data analysis. The Pearson's correlation analysis by IBM-SPSS software with version 22.0 was applied to compare the correlation between environmental factors and the species composition and density of the zooplankton groups and between the abundance and bio-indices in the Hau River. In addition, cluster and cumulative dominance index (K index) analyses of the zooplankton community were carried out using the PRIMER 6.1.5 (Plymouth Routines in Multivariate Ecological Research).

Results

Water quality parameters on the Hau River and its tributaries. Water quality parameters recorded during the study periods on the Hau River were shown in Figure 2. The mean water temperature at sampling sites ranged from 29.1±1.46 to 31.1±0.8°C. The average pH changed from 7.07±0.30 to 7.89±0.2 and tended to increase in the sites of Soc Trang province. The upstream (An Giang) and midstream (Can Tho) collection points are located in freshwater environments where salinity is less than 0.5 ppt. In contrast, salinity at the downstream (Soc Trang) sites ranged from 6.1±4.9 to 7.5±5.1 ppt. DO concentrations in An Giang and Can Tho were higher than those in Soc Trang sampling points. For TSS content, there was high fluctuation between the sampling points, varying from 19.50±7.15 to 230.83±19.01 mg L^{-1}. The points in Soc Trang had highest TSS concentration both in the rainy and dry seasons.

The BOD concentration ranged from 2.61±0.59 to 4.84±1.24 mg L^{-1}. The average BOD concentration reached the lowest value at the sampling points in An Giang province both in the rainy and dry seasons. The concentration of TAN fluctuated largely among the sampling points, in which TAN in the sampling points on the tributaries was always higher than those on the main river. Highest NO_3^- content was found in the points of An Giang provinces in the dry seasons. During the dry season, the average NO_3^- and PO_4^{3-} concentrations in both main stream and tributaries reached their highest levels. Similarly, concentrations of TN and TP at the survey sites varied from 1.44±0.53 to 3.47±0.93 mg L^{-1} and from 1.54±0.71 to 2.51±0.67 mg L^{-1}, respectively, and tended to increase higher at the sampling points on tributaries both in the rainy and dry seasons. In general, changes in water quality parameters in the study area varied seasonally and regionally in Hau River.



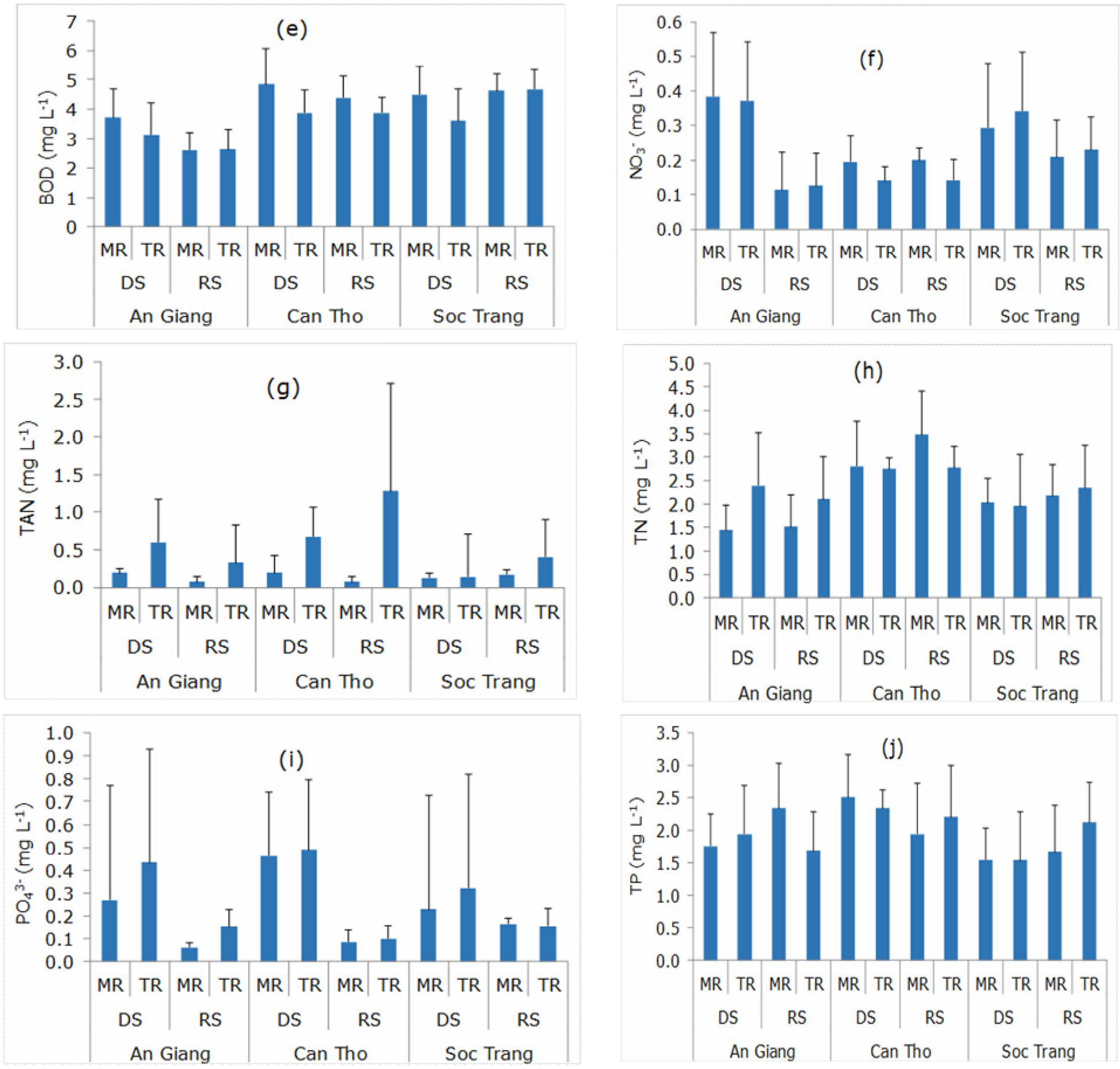


Figure 2. Physico-chemical parameters recorded on Hau River and its tributaries including (a) temperature, (b) pH, (c) dissolved oxygen (DO), (d) total suspended solids (TSS), (e) biological oxygen demand (BOD), (f) nitrate (NO_3^-), (g) total ammonia nitrogen (TAN), (h) total nitrogen (TN), (i) phosphates (PO_4^{3-}), (j) total phosphorus (TP).

Composition of zooplankton on Hau River

General species composition. A total of 148 species was recorded in the Hau River belonging to An Giang, Can Tho, and Soc Trang provinces (Figure 3). Rotifera was the most abundant group with 52 species (accounting for 35%), followed by Protozoa with 48 species (32%), Copepoda with 22 species (15%), Cladocera with 16 species (11%), and the Meroplankton group with 10 species (7%). The common species observed in all sampling sites are *Brachionus falcatus*, *B. calyciflorus*, *B. angularis*, *Filinia terminalis, Keratella tropica*, *Keratella serrulata*, *Anuraeopsis fissa* and *Polyarthra vulgaris* (Rotifera), *Difflugia* sp., *D. acuminata* and *Centropyxis aculeata* (Protozoa), *Bosmina longirostris*, *Bosminopsis deitersi*, *Moina macrocopa*, *Diaphanosoma sarsi* (Cladocera) and *Cyclops bicuspidatus*, *Mesocyclops leuckarti, Thermocyclops* sp. (Copepoda). Some meroplankton groups such as Bivalvia larva, Polychaeta larva, Insect larva and Nematoda were also commonly recorded. The study also identified 53 species of zooplankton distributed in all

3 study areas, of which 10 species were only characteristically distributed in An Giang, 13 species only appeared in Can Tho and 24 species were only detected in Soc Trang (Figure 4).

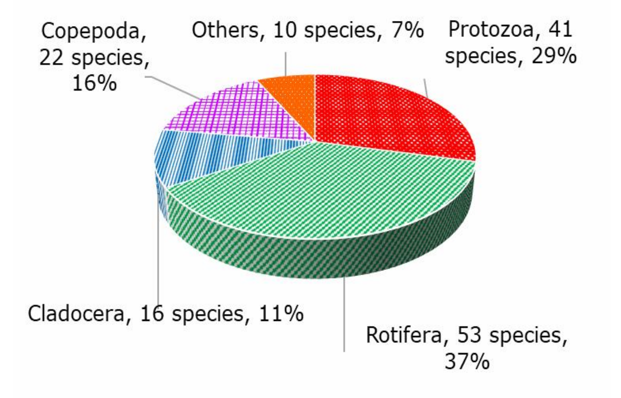


Figure 3. Zooplankton species composition recorded on the Hau River and its tributaries.

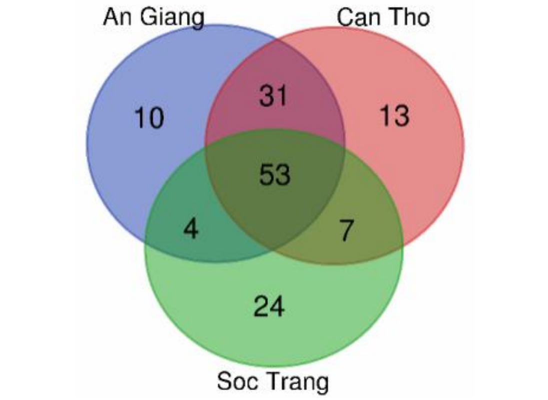


Figure 4. Shared zooplankton species composition between in the sampling locations in An Giang, Can Tho and Soc Trang provinces.

Species composition of zooplankton through the sampling periods (temporal dimension). Zooplankton composition during the sampling periods changed from 93 to 112 species (Table 2). The highest number of zooplankton species was recorded in June, with 112 species, followed by 109 species in September and 105 species in March, while the lowest number (93 species) was noticed in December. Rotifera was the most diverse group, with the highest number of species found in June and the lowest in December. For Protozoa, highest species number was recorded in March, and the lowest was in September. The species number of Copepoda did not vary remarkably during the study period, ranging from 14 to 18 species. Cladocera had lowest species number in June and the highest in September. The species number of the other groups, including Bivalvia and Gastropoda larvae, Ostracoda, and Nematoda, was relatively low, varying from 6 to 9 taxa.

Table 2

Species composition of zooplankton through the sampling periods

No	*Groups*	*March*	*June*	*September*	*December*
1	Protozoa	31	30	24	29
2	Rotifera	37	53	47	33
3	Cladocera	10	8	13	9
4	Copepoda	18	15	18	14
5	Others	9	6	7	8
	Total	105	112	109	93

Seasonal fluctuation of zooplankton composition. The number of zooplankton species in the main river and tributaries in the rainy season tended to be higher than in the dry season. Species composition in the rainy and dry seasons varied from 66-89 species to 47-87 species, respectively (Figure 5). The species numbers of Rotifera and Cladocera were found to be higher in the rainy season and lower in the dry season. In contrast, Protozoa species numbers tended to increase in the dry season. For Copepoda, the species number did not change significantly among the sampling points. In both dry and rainy seasons, zooplankton species composition was lowest in sampling sites of Soc Trang province.

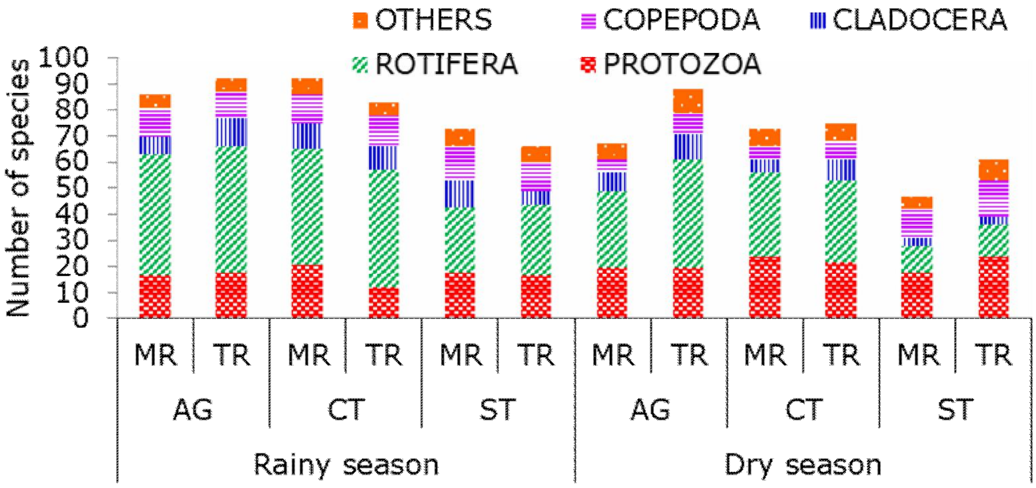


Figure 5. Number of zooplankton species in main river and tributaries in the rainy and dry seasons.

Mean zooplankton density in the rainy and dry seasons fluctuated from 124,850±27,461 to 608,292±165,373 ind m^{-3} and from 51,447±23,785 to 722,553±539,266 ind m^{-3}, respectively (Figure 6). Rotifera predominated in the sampling points of An Giang and Can Tho, while Protozoa was more abundant in Soc Trang in both main river and tributaries. Densities of Rotifera, Cladocera, Copepoda, and nauplius of Copepoda in the rainy season were higher than in the dry season in most study sites. Similarly, the density of zooplankton at all sampling sites on the main river was always higher than those in tributaries. In the rainy season, zooplankton abundance was highest on the tributaries of Can Tho, with the predominance of Rotifera (314.213±79,457 ind m^{-3}). High densities were observed for *Polyarthra vulgaris*, *Filinia terminalis*, *Anuraeopsis fissa*, and *Brachionus angularis*. In the dry season, at the sampling sites on tributaries of Soc Trang where salinity was higher, highest zooplankton density was noticed. Protozoa was most abundant (434,035±378,664 ind m^{-3}) in this area with species such as *Tintinnopsis parvula* and *Tintinnopsis* sp.

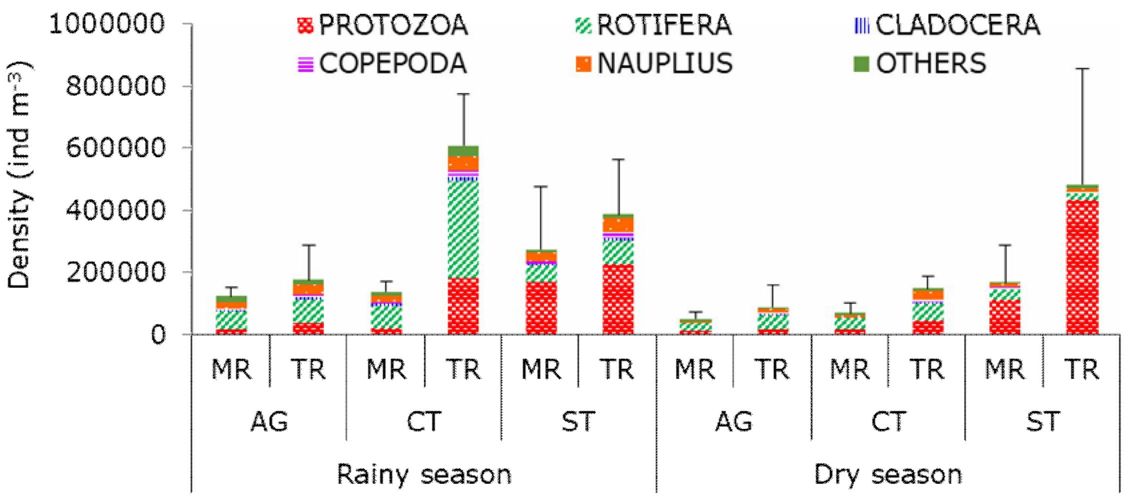


Figure 6. Mean of zooplankton density in main river and tributaries in the rainy and dry seasons.

Diversity of zooplankton in the study areas. The results of the Shannon-Wiener diversity index (H') and Margalef diversity index (D) are presented in Figure 7. It can be seen that the trends of all average indices in all sampling sites were generally the same during the sampling period. Mean H' index ranged from 1.8 to 3.2 and from 1.6 to 2.7 in the rainy and dry seasons, respectively. The results also showed that the species diversity of zooplankton in the rainy season was higher than in the dry season. In the dry season, the mean H’ value in the main river tended to be higher than that in the tributaries. In contrast, in the rainy season, this value in the tributaries in An Giang and Can Tho was higher than that in the main river. In addition, all the sampling locations in Soc Trang had lowest H’ value in both seasons, indicating lower zooplankton diversity.

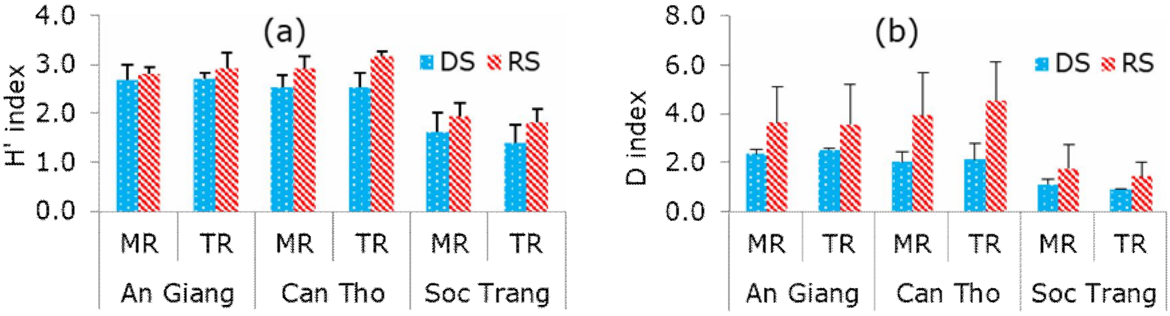


Figure 7. (a) Shannon-Wiener diversity index and (b) Margalef index of zooplankton on Hau River (DS: dry season; RS: rainy season)

Similarly, Margalef’s index (D) or species richness index, varied considerably between the rainy and dry seasons. The D value in the main and tributaries in study areas ranged from 1.4 to 4.6 in the rainy season and from 0.9 to 2.5 in the dry season. The lowest D value was observed in Soc Trang. In the same area, the D value was not significantly different between the main river and its tributaries. However, the D value increased during the rainy season at the majority of sampling sites in Can Tho both the main river and its tributaries. The species composition of zooplankton was considered to be the most diverse in the rainy season.

Correlation between zooplankton diversity and water quality parameters in the Hau River. The output of Pearson correlation coefficients between zooplankton species, density, and physical-chemical parameters in all sampling sites revealed that water temperature was weakly correlated with the distribution of zooplankton species and density on the Hau River during the study periods. Protozoa had a negative correlation ($p < 0.01$) with DO concentration, but a positive relationship with TSS ($p < 0.01$) and TN content ($p < 0.01$).

A significantly negative correlation was observed between the density of Rotifera and pH ($p < 0.01$) in the study area. Rotifera also had a negative correlation with NO_3^- content ($p < 0.01$) but a positive correlation with TAN concentration ($p < 0.01$). In case of Cladocera, there was no close correlation with most of water quality parameters except NO_3^- and coliforms. The densities of Copepoda were not clearly correlated with most of the physico-chemical parameters, whereas densities of Protozoa, Cladocera, and Rotifera showed a significantly positive correlation with water parameters ($p < 0.01$). Furthermore, nauplius had a strong negative correlation with NO_3^- and PO_4^{3-} concentrations ($p < 0.05$), but a significant positive relationship with TAN ($p < 0.05$). Finally, the correlation between the total number of zooplankton species and biodiversity indices (H’ and D) and water quality parameters during the study periods was relatively similar in the study area. They were significantly negatively correlated with pH, TSS, BOD, NO_3^- and PO_4^{3-} ($p < 0.01$) but positively correlated with temperature and DO ($p < 0.01$) (Table 4).

Cumulative dominance index (K index). The cumulative dominance index of zooplankton in the study area is shown in Figure 8.

Table 4

Pearson correlation of water quality parameters and zooplankton composition

Parameters	*Protozoa*	*Rotifera*	*Cladocera*	*Copepoda*	*Nauplius*	*Others*	*Total*	*Species. no*	*H'*	*D*
Temperature	-0.061	0.078	0.05	-0.006	0.113	0.173	-0.012	0.289**	0.582**	0.304**
pH	0.049	-0.278**	-0.145	-0.049	-0.148	-0.166	-0.065	-0.461**	-0.464**	-0.446**
DO	-0.374**	0.026	-0.029	-0.099	-0.135	0.149	-0.320**	0.305**	0.367**	0.337**
TSS	0.420**	-0.122	-0.124	0.062	0.103	-0.088	0.323**	-0.267**	-0.314**	-0.295**
BOD	-0.006	-0.168	-0.127	-0.043	-0.094	-0.139	-0.073	-0.292**	-0.256**	-0.264**
TAN	-0.005	0.520**	0.108	0.105	0.193*	0.183*	0.178	0.057	0.186*	0.007
TN	0.356**	-0.104	-0.08	0.158	0.074	-0.095	0.279**	-0.499**	-0.550**	-0.526**
NO_3^-	0.021	-0.248**	-0.295**	-0.103	-0.230*	0.097	-0.088	-0.447**	-0.205*	-0.423**
TP	-0.159	-0.002	-0.113	-0.123	-0.119	0.055	-0.153	0.047	0.091	0.069
PO_4^{3-}	-0.037	-0.174	-0.157	-0.11	-0.211*	-0.038	-0.114	-0.281**	-0.353**	-0.270**

** = correlation is significant at the 0.01 level (2-tailed); * = correlation is significant at the 0.05 level (2-tailed).

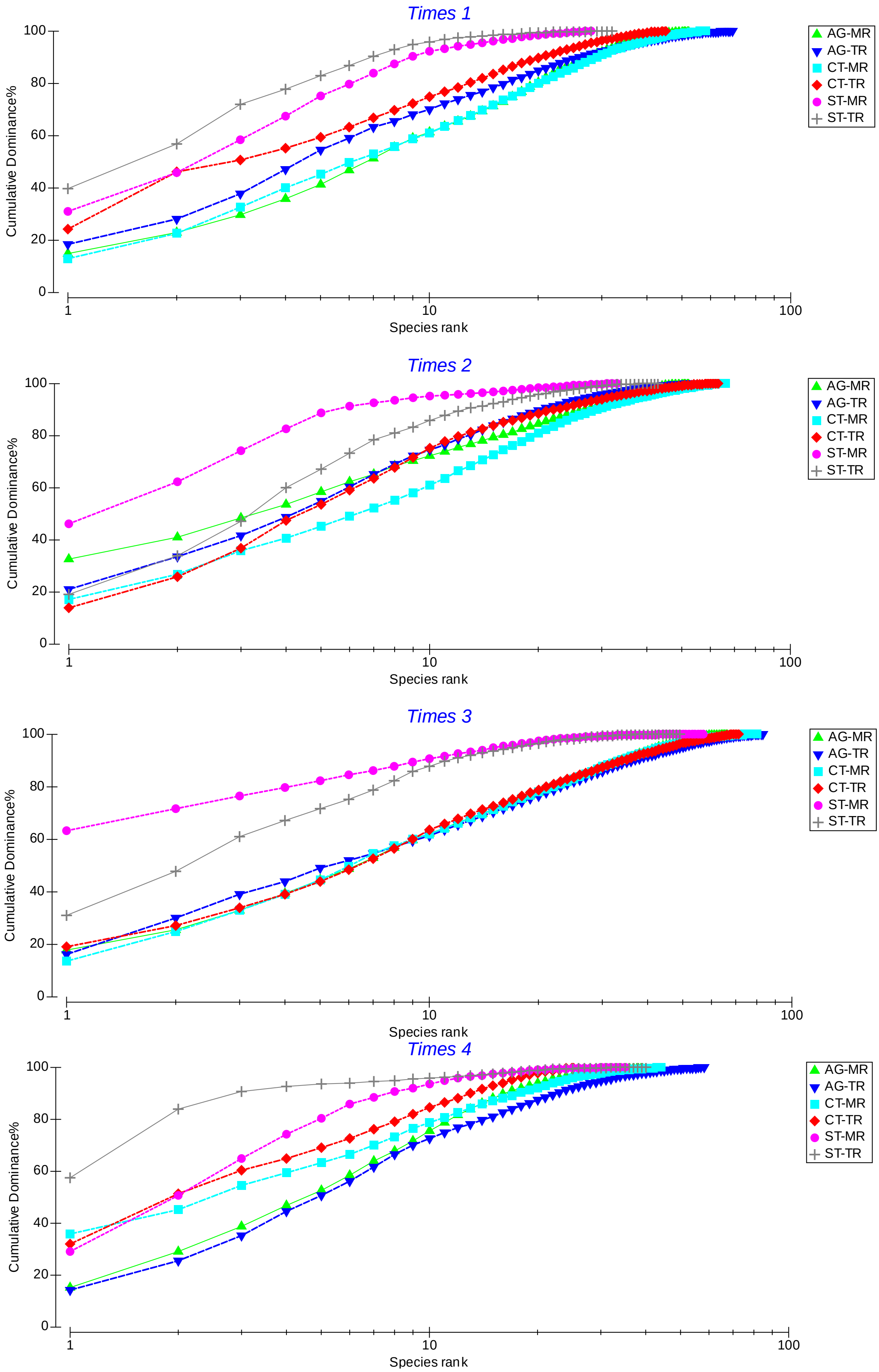
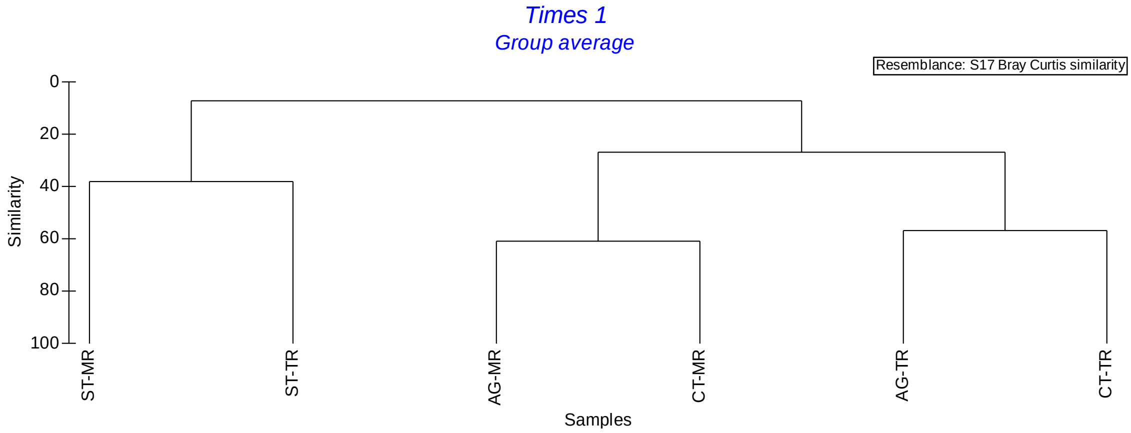
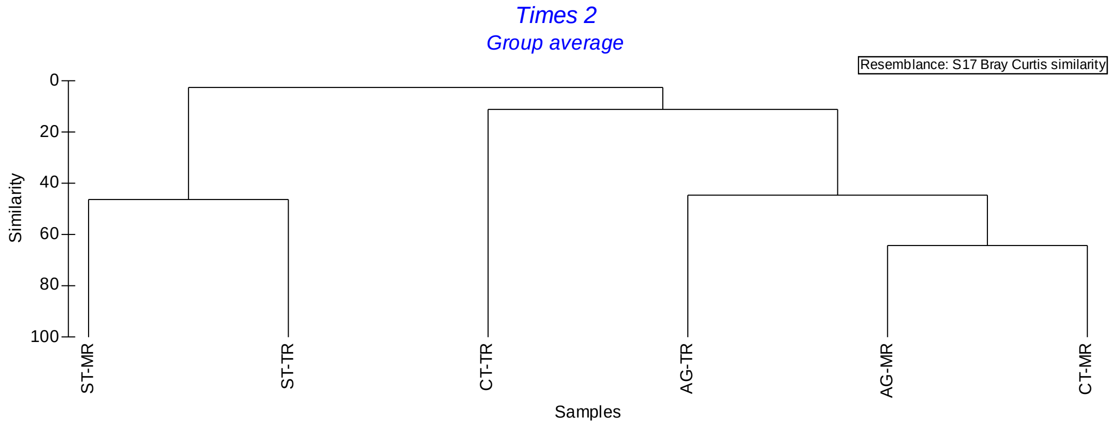


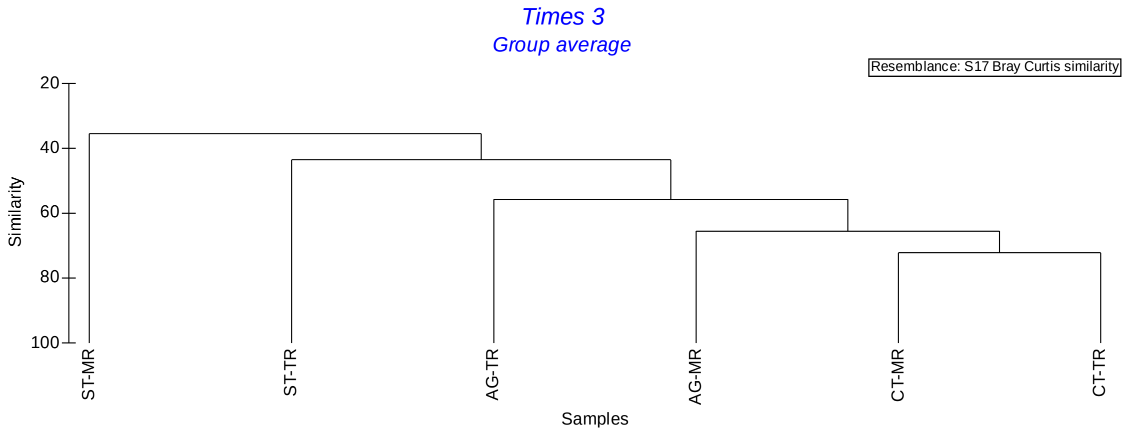
Figure 8. Cumulative dominance index for zooplankton abundance in March (Times 1), June (Times 2), September (Times 3) and December (Times 4).

In the dry season, the collection points on tributaries in Soc Trang in March and December had the highest K index. Three protozoa species had a K index of over 72% in March, including *Tintinnopsis parvula*, *Tintinnopsis amphora*, and *Tintinnopsis uruguayensis*. Similarly, three zooplankton species had the highest K index in December (91%), such as *Tintinnopsis parvula*, *Tintinnopsis* sp., and *Tintinnopsis baltica*. The main river sampling points in March in both Can Tho and An Giang had the lowest K-index among the survey sites, while the K-index in December at all points in An Giang was lowest among study sites. On the contrary, in the rainy season, the K index in the main river sites of Soc Trang province was the highest in June and September. The K index of the first three species of zooplankton was over 74% in June, including *Tintinnidium* sp., *Tintinnopsis* sp., and *Tintinnopsis parvula*. Similarly, the K index of the first three species of zooplankton at points in the main river of Soc Trang had the highest rate in September, reaching over 76%. The remaining collection points had a lower K index.

Similarity between sampling points on the Hau River. Based on the similarity of species components and abundance of the zooplankton, the sampling sites in different water bodies can be divided into different groups (Figure 9). In March (Times 1), June (Times 2), and December (Times 4), the data indicated the presence of two clusters. The first cluster included points that belong to freshwater areas in An Giang and Can Tho, with two sub-clusters (AG-MR, AG-TR, CT-MR, and CT-TR). The second cluster included the rest of the locations in Soc Trang (ST-MR and ST-TR). However, in September (Times 3), the middle of the rainy season, the zoning of water bodies was not clearly defined but still showed the difference in zooplankton composition between the survey areas. The data can be divided into three clusters. The first cluster was between locations ST-MR and ST-TR, with lowest similarity. The second cluster was between sites AG-MR and AG-TR. The third cluster was between sites CT-MR and CT-TR, with highest similarity.







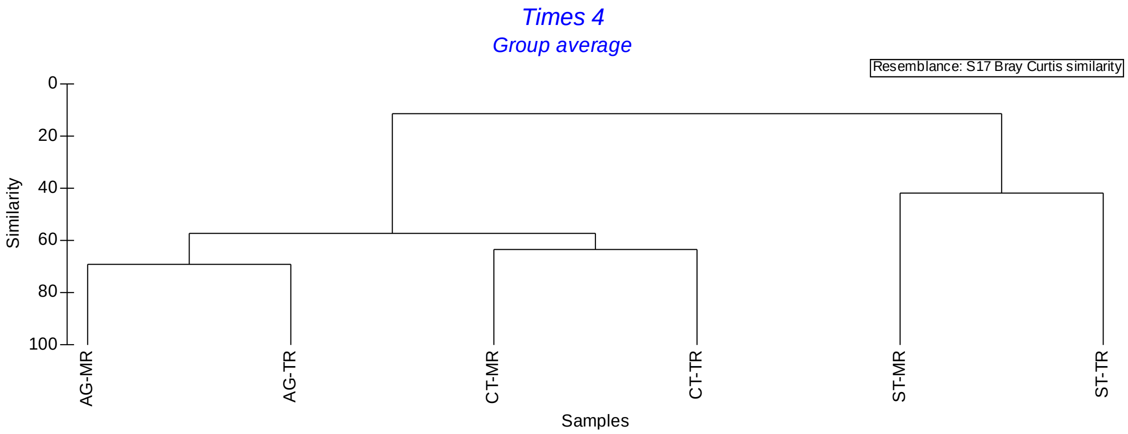


Figure 9. Dendrogram representing the similarity between sampling sites during the periods in March (Times 1), June (Times 2), September (Times 3) and December (Times 4).

Discussion. Physical-chemical parameters and nutrient factors in water play a major role in the distribution characteristics and species composition of plankton (Mahar et al 2000; Manickam et al 2015). Changing physicochemical conditions will directly or indirectly affect the distribution and occurrence of zooplankton. Water temperature and DO values are the most critical factors affecting the abundance of zooplankton (Park & Marshall 2000). Water temperature is one of the most essential parameters that manage the chemical and biological activity of organisms in aquatic life. An increase in water temperature has been connected with higher densities and species diversity of zooplankton in water ecosystems (Castro et al 2005; Buyurgan et al 2010). In the present study, water temperature tended to increase in the rainy season (31.1±0.8°C), while species composition and density of zooplankton also increased in the rainy season. In addition, salinity was also an important environmental factor shaping zooplankton biodiversity and abundance (Yuan et al 2020). The peak of zooplankton abundance was detected in locations with higher salinity, located downstream of the Hau River. pH affects the distribution of zooplankton because it affects most biotic progressions and biochemical responses (Berzins & Pejler 1987). pH is due to the occurrence or lack of free carbon dioxide (aqueous CO_2) and carbonates. The higher photosynthetic activity increases the production of phytoplankton, which supports an increase in pH (Das & Srivastava 1956). The higher pH is also attributed to anthropogenic activities like washing clothes with detergents and mixing sewage. In this study, the pH (7.89±0.20) tended to be close to the natural level that would be suitable for primary and secondary productivity. Higher TSS can prevent sunlight from entering the water, affecting photosynthesis and algae growth. Algae are the first link in the food chain that affects species composition and density of zooplankton (Golmarvi et al 2017). In the present study, during the rainy season, TSS concentrations were lower upstream and higher downstream because of strong flows.

The concentration of DO is one of the most essential critical parameters that reflect the physical and biological processes that prevail in water (Fakruzzaman & Zaman 1996). Moreover, according to Singh et al (1993), DO level in natural water depends upon atmospheric air compression, photosynthetic activity, temperature, and salinity. The solubility of oxygen rises with a reduction in temperature. In the present investigation, DO values (5.58±0.48 mg L^{-1}) increased in the dry season when temperatures decreased in the dry season. Water with high nutrient contents, such as phosphate and nitrate, will increase the dominance of certain aquatic organism species in the aquatic environment. In addition, several studies have shown that water temperature, DO and nutrient contents in water play an important role in controlling the diversity and density of Cladocera (Golmarvi et al 2017). In the present study, NO_3^- and PO_4^{3-} were higher in dry season (0.38±0.19 and 0.49±0.31 mg L^{-1}, respectively) and lower in the rainy season (0.11±0.11 and 0.06±0.02 mg L-1, respectively).

Rotifera was the most abundant group in the study areas of the Hau River. This result is in agreement with other studies showing Rotifera is the most dominant group in freshwater ecosystems and is the most abundant group in the Hau River (Barrabin 2000; Saler 2004; Nguyen et al 2014, 2020). In the present study, Rotifera dominated in all study areas, with 51, 54, and 42 species recorded in An Giang, Can Tho, and Soc Trang, respectively. Herzig (1987) indicated that they are commonly rich in eutrophic freshwater ecosystems and are more abundant than other zooplankton assemblages because of their short generation time and high reproductive proportion. Components of Rotifera can be used as biotic indicators and for water quality monitoring as they respond to the fluctuations of environmental parameters (Sladecek 1983). Aboul-Ezz et al (1996) suggested that Rotifera is the most important zooplankton in eutrophic waters. Čeirāns (2007) also showed that Rotifera, mainly species of *Brachionus*, are better trophic indicators than crustaceans as they are less affected by phytoplankton abundance. In the current study, common species including *Brachionus falcatus*, *B. calyciflorus*, *B. angularis, Filinia terminalis, Keratella tropica, Keratella serrulata, Anuraeopsis fissa,* and *Polyarthra vulgaris* were recorded. The thriving of *B. caudatus personatus*, *B. diversicornis*, and *Filina longiseta* has been considered as an indicator of eutrophication (Sharma 1992; Dutta & Patra 2013).

Crustacean zooplankton (Cladocerans, Copepods, and Ostracods) hold the highest station both in terms of organization and as secondary users in the aquatic diet chain. Some Cladocera genera are planktonic in freshwater, while the majority of them are coastal, alive among the weed, and some of them live on the bottom mud (Bhavan et al 2015). In the present study, the species composition of copepods and cladocerans was lower than that of other groups, with 27 species and 18 species, respectively. Both assemblages are bigger in size compared to rotifers, which are less than 250 µm (Shiel 1995). Due to fish predation, the large size of cladocerans and copepods will reduce their abundance (Karus et al 2014). Based on the survey by Vu et al (2015), the most abundant orders of fish in the Hau River are the Perciformes and the Cypriniformes, which might be predators of both groups. Perciformes are probably a main element in the decline of cladocerans and copepod abundance in the study sites. Copepoda domination indicates that there was an abundance of diatoms (Bacillariophyceae) and blue green algae (Cyanophyceae), and these phytoplankton groups are more important food sources for all the developmental stages of cyclopoid Copepods (Lewis 1978).

Ciliated protozoans are an important component of the plankton and benthos of freshwater environments. Protozoa are characteristically phagotrophic, especially on bacteria, unicellular algae, and other protists, and their phagotrophy underpins their ecological importance in microbial food webs (Pace 1982; Madoni & Bassanini 1999). Protozoa are an abundant and ubiquitous group of oceanic animals. Tintinnids and colorless flagellates may exist in enormous numbers in the plankton community (Lohmann 1908). In the present study, protozoa were the most dominant and abundant in the estuarine waters of Soc Trang, especially in the dry season. A similar trend was also found by Nguyen et al (2020) when salinity increased to more than 5 ppt, protozoans and copepods were more abundant. Water clarity is relatively higher in the river than in the interior canals and lake, which may have enhanced the predation of large-bodied zooplankton since increased water clarity favors the activity of predator fish (Abrahams & Kattenfeld 1997). The canal site had higher turbidity and TSS than the river, which may have reduced the predation risk of large zooplankton in the river (Chen & Chen 2017). In this study, species composition and density in its tributary were higher than in the main river.

Biodiversity indices are used to describe and assess the composition of any community living in an aquatic environment, which is distinguished by its ease of access and exposure to current environmental factors. The most common indicator for determining biodiversity is the Shannon-Wiener index, which measures the number of species in the sample and the distribution of individuals among these species. Another widely used indicator of biodiversity is the species richness index which refers to the absolute number of units in a biosphere within the water surface. According to Ren et al (2011), the degree of water pollution in the environment can be categorized as follows based on the H' value: H' = 0-1: heavy pollution; H' = 1-2: moderate-ɑ pollution; H′ = 2-3: moderate-β pollution; H' > 3: light pollution or clean water. In the present study, the results showed that the Shannon-Wiener diversity index (H') fluctuated from 1.6 to 3.2 and Margalef's diversity index (D) varied from 0.9 to 4.6 indicating that water quality of the study locations was from light to moderate-ɑ pollution. Moreover, in this study, the density of zooplankton was in a higher range of 33,837-888,728 ind m^{-3} compared to the assessment standard of diversity indexes that indicated oligotrophic to moderate during the study period.

Based on the output of Pearson correlation coefficients between mean zooplankton abundance and water quality parameters in all sampling areas, it revealed that protozoa had a negative correlation ($p < 0.01$) with DO concentration, while they had a positive correlation with TSS content ($p < 0.01$). Environmental variables such as DO and nutrients are important for the presence and distribution of zooplankton. For example, DO below 1.0 mg L^{-1} would limit the development of zooplankton. Nutrients such as NH_4^+ and PO_4^{3-} are essential for the growth of phytoplankton, which serves as food for zooplankton. Moreover, pH and TSS are essential for the distribution of zooplankton (Orsi & Mecum 1986; Ferdous & Muktadir 2009). All sampling sites, mainly on the tributaries in Soc Trang, had a higher density of protozoa that coincided with high TSS and low DO concentrations indicating that protozoa are distributed and favorable in the environmental conditions with high nutrient contents. The effect of wastewater discharged on the substrate has often been neglected. Ciliates are an important group of protozoa that are sensitive to pollutants, and any changes in ciliate diversity and community structure reflect the habitat quality (Chen et al 2009). The high density of protozoa in sites of Soc Trang indicated higher organic pollution level in this area.

The significantly negative correlation was observed between the density of Rotifera and pH ($p < 0.01$) in the study area. Rotifera is an important group of zooplankton which can be considered a valuable component of a freshwater ecosystem. Its community structure can be used as a bio-indicator of water quality assessment, whereas its long-term changes need to be monitored. The population dynamics of rotifers are strongly related to the trophic state of their environment (Duggan et al 2001). In the present study, Rotifera had a negative correlation with NO_3^- content ($p < 0.01$) but there was a positive correlation with TAN concentration ($p < 0.01$). According to Whitman et al (2004), strong correlations were observed between differences in lake trophic status and the zooplankton community. The rotifers were found to be the best indicators of trophic status when compared to the other groups. In the present study, Rotifera also had a higher density in the rainy season, coinciding with the time when the water environment contained high nutrients, especially at locations in tributaries. In addition, rotifers' contributions to the zooplankton community may increase with eutrophication (Park & Marshall 2000).

For Cladocera, except for NO_3^-, there was no close correlation with most of water quality parameters. In the current research, Cladocera had a significantly negative relationship with the concentration of NO_3^- ($p < 0.01$), while they had a significantly positive correlation with coliforms ($p < 0.01$). Cladocera species are highly sensitive to even low concentrations of pollutants. Most of the physico-chemical parameters were not clearly related to Copepoda abundance. However, they had a significant positive corelation ($p < 0.01$) with densities of Protozoa, Cladocera, and Rotifera. According to Kalff (2002), copepods in general can withstand harsher environmental conditions as compared to Cladocera. Nauplius of Copepoda had a significantly negative correlation with concentrations of NO_3^- and PO_4^{3-} ($p < 0.05$). These results indicated that the nauplius of Copepoda could not reach high abundance in eutrophic conditions. In addition, the total density of zooplankton was positively related to the concentration of TSS ($p < 0.01$) in the study area. The same results were also found in the Can Giuoc River in southern Vietnam (Duc et al 2016).

The correlation between the total number of zooplankton species, the H' and D indices, and water quality parameters during the study periods was relatively similar in the study area. There was a significantly negative correlation with pH, TSS, BOD, NO_3^- and PO_4^{3-} ($p < 0.01$) but a significantly positive relation with factors of temperature and DO. The results from the K-index also showed that the zooplankton component in the An Giang and Can Tho areas was more diverse than those in Soc Trang. In the dry season (March and December), the diversity of zooplankton species on tributaries in Soc Trang province (ST-TR) was lower than at other collection points, and these results were also shown with the highest K index. However, in the rainy season (June and September), the main river collection points in Soc Trang province (ST-MR) had a lower diversity of zooplankton species than other sites. The zooplankton populations had a distinct division between freshwater and brackish water waterbody groups in March, June, and December. In the study area, sites in the same freshwater or brackish water ecosystem had high similarities in species composition and abundance of zooplankton. The fluctuations in water quality elements and salinity can explain the differences in zooplankton community structure and density in the Hau River. In general, zooplankton populations were quite diverse in the Hau River where domestic sewage, aquaculture, and industrial waste were abundant and provided adequate nutrients for zooplankton development.

Conclusions. Water quality on the Hau River can be categorized as light to α-mesosaprobic. The zooplankton community in brackish waterbodies displayed lower diversity than in the freshwater areas. High similarity in zooplankton abundance was found between the upstream and midstream regions, and their abundance was different from the downstream region. NO_3^- and PO_4^{3-} concentrations in the dry season were higher than in the rainy season. In contrast, zooplankton diversity and abundance during the rainy season were greater than that in the dry season. In general, water quality parameters influence directly or indirectly the density and distribution of zooplankton on the Hau River. Hence, studies on the spatial and temporal or seasonal variability of zooplankton communities are important to improve our understanding of the function of river ecosystems.

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