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ORIGINAL RESEARCH ARTICLE

Unravelling the spatio-temporal variation of zooplankton community from the river Matla in the Sundarbans Estuarine System, India

Tanmoy Nandy, Sumit Mandal*

Marine Ecology Laboratory, Department of Life Sciences, Presidency University, Kolkata, India

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KEYWORDS
Sundarbans;
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Summary Zooplankton is an important bioindicator of ecosystem functioning. Knowledge of the seasonal fluctuation in the zooplankton population in estuarine waters of the Indian Sundarbans is rather limited. In the present study, we analysed the community structure of zooplankton assemblages and their spatio-temporal variations based on different multivariate statistics and indicator value analysis. A total of 56 taxa were identified and the density was primarily dominated by planktonic copepods and few meroplankton communities during four sampling seasons. The most abundant species were: *Acartia spinicauda, Acartia* sp., *Bestiolina similis, Euterpina acutifrons, Labidocera acuta, Paracalanus aculeatus, Paracalanus parvus* and *Paracalanus indicus*. Canonical Correspondence Analysis highlighted that temperature, pH, DO, salinity and nutrients were the prevailing environmental parameters associated with significant spatio-temporal changes of zooplankton distribution in this area. The highest abundance of zooplankton was recorded in winter, followed by monsoon, summer and spring. Throughout the study period, different zooplankton indices were observed in good condition. Seasonal occurrence of dominant zooplankton with high *IndVal* index was markedly observed and it might be used as a potential bioindicator for a particular season and environmental condition in this estuarine complex. The results of this study provide evidence for the presence of warm water species in the estuarine waters of the Indian Sundarbans and can be a clear indication of climate change-mediated elevated temperature in the estuarine system. Our results underscore

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* Corresponding author at: Marine Ecology Laboratory, Department of Life Sciences, Presidency University, 86/1, College Street, Kolkata-700073, India.
E-mail address: sumit.dbs@presiuniv.ac.in (S. Mandal).

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the high diversity of zooplankton from mangrove dominated estuarine complex and emphasize the need for long-term monitoring in ecologically fragile ecosystems like the Sundarbans Estuarine System.

1. Introduction

Estuarine ecosystems have been recognised as a mosaic of habitats exhibiting different biogeochemical processes and act as a transitional ecotone with marked gradients of physical, chemical and biological components (Moderan et al., 2010; Nandy et al., 2018; O'Higgins et al., 2010; Van der Maarel, 1990). Due to their connections with adjoining freshwater and marine ecosystems, estuaries always face a strong physicochemical fluctuation at spatio-temporal scale. Moreover, the fluctuations of numerous physicochemical factors are more evident in the estuarine environment than in other aquatic systems (David et al., 2016). In addition, estuaries act as a nursery ground for different aquatic organisms by providing food and shelter for larvae and juveniles (Dorak and Albay, 2016; Telesh, 2004). Furthermore, estuary acts as a hotspot for many benthic animals larval forms which spend some time, depending upon their larval duration, in the estuarine realm before returning to their benthic mode of life in coastal waters (Morgan, 1995; Shanks, 1995). In estuarine areas, the spatial and temporal variations of different biological communities are always driven by several environmental variables. Howbeit, it is essential to improve our knowledge of estuarine ecosystem functioning with a sound understanding of biogeochemical gradients and their interactions with biological entities.

In an estuarine ecosystem, most of the zooplankton are efficient grazers of the phytoplankton and mainly detritus, referred to as living machines transforming plant energy into animal tissue (De Young et al., 2004; Dorak and Albay, 2016; Sampey et al., 2007). Therefore, the zooplankton play a significant role in energy transfer from primary producers to higher trophic levels, occupying a fundamental niche in the estuarine food web (Degerman et al., 2018). Moreover, the estuarine ecotone and profit of coastal fisheries are always influenced by the zooplankton population due to its role as a major food item for fishes (Ayon et al., 2008; Bianchi et al., 2003). Due to the zooplankton large density, shorter life span, drifting nature, high taxa/species diversity and different tolerance to the environmental stress, they are being used as indicator organisms for the physical, chemical and biological processes in the aquatic ecosystem (Longhurst, 2007; Uriarte and Villate, 2004). The seasonal and spatial dominance of certain zooplankton taxa may indicate the relative influence of different water parameters on the estuarine ecosystem and serve as an early indication of a biological response to environmental and climatic changes (Hays et al., 2005; Ziadi et al., 2015). Though zooplankton organisms serve as a good indicator of biodiversity because of high sensitivity to environmental fluctuations (Gorokhova et al., 2016), they have been generally less used in studying biological responses in changing environment (Gorokhova et al., 2016; Mialet et al., 2011). The identification of indicator species and tracking changes in species composition are essential to detect local and global changes in estuarine biogeochemistry (Fernandez De Puelles et al., 2009).

In the Indian part of the Sundarbans estuarine complex, knowledge about zooplankton communities is relatively limited (Bhattacharya et al., 2015; Nandy et al., 2018) and restricted to the eastern part of this system. We are fortunate enough to get access to the central part of the Sundarbans under the restricted biosphere reserve area for conducting research work funded by MoES. This system is under the influence of southwest monsoon, thus, it is essential to study the seasonal succession of zooplankton communities in order to understand the major influential factors governing the biological productivity of the Sundarban mangrove ecosystem. Nevertheless, knowledge of the zooplankton community is also fundamental in understanding the biogeochemical cycles and energy flows of marine ecosystems because of its roles in the biological pump (Giering et al., 2014; Mitra et al., 2014).

To evaluate the changes in the dynamics of the zooplankton community associated with natural environmental variables, a seasonal observation over a spatial scale is of utmost importance. Studies related to seasonal variation in estuarine waters, particularly in fishing grounds of the Sundarbans, are meagre, hence the present study was carried out and the relationship between zooplankton abundance and hydrological parameters on spatio-temporal scale has been established. Moreover, the effects of some physicochemical variables and seasonal flow patterns on zooplankton community structuring were analyzed. Therefore, the primary goals of the present study were to (i) investigate the seasonal succession and spatial variability of the zooplankton community of the river Matla in the Sundarbans Estuarine System (SES) in terms of composition, abundance and diversity; (ii) evaluate the zooplankton dynamics in relation to environmental variables and (iii) identify the indicator zooplankton species for a particular season as well as for a specific environmental condition.

2. Material and methods

2.1. Study area

The Indian Sundarbans Estuarine System (SES) is a unique bioclimatic zone situated in land-ocean boundaries of the northern coast of Bay of Bengal. The estuarine phase of this macrotidal (tidal amplitude: > 5 m) area is fully covered by true mangrove forest (Biswas et al., 2004). Moreover, the estuarine complex experienced huge monsoonal precipitation (70—80% of annual rainfall) during the summer

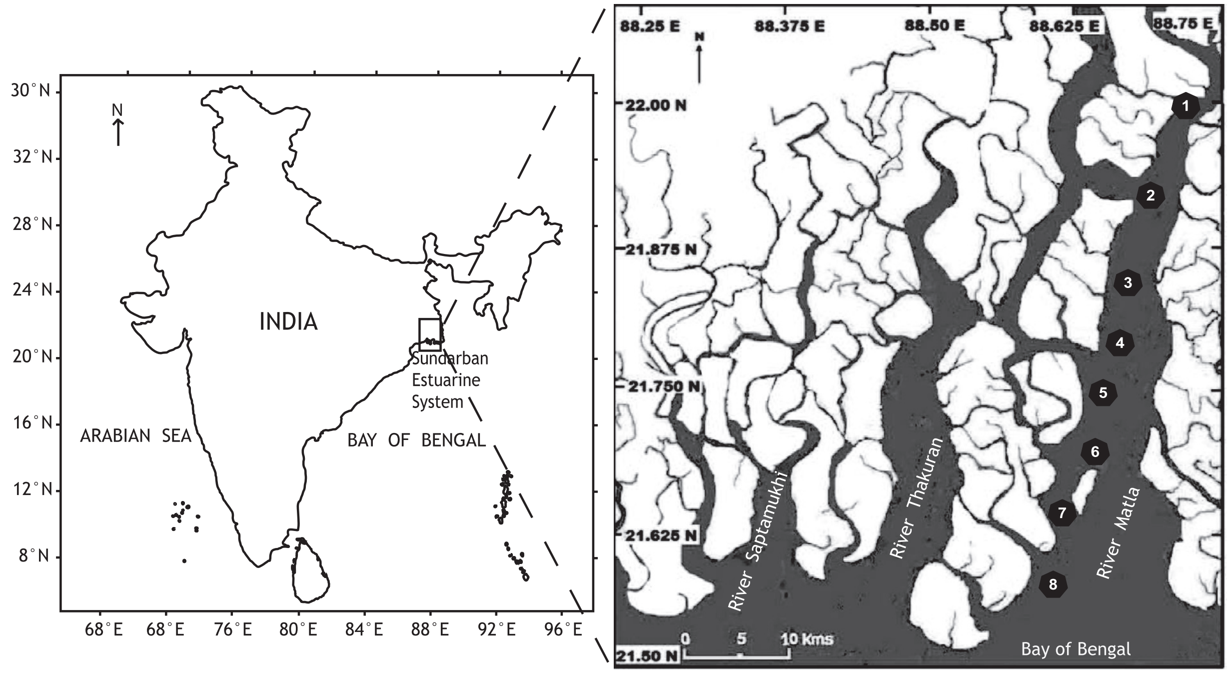


Figure 1 Map of the study area with sampling stations.

monsoon period, i.e. June to September (Mukhopadhyay et al., 2006). The surface water quality of this region is highly influenced by tidal amplitude, particularly during monsoon (Nandy et al., 2018). The SES serves as an important spawning ground and nursery for a wide variety of fishes and crustaceans, due to its ample riverine network with dense mangrove vegetation. It also plays a major role in the natural filtration of anthropogenic pollutants and acts as the most important pathway for nutrients recycling (Chatterjee et al., 2013).

The present study was conducted on the river Matla, situated at the central part of the Indian Sundarbans. A total of 8 study stations were selected according to different salinity gradients at the north-south direction (Fig. 1, Supplementary Table 1). The zooplankton of the river Matla in the Sundarbans Estuarine System was analyzed to determine the response of zooplankton population to contrasting levels of water quality (e.g. temperature, salinity, oxygen, turbidity, nutrients and phytopigments). The surface water sample was collected during four distinct seasons (once per season): monsoon (September, 2016), winter (December, 2016), spring (February, 2017) and summer (May, 2017). The water and zooplankton samples (triplicate) were collected from each station during the overall study period, at day time high tide conditions. Sampling was restricted to the surface layer because of the low (˜ 1 m) euphotic depth and spatial variation of river bathymetry in this study area.

2.2. Collection and analysis of water samples

To determine the water quality of the estuary, a water sample was collected at a 0.5 m depth using Niskin's water sampler (Hydro bios). The sample was collected in 500 ml pre-cleaned plastic container (HDPE, Tarsons) and stored in an ice box for further analysis. Water temperature, salinity, dissolved oxygen (DO) and pH were measured *in situ*. Winkler's titrimetric method and argentometric method (Strickland and Parsons, 1972) were followed to determine the DO and salinity (practical salinity scale) of the water, respectively. Surface water temperature was measured onboard with the help of mercury thermometer and Secchi disc was used to determine the transparency of water at each station. The portable digital pH meter (Model: Orion star A3110, Thermo-Scientific) was used to determine the pH of the water. The dissolved micro-nutrients such as nitrite (NO_2-N), nitrate (NO_3-N), ammonium (NH_4-N), phosphate (PO_4-P) and silicate (SiO_4-Si) were analysed using the standard method described by Grasshoff et al. (1999) after filtering the water through GF/F filter paper ($0.07\mu m$). For the chlorophyll-*a* (Chl-*a*) and phaeopigment (Phaeo) analysis 1000 ml seawater was filtered through GF/F filter paper and the analysis was done by acetone extraction method by Parsons et al. (1984). Suspended particulate matter (SPM) analysis was performed according to the method of Grasshoff et al. (1999).

2.3. Collection and analysis of zooplankton samples

Zooplankton was collected using 200 μm plankton net (60 cm diameter, 2 m length), equipped with a flowmeter (Hydro bios) by horizontal tow at subsurface layer (0.5—1 m); the average volume of water filtered per sample was 100 ± 23 m^3. The catch was transferred to a plastic bottle and fixed immediately with 10% buffered formaldehyde solution and transported to the laboratory for further analysis. To determine the abundance and composition of zooplankton, subsamples were obtained using Folsom-splitter to give a minimum number of 300 individuals per sample. In the laboratory, the triplicate subsample was taken on to a Sedgwick rafter counting chamber and was enumerated under the stereozoom microscope (Olympus, Magnus: MS24) for their mean abundances expressed as individuals per cubic meter (ind. m^{-3}). Zooplankton were identified up to species level using a compound microscope (Nikon Eclipse: E200) following standard descriptions of Conway et al. (2003), Kasturirangan (1963), Yousif Al-Yamani et al. (2011). The biomass (wet weight) of the zooplankton was determined by weighing one portion of subsample after carefully removing all the adhered water particles using a blotting paper.

2.4. Data analysis

The square root transformed data of zooplankton were used to construct a Bray-Curtis similarity matrix with average linkage group classification (Field et al., 1982) to unravel the significant spatio-temporal variation in the composition of zooplankton. In addition, SIMPER analyses were conducted to investigate which species contributed the most to the groups formed during each season's cluster analysis. To determine the variations among sampling seasons, nonmetric multidimensional scaling (nMDS) ordinations were computed (Hunt et al., 2007; Kruskal and Wish, 1978) and Analysis of Similarities (ANOSIM) was applied to detect significant ($p = 0.001$) differences between seasons (Clarke and Warwick, 2001) with respect to zooplankton species composition.

The Canonical Correspondence Analysis (CCA) was conducted to understand the relationship between zooplankton composition and water quality parameters. The outcomes of CCA results were presented as the species and station biplots, in which the biotic and abiotic variables were represented together. The correlations between biological and environmental variables were tested using the Spearman's correlation coefficient.

For assessing the current status and to know the species homogeneity among the populations, different ecological diversity indices, like species richness (*d*) (Margalef, 1967), species diversity index (*H'*) (Shannon, 1948) and evenness index (*J'*) (Pielou, 1966), were computed.

Indicator species analysis (Dufrene and Legendre, 1997) was performed to identify potential indicator species of zooplankton for particular environmental conditions in each season. When all the individuals of particular taxa occur in a single season, Indicator Value *(IndVal)* index reaches the maximum (100%) indicating the asymmetric distribution of that taxa. However, *IndVal* index reaches the lowest level when the taxa is symmetrically distributed between seasons (Hunt and Hosie, 2006). According to Dufrene and Legendre (1997) a minimum 25% *IndVal* can be considered as the threshold limit to determine the indicator species in a group of observations. In our study, $\geq$40% value was used as the threshold to demarcate the *IndVal* index.

Additionally, a one-way analysis of variance (ANOVA) was applied to identify the significant ($p \leq 0.05$) differences between four distinct seasons for all biotic and abiotic variables. We also conducted the permutation (1000 ×) multivariate analysis of variance (PERMANOVA) to find out the significant ($p \leq 0.05$) differences in zooplankton abundance in terms of the season (monsoon, winter, spring and summer) and site (station 1 to 8).

All the graphs and statistical analysis was carried out using Microsoft Excel (MS Office-2013), PRIMER-version 6.0 (Clarke and Gorley, 2006) software and Multivariate Statistical Package (MVSP) program version 3.1 (Kovach, 1998).

3. Results

3.1. Spatio-temporal variation of hydrological parameters

The hydrological changes in the study area on a spatio-temporal scale are presented in Fig. 2 and Table 1. Physicochemical parameters, like temperature, salinity, Secchi depth, DO, pH, Chl-*a*, nutrients and SPM showed a wide range of variability among studied stations. The significant ($p \leq 0.05$) seasonal changes of all environmental parameters along with their ANOVA value are presented in Table 1.

The seasonal mean of surface water temperature ranged from 22.34 ± 1.29°C (winter) to 31.98 ± 0.94°C (summer) during the study period. The highest (33.4°C) and the lowest value (20.5°C) were observed at station 6 during summer and winter, respectively (Fig. 2a). Salinity varied between 11.93 ± 3.96 and 31.93 ± 1.97 during the overall sampling period (Table 1). Moreover, its range varied at different sampling stations according to their distance from the sea. Upstream stations showed more or less low saline regime in comparison to downstream stations (Fig. 2b). The highest pH value (8.42) was recorded at station 8 and the lowest value (7.40) was recorded at station 5 during monsoon and spring, respectively (Fig. 2c). The DO of surface water varied from 4.77 ± 0.13 mg L^{-1} (during summer) to 6.56 ± 0.80 mg L^{-1} (during monsoon). A significant spatial variation has been documented during all sampling seasons (monsoon, winter, spring and summer). The upstream stations showed elevated oxygenated water in comparison with the rest of the stations, and a decreasing trend was observed from the riverside to seaside (Fig. 2d). The transparency of water was measured by Secchi depth and it ranged from 55 ± 7.07 cm to 20.13 ± 7.22 cm during the study period (Fig. 2e). The mean concentration of SPM was recorded at maximum (261.18 ± 96.68 mg L^{-1}) during summer and at minimum (27.38 ± 9.16 mg L^{-1}) during spring (Fig. 2f).

The essential micronutrients concentrations varied both spatially and temporally in the present study. The average NO_2-N concentration varied between 0.31 ± 0.08 μM and 0.61 ± 0.41 μM. The maximum value of NO_2-N was detected at seaward stations, and the highest value (1.32 μM) being recorded at station 6 during spring (Fig. 3a). A similar type of seasonal trend was also noticed for NO_3-N, PO_4-P and SiO_4-Si. The mean concentration was found to be decreasing from monsoon to spring and again starting to increase during summer (Fig. 3b, c and d). The average NO_3-N and PO_4-P concentrations were recorded from 17.47 ± 3.55 μM to 4.18 ± 1.29 μM and 1.64 ± 0.69 μM to 0.23 ± 0.17 μM, respectively, during the study period. The SiO_4-Si value was higher (53.05 ± 7.56 μM) during monsoon and lower (17.70 ± 5.55 μM) during spring. The highest value of SiO_4-Si (64.08 μM) occurred at station 1 during

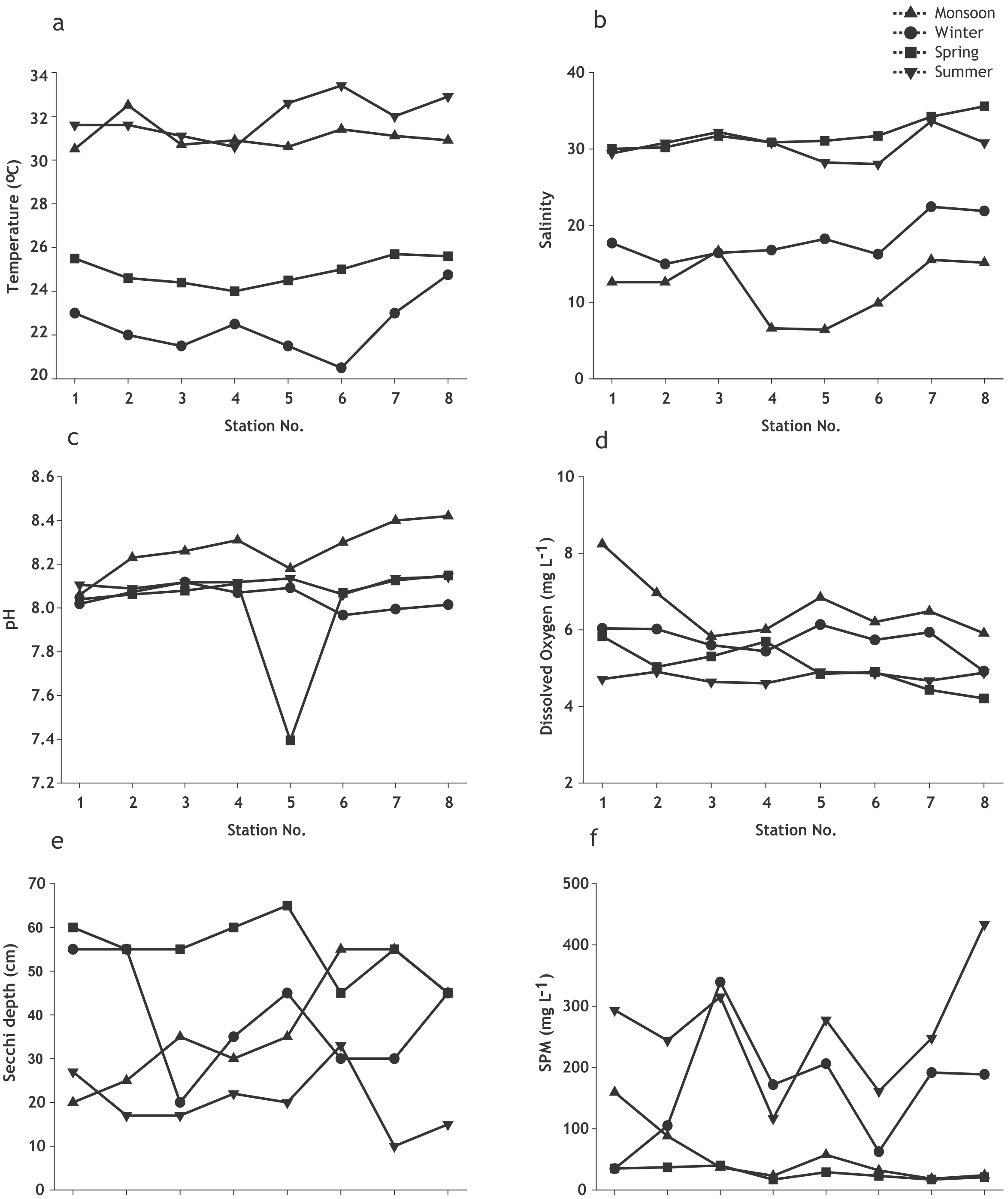


Figure 2 Spatio-temporal variation of hydrological parameters (a — water temperature, b — salinity, c — pH, d — dissolved oxygen, e — secchi depth, f — suspended particulate matter).

monsoon and the lowest value (11.25 μM) at station 6 during spring. Lower NH_4-N concentration was registered during winter (0.17 ± 0.11 μM) and higher values in summer (2.32 ± 0.65 μM) (Fig. 3e).

During monsoon, the mean concentrations of Chl-*a* and Phaeo were recorded at maximum (4.14 ± 1.98 μg L^{-1} and 0.50 ± 0.47 μg L^{-1}, respectively). However, minimum values of Chl-*a* and Phaeo (2.53 ± 1.12 μg L^{-1} and 0.18 ± 0.14 μg L^{-1}) were observed during winter and spring, correspondingly. An elevated Chl-*a* concentration was recorded at the middle stretch of the estuary (stations 3—5) during all sampling seasons (Fig. 3f). However, there were no sig-

Table 1 Mean values and standard deviation (SD) of biogeochemical parameters of 8 stations sampled during four seasons. In the last column, results of ANOVA test for the comparison between these four seasons is presented. Asterisks denote significant ($p \leq 0.05$) differences.

Parameters	Monsoon				Winter				Spring				Summer				*(p values)*
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	
Temperature (°C)	30.50	32.50	31.08	0.64	20.50	24.75	22.34	1.29	24.00	25.70	24.91	0.63	30.60	33.40	31.98	0.94	0.0001*
Secchi depth (cm)	20.00	55.00	37.50	13.09	20.00	55.00	39.38	12.66	45.00	65.00	55.00	7.07	10.00	33.00	20.13	7.22	0.0025*
Salinity	6.41	16.68	11.93	3.96	14.98	22.46	18.11	2.71	30.01	35.58	31.93	1.97	28.04	33.64	30.51	1.90	0.0057*
DO (mg L^{-1})	5.83	8.24	6.56	0.80	4.92	6.14	5.73	0.40	4.21	5.83	5.03	0.57	4.61	4.91	4.77	0.13	0.0073*
pH	8.06	8.42	8.27	0.12	7.97	8.12	8.04	0.05	7.40	8.15	8.00	0.25	8.06	8.14	8.11	0.03	0.0001*
Nitrate-N (μM)	12.12	23.10	17.47	3.55	3.44	18.14	10.22	5.13	1.94	5.88	4.18	1.29	12.23	14.17	13.40	0.54	0.0221*
Nitrite-N (μM)	0.21	0.40	0.31	0.08	0.21	0.59	0.39	0.11	0.13	1.32	0.61	0.41	0.28	0.56	0.41	0.10	0.0188*
Phosphate-P (μM)	0.90	2.93	1.64	0.69	0.81	2.17	1.42	0.38	0.04	0.53	0.23	0.17	0.91	1.88	1.37	0.35	0.1131
Silicate (μM)	43.67	64.08	53.05	7.56	3.44	46.98	32.38	13.35	11.26	28.22	17.70	5.55	28.32	30.90	29.56	0.91	0.006*
Ammonium-N (μM)	0.23	0.59	0.35	0.11	0.06	0.39	0.17	0.11	0.19	0.42	0.30	0.09	1.80	3.82	2.32	0.65	0.0827
Chl-*a* (μg L^{-1})	1.20	6.90	4.14	1.98	1.04	4.10	2.53	1.12	3.01	4.64	3.73	0.54	3.06	4.90	4.11	0.55	0.1820
Phaeopigments (μg L^{-1})	0.08	1.36	0.50	0.47	0.14	1.18	0.46	0.44	0.03	0.41	0.18	0.15	0.12	0.73	0.45	0.20	0.0179*
SPM (mg L^{-1})	18.21	159.40	54.90	48.06	34.61	339.34	162.44	95.98	17.00	40.00	27.38	9.16	116.60	433.80	261.18	96.68	0.0598
Zooplankton abundance (ind. m^{-3})	324.00	2154.00	1202.88	768.38	331.00	4185.00	1616.00	1391.01	257.00	1126.00	573.38	270.22	428.00	1566.00	951.38	482.40	0.0026*
Zooplankton biomass (g m^{-3})	1.05	4.93	2.68	1.48	0.95	6.18	3.28	1.87	0.95	2.70	1.88	0.61	1.15	4.80	2.69	1.35	0.0186*

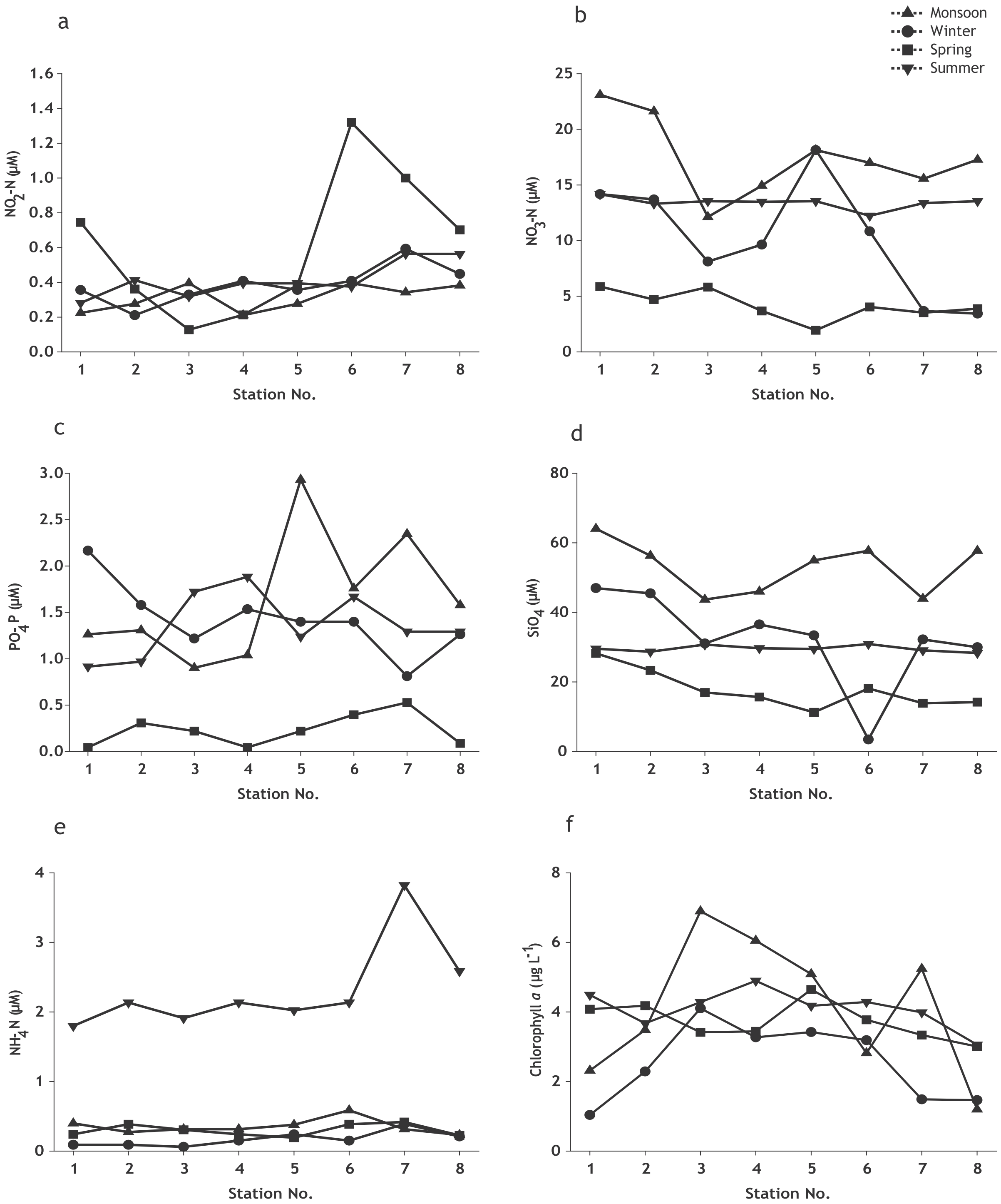


Figure 3 Spatio-temporal variation of nutrients (a — nitrite-N, b — nitrate-N, c — phosphate-P, d — silicate, e — ammonium-N) and f — Chl *a* concentration.

nificant spatial distribution differences for Phaeo concentration throughout the study period.

3.2. Community structure and composition of zooplankton

In the present study, a noticeable change in the zooplankton community structure with regard to density and diversity was evident among the study stations and between different seasons. The average zooplankton abundance ranged from 573 ± 270 ind. m^{-3} (during spring) to 1616 ± 1392 ind. m^{-3} (during winter). The highest abundance was observed at station 6 during winter (4185 ind. m^{-3}), howbeit, the lowest value was documented during spring at station 6 (257 ind. m^{-3}) (Fig. 4a). Station-wise variations in zooplankton biomass during four sampling seasons are plotted

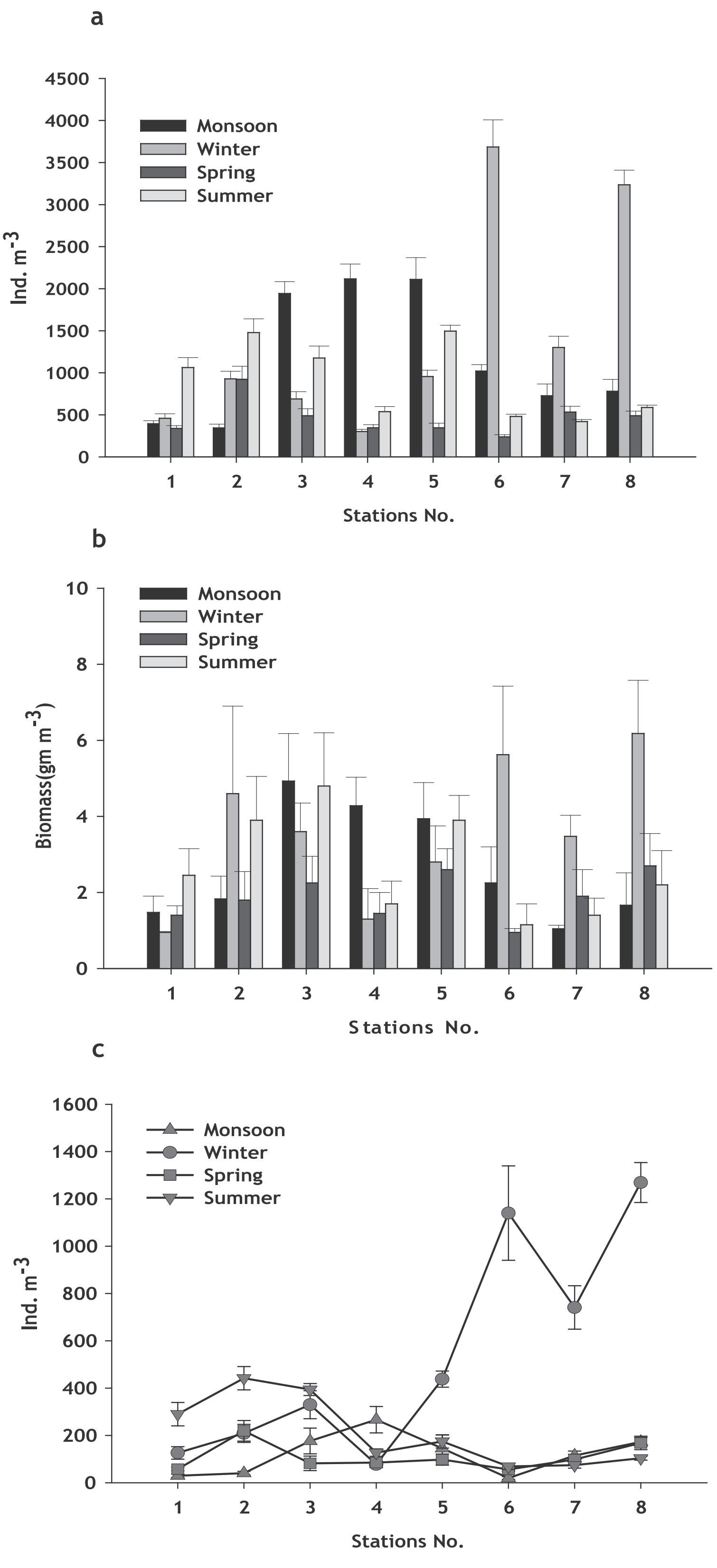


Figure 4 Spatio-temporal variation of a — total zooplankton abundance, b — zooplankton biomass and c — meroplankton population.

in Fig. 4b. The total biomass was recorded higher during winter (ranging from 6.18 to 0.95 gm m^{-3}) and lower during spring (ranging from 2.70 to 0.95 gm m^{-3}); the variation among seasons was found to be significant with $p= 0.0186$ (Fig. 4b).

A total of 56 zooplankton taxa have been documented through the analysis of 32 samples collected from 8 stations during 4 seasons. Copepoda were the most abundant, both quantitatively and qualitatively. They were represented by 36 species belonging to 4 orders. Calanoida emerged as a dominant group with 25 species followed by Cyclopoida (5 species), Harpacticoida (4 species) and Poecilostomatoida (2 species). Out of 36 species of Copepoda recorded, only 8 species had been identified as perennial existing during four sampling seasons. These species are: *Acartia spinicauda, Acartia* sp., *Bestiolina similis, Euterpina acutifrons, Labidocera acuta, Paracalanus aculeatus, P. parvus* and *P. indicus*. Additionally, 5 taxa of other groups (like: Bivalvia, Gastropoda, Polychaeta, *Zonosagitta bedoti* and Decapoda zoeae) have been recorded as perennial during entire study period. Different larval stages of noncopepods, especially the meroplankton community, have also been observed in a significant amount. The shellfish larval populations (like Bivalve D-larva, Gastropoda veliger larvae, crab zoea larva and shrimp larvae) were documented as a second dominant group of the total zooplankton abundance. Except during the winter period, their mean density declined considerably towards the downstream stations during the overall study period. Among all seasons the maximum shellfish larval population (ranging from 78 ± 13 to 1269 ± 84 ind. m^{-3}) was recorded during winter, especially at mouth stations of the estuary facing Bay of Bengal. On the other hand, the minimum shellfish larval density was documented during spring (ranging from 56 ± 8 to 219 ± 44 ind. m^{-3}) (Fig. 4c).

The spatio-temporal changes of different diversity indices are presented in Fig. 5. Shannon index of diversity (*H'*) values generally increased in parallel to the species number throughout the study period. The highest diversity ($H'=2.83$) was observed during spring and lowest ($H'=1.78$) during monsoon at station 5 and 6, respectively. The species evenness (*J'*) varied between 0.74 and 0.95 in monsoon; 0.82 and 0.91 in winter; 0.89 and 0.93 in spring and, 0.85 and 0.95 during the summer season. The maximum richness value (*d*) was recorded during spring ranging from 2.68 to 3.62, however, monsoon samples showed lower values ranging from 1.29 to 2.70 (Fig. 5).

The spatio-temporal changes of zooplankton distribution and cluster formation are shown in Fig. 6. Table 2 is generated from SIMPER analysis of the dendogram plot (Fig. 6) to determine the contribution percentages of different zooplankton taxa in the formation of a specific cluster. During monsoon, lowest zooplankton abundances (324 ind. m^{-3}) were recorded at station 2 and highest (2154 ind. m^{-3}) at station 5, with an average of 1203 ± 768 ind. m^{-3}. The community was largely dominated (87%) by Copepoda. The cluster analysis revealed a clear spatial distribution of zooplankton during this season. Two distinct groups were formed: group I (station 1—3) and group II (station 4—8) with 72.18 and 73.36% of average similarities, respectively. *B. similis, P. parvus, P. aculeatus* and *Oithona similis* showed maximum contribution to form group I; however, *P. parvus, P. aculeatus, Oithona brevicornis* and *A. spinicauda* contributed maximum percentages to form group II. In winter, the zooplankton standing crop increased to reach an average of 1616 ± 1391 ind. m^{-3}. It showed high fluctuation between 331 ind. m^{-3} (station 4) and 4185 ind. m^{-3} (station 6). The contribution of Copepoda to the total zooplankton population has been represented by 59%, which drastically dropped compared to the previous season. However, the Mollusca

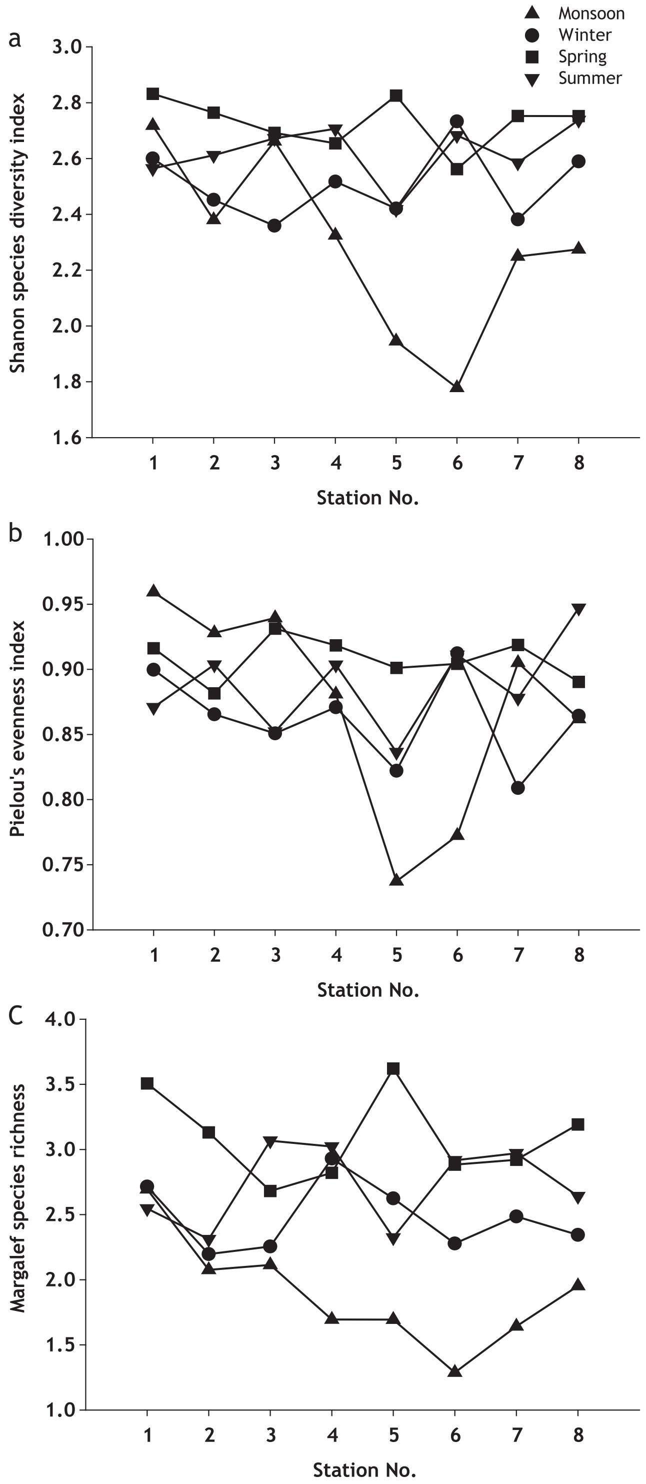


Figure 5 Spatio-temporal variation of different diversity indices.

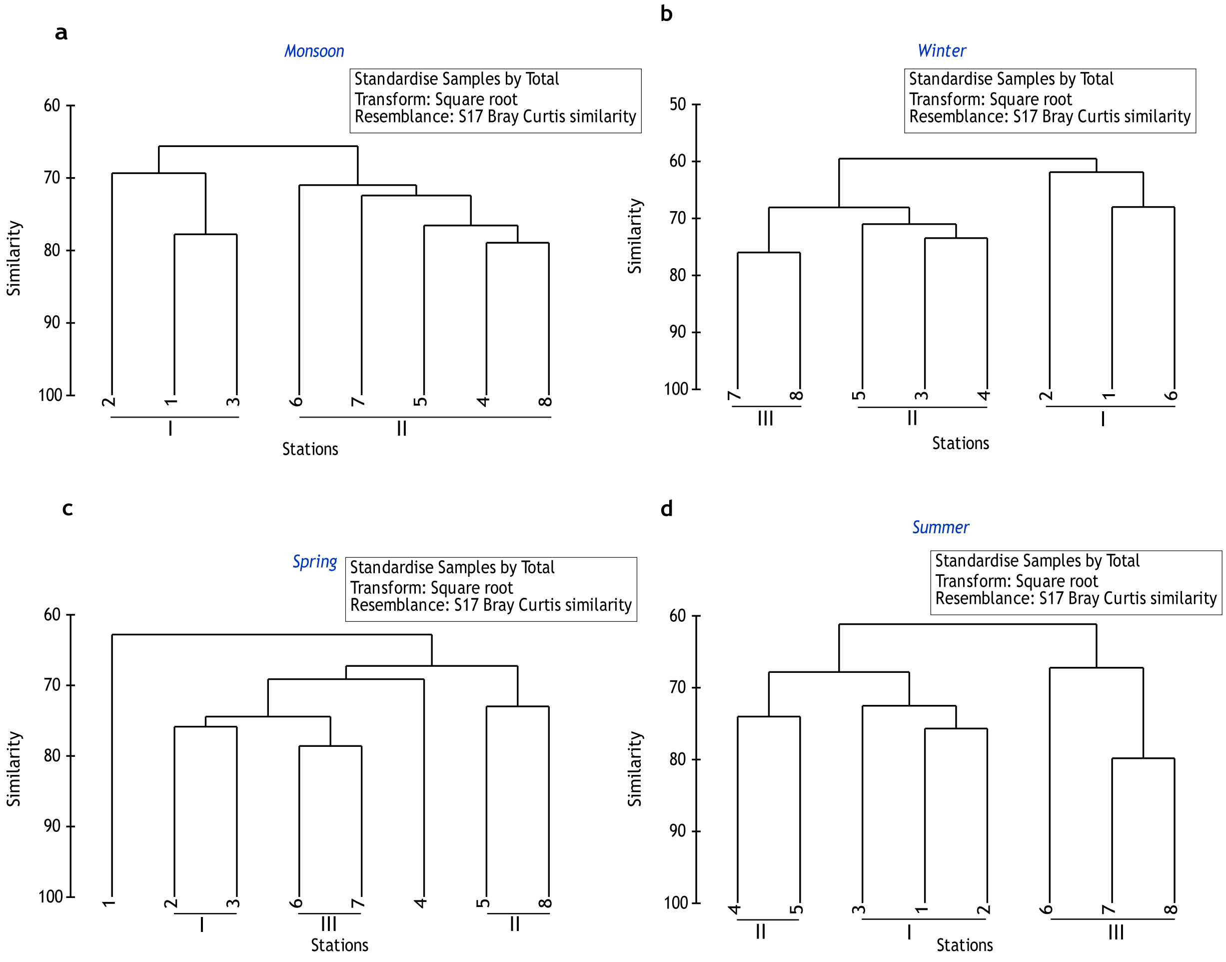


Figure 6 Dendogram plot of cluster analysis based on total zooplankton abundance during four seasons.

larvae were the second most abundant group and they are dominated by Gastropoda veliger larvae (14%) and Bivalvia-D larvae (9%) of the total zooplankton count. Three separate cluster group were generated with 63.96%, 71.86% and 76.02% of similarity in group I (station 1, 2 and 6), II (station 3—5) and III (station 7—8), respectively. The major contribution of *P. parvus* and Gastropoda veliger larvae plays a pivotal role to form these groups in conjunction with other zooplankton taxa.

The zooplankton average abundance was the lowest during spring (573 ± 270 ind. m^{-3}) ranging between 257 ind. m^{-3} (station 6) and 1126 ind. m^{-3} (station 2). Mature Copepoda and their nauplii together contributed 66% of the total zooplankton. Three groups (I, II and III) and two separate stations (station 1 and 4) were generated from the cluster analysis. The prevalent distribution of Copepoda nauplii contributed 9.79%, 11.28% and 8.38% in group I (station 2—3), II (station 5 and 8) and III (station 6—7), respectively, during this season. After spring, the zooplankton community increased in number during summer to reach an average of 951 ± 482 ind. m^{-3}. Average zooplankton abundance fluctuated from 420 ± 24 ind. m^{-3} (station 7) to 1495 ± 70 ind. m^{-3} (station 5) and the community was dominated by Copepoda (63%) during this season. A significant spatial distribution of zooplankton was documented from the cluster analysis, comprising with group I (station 1—3; 73% similarity), group II (station 4 and 5; 74.05% similarity) and group III (station 6—8; 71.46%).

The PERMANOVA analysis was performed to identify the major changes of zooplankton population. There were significant variations documented both spatially ($F = 713.12$, $p = 0.001$) and seasonally ($F = 150.66$, $p = 0.001$). Altogether, the spatio-temporal ($F = 288.33$. $p = 0.001$) variations were found to be significant in the present study.

3.3. Influence of environmental factors on zooplankton distribution

The statistical relationships between the composition of zooplankton and the physicochemical variables were also analysed at different study stations. We used CCA to explore the relationship between environmental variables and zooplankton assemblages and two graphs are generated as station and species biplots (Fig. 7). The station biplot depicts the responsible environmental parameters for clustering different study stations during different seasons. In the present study, all sampling stations distinctly clustered together depending on the particular season as governed

Table 2 SIMPER analysis of zooplankton assemblages determined by dendrogram plot considering each season: average similarity (%) and main taxa contribution (%).

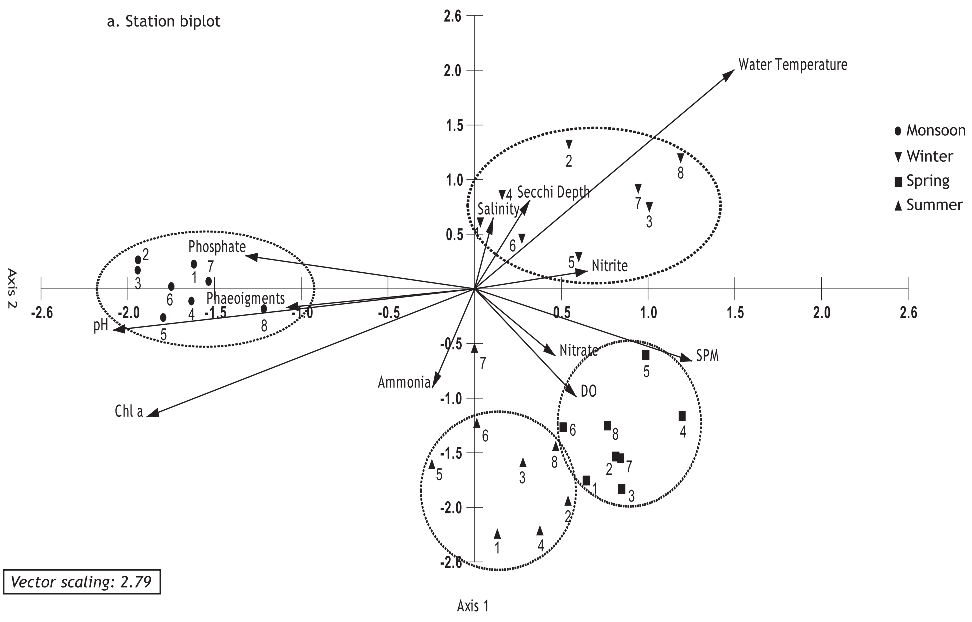
Groups			
Monsoon	I	II	
Average similarity (%)	72.18	73.36	
Main taxa contribution (%)	*Bestiolina similis* (12.33)	*Paracalanus parvus* (22.47)	
	Paracalanus parvus (10.52)	*Paracalanus aculeatus* (11.88)	
	Paracalanus aculeatus(9.42)	*Oithona brevicornis* (10.31)	
	Oithona similis(8.75)	*Acartia (Odontacartia) spinicauda* (9.11)	
Winter	I	II	III
Average similarity (%)	63.96	71.86	76.02
Main taxa contribution (%)	*Paracalanus parvus* (13.80)	Gastropoda veliger (15.72)	Decapoda Brachyura zoeae (15.13)
	Gastropoda veliger (11.64)	*Paracalanus parvus* (11.96)	*Paracalanus parvus* (10.76)
	Bestiolina similis (9.99)	Decapoda Brachyura zoeae (8.11)	Gastropoda veliger (9.09)
	Bivalvia D larva (9.64)		
	Labidocera minuta (9.26)		
Spring	I	II	III
Average similarity (%)	75.88	73.01	78.63
Main taxa contribution (%)	*Paracalanus parvus* (10.80)	Copepoda nauplii(11.28)	*Paracalanus parvus* (12.00)
	Copepoda nauplii (9.79)	*Paracalanus parvus* (10.45)	*Bestiolina similis* (10.08)
	Zonosagitta bedoti (8.58)	Gastropoda veliger (9.88)	Gastropoda veliger (8.92)
			Copepoda nauplii (8.38)
Summer	I	II	III
Average similarity (%)	73.6	74.05	71.46%
Main taxa contribution (%)	Gastropoda veliger (12.82)	*Bestiolina similis* (11.74)	*Paracalanus parvus* (13.79)
	Bivalvia D larvae (10.84)	*Paracalanus parvus* (9.70)	*Bestiolina similis* (10.83)
	Paracalanus parvus (10.43)	*Eucalanus* sp. (9.69)	*Paracalanus aculeatus* (10.09)

by most responsible physicochemical parameters. For example, the samples collected during monsoon season were regulated by PO_4-P, pH and Phaeo enriched estuarine environment. Winter season showed preferences with respect to salinity, Secchi depth and temperature of the surface water. Furthermore, spring season samples were clustered in close association with DO, NO_2-N and SPM; and summer samples slightly accumulated near the elevated NH_4-N concentration (Fig. 7a). The species biplot was done to investigate the role of environmental parameters on zooplankton species distribution. In this plot, distinct clusters and species associations are formed depending on their preferred environmental conditions. A total of 56 zooplankton taxa were used in the CCA gradient analysis. Eigenvalues for CCA axis 1 and axis 2 represent 30.86% of the cumulative variance in the species data. Species-environment correlations were high for both axes (Axis 1=0.91; Axis 2=0.90) (Fig. 7b). *Acrocalanus longicornis, O. similis* and *O. brevicornis* preferred the environment with high pH values during the study period, mostly recorded in monsoon season. Few herbivorous copepods, like *Acartia* sp., *Acrocalanus gracillis, Canthocalanus pauper, Oithona simplex* and *Paracalanus* sp. were found to be positively correlated with PO_4-P. Some winter season notable taxa, like Pycnogonida, Bryozoa cyphonautes, *Subeucalanus subcrassus, Longipedia weberi* and *Centropages* sp. were favoured by transparent and high saline estuarine environment. However, few taxa, like nauplius larva, *Belzebub penincilifer,* Crustacea zoeae, and Copepoda, like *Acartia clausi, Labidocera acuta, L. minuta* and *Temora discaudata*, slightly correlated with water temperature and these species were totally absent during monsoon season. The distribution of carnivorous zooplankton Hydrozoa actinulae, *Corycaeus crassiusculus* and *Labidocera* sp. were associated with SPM of surface water. Species like *Acartia danae, E. elongatus elongatus, Euterpina acutifrons*, Copepoda nauplii, Euphausiacea calyptopis, Echinodermata larvae and Decapoda larvae were found to prefer moderate to low oxygen and NO_3-N content water mass, recorded during post-monsoon period, especially in spring. Some omnivorous zooplankton, like Polychaeta larvae, fish larvae, *Pseudodiaptomas serricaudatus* and *Oncaea venusta*, had been associated with NH_4-N enriched water. The Chl-*a* concentration did not exhibit any significant contribution to the distribution pattern of zooplankton population during the present study (Fig. 7b).

3.4. Seasonal occurrences of indicator species

The analysis of nMDS was performed to unravel the seasonal variation on the basis of total zooplankton population dynamics (Fig. 8). Table 3 showed the different dissim-

a. Station biplot



b. Species biplot

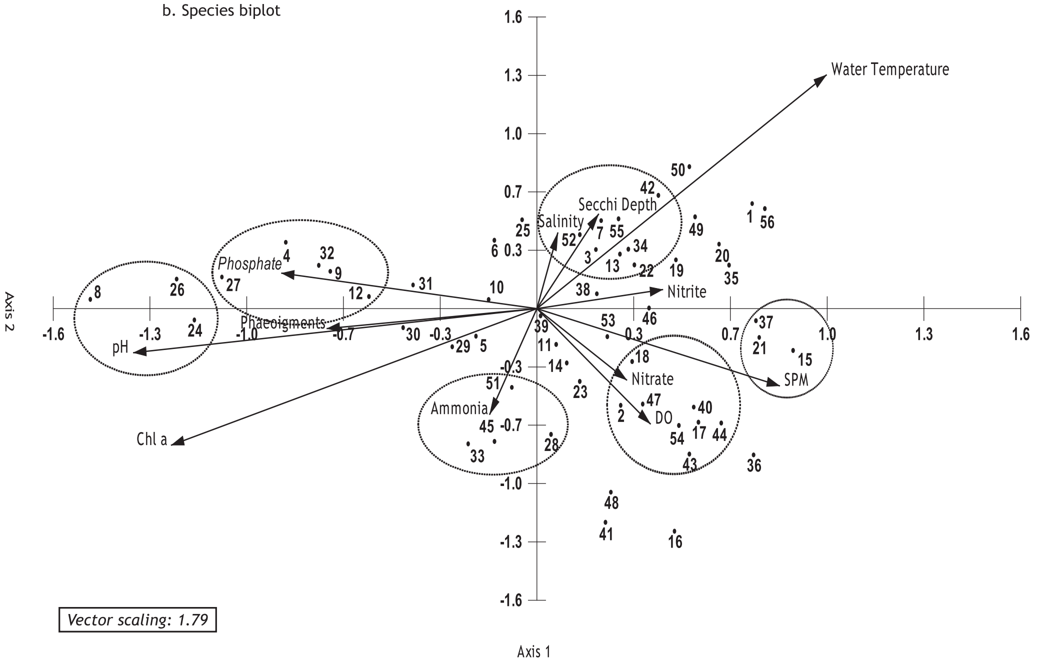


Figure 7 CCA analysis of different zooplankton taxa with associated environmental variables and study stations. (a — station biplot, b — species biplot; Code no. of zooplankton taxa are given in Table 4).

ilarity percentages of four seasons along with their ANOSIM value, indicating the significant variation amongst them. The positive or the value closest to 1 specifies the significant changes between two seasons. The remarkable changes of mean abundances of some zooplankton taxa between different seasons (responsible for seasonal variation) might show the indicator species for the particular season due to their exclusive seasonal occurrences. The result of *IndVal* analysis demarcated altogether 10 Copepoda and 12 non-Copepoda taxa as major indicators of different studied seasons (Table 4). During the monsoon, *Acartia* sp., *O. brevicornis, O. similis, O. simplex, P. parvus* were the indicator species for all study stations. However, in winter *A. clausi*, *Labidocera minuta*, Bryozoa cyphonautes, Gastropoda veliger, *Zonosagitta bedoti* and Decapoda zoeae were found to be dominant and maximum *IndVal* index was encountered. *C. crassiusculus*, Copepoda nauplii, Euphausiacea calyptopis, Echinodermata larvae and Hydrozoa were the significant indicator species for spring season, lastly high value of *IndVal* index was documented for *Eucalanus* sp., *E.*

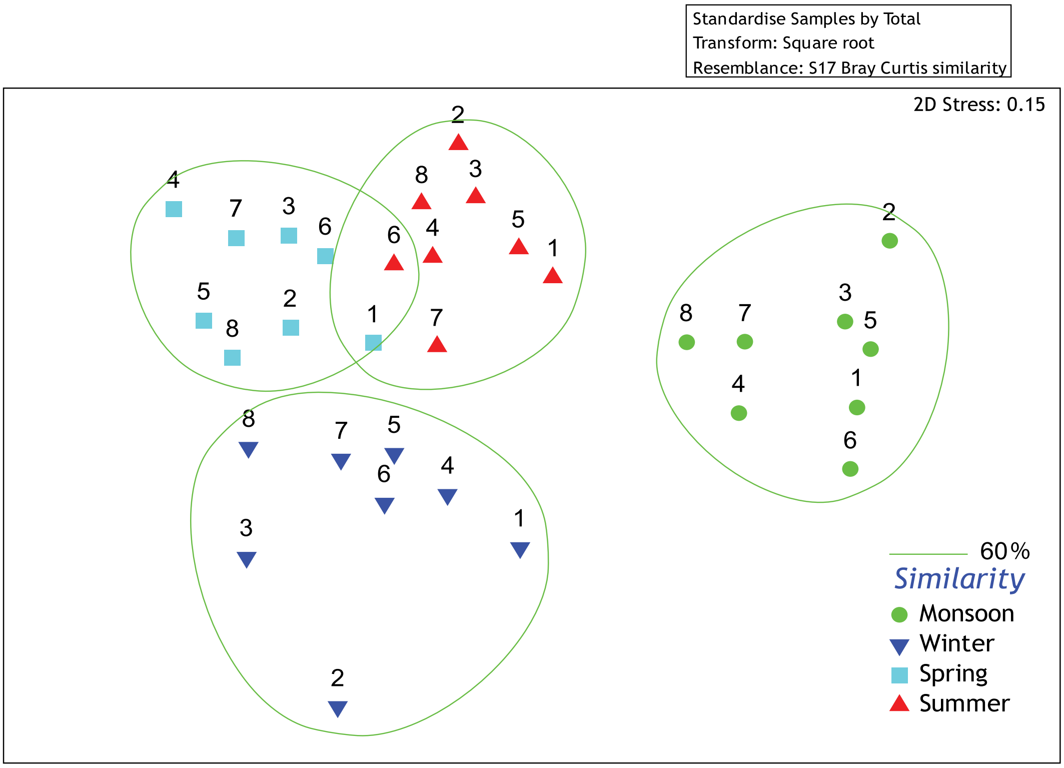


Figure 8 NMDS plot for seasonal zooplankton assemblages sampled in the river Matla.

Table 3 SIMPER analysis for zooplankton assemblages formed by NMDS considering each season: average dissimilarities (%) and ANOSIM results between two seasons are presented.

Seasons	Average dissimilarity (%)
Monsoon and Winter (ANOSIM, global R= 0.956, p=0.001)	55.46
Monsoon and Spring (ANOSIM, global R=0.997, p=0.001)	58.34
Monsoon and Summer (ANOSIM, global R=0.946, p=0.001)	50.13
Winter and Spring (ANOSIM, global R=0.742, p=0.001)	44.33
Winter and Summer (ANOSIM, global R=0.766, p=0.001)	46.06
Spring and Summer (ANOSIM, global R=0.628, p=0.001)	40.77

elongatus elongatus, Ctenophora, *Belzebub hanseni* and Decapoda larvae during summer (Table 4).

4. Discussion

4.1. Changes in the environmental variables

Physico-chemical variables in the estuarine ecosystem are subjected to wide temporal variations. The river Matla in SES is largely influenced by southwest monsoonal rainfall in India. According to Santhosh Kumar and Perumal (2011), the monsoonal rainfall is an important phenomenon in tropical countries as it regulates the biogeochemical characteristics of the coastal and estuarine environment. In the present study, each of the hydrographic parameters such as water temperature, salinity, pH and DO showed remarkable spatio-temporal variations. In general, the higher temperature was recorded in pre-monsoon period at summer season while the lower temperature was observed during winter. SES is located at the north-western coast of Bay of Bengal and the temperature over the bay is primarily regulated by several climatic events, like the atmospheric weather condition and rainfall event (Kannan and Kannan, 1996). Temperature variations throughout the present study period could also be governed by the seasonal changes in atmospheric conditions and monsoonal rainfall.

The salinity acts as a limiting factor in the distribution pattern of marine organisms. Moreover, changes in salinity due to the effect of dilution and evaporation can regulate the faunal composition in the coastal ecosystem (Balasubramanian and Kannan, 2005; Sridhar et al., 2006). In the present study, the lower salinity values during monsoon season could be attributed to the combined effect of precipitation and freshwater influx from surrounding land runoff.

The pH recorded during summer and monsoon period was found to be comparatively higher than in winter and spring season. Influence of seawater inundation and biological activity of photosynthetic organisms might be the possible reason for high summer pH. Furthermore, the observed high pH along with elevated DO during monsoon season might be the

Table 4 List of identified zooplankton taxa with their indicator values for each season. Bold values are considered major indicator species (*IndVal* index $\geq$ 40) for the present study.

CCA code	Name of identified zooplankton taxa	Monsoon	Winter	Spring	Summer
1	*Acartia (Acartiura) clausi* Giesbrecht, 1889	0	**74.47**	9.31	0
2	*Acartia (Acartia) danae* Giesbrecht, 1889	0	0	1.79	21.43
3	*Acartia (Acartia) negligens* Dana, 1849	0	32.29	0.69	1.04
4	*Acartia* sp.	**56.85**	6.05	1.21	0.41
5	*Acartia (Odontacartia) spinicauda* Giesbrecht, 1889	33.80	20.83	6.35	29.10
6	*Acartia sewelli* Steuer, 1934	6.82	32.95	0	0.85
7	*Acrocalanus gibber* Giesbrecht, 1888	0	12.5	0	0
8	*Acrocalanus gracilis* Giesbrecht, 1888	26.47	0	0	7.35
9	*Acrocalanus longicornis* Giesbrecht, 1888	**50**	0	0	0
10	*Bestiolina similis* Sewell, 1914	29.52	34.63	11.94	1
11	*Bomolochus* sp.	0	0	12.5	0
12	*Canthocalanus pauper* Giesbrecht, 1888	25	0	0	0
13	*Centropages* sp.	0	12.5	0	0
14	*Clytemnestra scutellata* Dana, 1848	0	0	12.5	0
15	*Corycaeus crassiusculus* Dana, 1849	0	20.46	**57.58**	5.68
16	*Eucalanus* sp.	0	0	25.68	**70.65**
17	*Eucalanus elongatus elongatus* Dana, 1849	0	7.72	30.39	**49.02**
18	*Euterpina acutifrons* Dana, 1848	0.3	9.52	20.83	22.32
19	*Labidocera acuta* Dana, 1849	1.09	38.43	12.5	12.5
20	*Labidocera minuta* Giesbrecht, 1889	0	**63.03**	26.89	6.3
21	*Labidocera* sp.	0	0	12.5	0
22	*Longipedia weberi* Scott A., 1909	0	19.11	5.88	0
23	*Microsetella norvegica* Boeck, 1865	0	0	0	12.5
24	*Oithona brevicornis* Giesbrecht, 1891	**83.01**	0	3.75	5.5
25	*Oithona nana* Giesbrecht, 1893	12.5	0	0	0
26	*Oithona similis* Claus, 1866	**91.3**	0.36	0	1.45
27	*Oithona simplex* Farran, 1913	**62.19**	0	6.1	0.61
28	*Oncaea venusta* Philippi, 1843	0	0	6.25	6.25
29	*Paracalanus aculeatus* Giesbrecht, 1888	34.45	26.72	7.84	27.17
30	*Paracalanus indicus* Wolfenden, 1905	36.02	17.72	0.2	16.54
31	*Paracalanus parvus* Claus, 1863	**45.94**	25.7	10.52	17.84
32	*Paracalanus* sp.	36.16	0	3.57	0
33	*Pseudodiaptomus serricaudatus* Scott T., 1894	0	0	0	37.5
34	*Subeucalanus subcrassus* Giesbrecht, 1888	0	25	0	0
35	*Temora discaudata* Giesbrecht, 1889	0	7.5	0.84	8.33
36	*Temora turbinata* Dana, 1849	0	0	2.78	29.17
37	Hydrozoa acrinulae	0	0	25	0
38	Arachnida	0	0	0	0
39	Bivalvia D larvae	26.16	34.77	7.95	26.16
40	Copepoda nauplii	0	17.63	**45.87**	13.46
41	Ctenophora	0	0	0	**62.5**
42	Cyphonautes larvae	0	**63.59**	2.17	1.63
43	Euphausiacea calyptopis	0	0	**62.5**	0
44	Echinodermata larvae	0	6.48	**55.55**	0
45	Fish larvae	2.5	0	5	30
46	Gastropoda veliger	8.52	**51.31**	12.12	26.84
47	Hydrozoa medusae	0	0	**62.5**	0
48	*Belzebub hanseni* Nobili, 1906	0	0	0	**87.5**
49	*Belzebub penicillifer* Hansen, 1919	0	21.4	1.78	0
50	Nauplius larvae (Cirripedia)	0	**82.8**	0.66	0
51	Polychaeta larvae	19.85	14.34	1.11	31.25
52	Pycnogonida	0	25	0	0
53	*Zonosagitta bedoti* (Béraneck, 1895)	9.87	**44.23**	16.59	28.85
54	Decapoda larvae	0	0	0	**87.5**
55	Star fish juvenile (Echinodermata)	0	37.5	0	0
56	Decapoda Brachyura zoeae	0.56	**71.19**	6.48	5.8

cumulative effect of higher wind velocity coupled with massive rainwater and the resultant freshwater mixing in the estuarine system (Das et al., 1997).

Nutrients levels are known to be a significant determinant of estuarine productivity and their spatio-temporal variations can play a crucial role by influencing the process of competition and community structure as well as trophic dynamics in the estuarine environment (Gaonkar et al., 2010). Distribution of nutrients in an estuary is principally controlled by season, tidal condition and freshwater runoff from surrounding landmass. Nitrite (NO_2-N), the most unstable form of nitrogenous nutrients in seawater, exhibited wide range of fluctuation. Its variations in surface water throughout the study period could be ascribed to the excretion of the planktonic organism, oxidation of ammonia, reduction of nitrate and bacterial decomposition of planktonic detritus (Govindasamy et al., 2000). In the present study, the high monsoonal value of major micronutrients (NO_3-N, PO_4-P and SiO_4-Si) concentration could be influenced by organic matter received from the catchment area (Das et al., 1997). The maximum recorded value of NO_3-N during monsoon season and the lowest recorded salinity clearly signifies the freshwater inflow as a major contributor of nitrate in the estuarine system. According to Karuppasamy and Perumal (2000), Santhanam and Perumal (2003) and Sarkar et al. (2007) nitrate level was generally increased by land drainage, precipitation, decomposition of mangrove litter and terrestrial runoff during monsoon season. In contrast, during post-monsoon period, the prevalent lower value of NO_3-N is linked to the biological utilization and primary productivity in shallow estuarine water (MacIntyre et al., 1996). Like nitrate, PO_4-P concentration also exhibited higher value during monsoon, indicating the influence of freshwater influx in the present study area. Maximum concentration of inorganic phosphates during monsoon might be due to the intrusion of seawater into the mangrove creeks and enrichment by freshwater drainage (Mathew and Pillai, 1990; Nair et al., 1984). The low value of phosphate in spring could be recognized by high salinity and utilization of phosphate by phytoplankton, along with the low freshwater influx in the estuarine system (Senthilkumar et al., 2002). The lower concentration of SiO_4-Si during the post-monsoon period, especially in spring, could be connected to its uptake by phytoplankton for their biological activity (Mishra et al., 1993; Ramakrishnan et al., 1999). Furthermore, the high silicate concentration during monsoon might be due to the resuspension of bottom sediment (Rakhesh et al., 2008). The higher concentration of NH_4-N recorded during summer could be partially due to the death, subsequent decomposition and excretion of ammonia by planktonic organisms (Segar and Hariharan, 1989).

4.2. Diversity and distribution of the zooplankton population

In the present study, 56 zooplankton taxa have been reported from the river Matla at SES, the number of zooplankton recorded in this river is in accordance with the published report from the river Saptamukhi (Nandy et al., 2018) and the northern part of the Sundarban mangrove wetland (Bhattacharya et al., 2015). Zooplankton community changes of the SES indicated a strong seasonal pattern showing lower abundances in the spring-summer period and higher density in monsoon-winter time. In dry weather during spring, lower temperature and the shortest daylight hours coupled with water transparency might have reduced the secondary productivity and had a cascading effect as was mirrored by diminished zooplankton abundance during this period. Contrarily, high to moderate temperature, low salinity and availability of sufficient nutrients were the favourable conditions for increasing the zooplankton abundance during and after the wet season in SES (Nandy et al., 2018) which corroborates present findings.

The high abundance of zooplankton in monsoon and post-monsoon seasons might be attributed to a combination of temperature, salinity and Chl-*a* concentration, which are considered the main factors in regulating the population dynamics (Peterson and Bellantoni, 1987). Seasonal studies in different coastal areas highlighted the similar relationship between the zooplankton abundance and the elevated temperature and Chl-*a* concentration (Biancalana et al., 2014; Vieira et al., 2003), and are also in agreement with present findings. In accordance with earlier studies in the Sundarbans (Bhattacharya et al., 2015; Nandy et al., 2018) as well as Indian coastal belt (Srichandan et al., 2015), our result also recorded high contribution of Copepoda among the total zooplankton. During the present study, the contribution of Copepoda to the total zooplankton population ranged from 59—87% as reported in many estuarine systems and coastal areas where Copepoda dominated the zooplankton community (Marques et al., 2006; Moderan et al., 2010; Mouny and Dauvin, 2002).

In the present study, a noticeable abundance of Copepoda with 87% of the total composition was documented during the peak monsoon season. The versatility of these taxa, which occupy several estuarine habitats is often due to their broad trophic spectrum. According to Jagadeesan et al. (2017), the temporal changes in the abundance of copepod community in a coastal area is generally influenced by the coastal upwelling and associated hydrographical changes of the estuarine environment. During the summer and winter seasons, Calanoida (e.g., *P. parvus, P. aculeatus, Bestiolina similis, Acartia* sp. and *A. spinicauda*) clearly outnumbered other Copepoda species. However, during the monsoon season, along with Calanoida few Cyclopoida (e.g., *Oithona nana, O. similis, O. simplex* and *O. brevicornis*) were also dominant in the community. The seasonal dominance of Cyclopoida in the SES was clearly highlighting the temporal shift in their composition. The overall ubiquitous dominance of genus *Oithona* during peak monsoon season suggests their high adaptability to trophic and hydrologic conditions, which might be due to their continuous reproduction and reduced mortality rates during this season (Nielsen and Sabatini, 1996; Pages et al., 1996).

SES is characterised by a rich population of Copepoda and meroplankton species adapted to endure changes in salinity and other hydrological parameters during winter. Moreover, the preponderance of meroplankton (e.g., Decapoda zoeae, Bryozoa cyphonautes, Bivalvia and Gastropoda veliger) in the SES suggests that these organisms take an important role in the coupling of benthic-pelagic food webs. The abundance and diversity of different larval forms (e.g., Zoea, nauplius, and veliger) and their enormous contribution to the total zooplankton population make SES a unique ecosystem during winter. Similar findings have also been reported by Rakhesh et al. (2008) at Kakinada Bay. During winter, different Mollusca veliger populations recorded maximum, especially at mouth stations, probably corresponding with their seaward migration from the estuarine system. These larval forms move into the water column from the bottom layer during tidal flooding, and they are flushed into downstream habitat by the ebb tides (Zhou et al., 2009). During this season the higher abundance of Chaetognatha (*Z. bedoti*), was recorded with high *IndVal* index (44.23). The previous study also reported their high abundance in SES due to their preference of estuarine environment during their development (Bhattacharya et al., 2015). Similarly, the high abundance of Chaetognatha during post-monsoon period was common in the coastal water of Adubidri (Resmi et al., 2011) and Rushikulla estuary (Srichandan et al., 2015) which is in agreement with our present observation.

In the present study, the lowest abundance of zooplankton occurred in the spring season. The increase of saline water in SES caused by excess evaporation and lower nutrients concentration during spring season might be the possible reason for recording low zooplankton abundance and biomass. In general, soon after monsoonal precipitation, the river runoff and water temperature start to decrease and cause depleted nutrients supply to the system, which has a cascading effect on lower productivity and might be the reason of less zooplankton abundance during this season. In tropical estuarine system zooplankton generally breed during post-monsoon season (winter). As it takes time for zooplankton to breed and grow, there is a time-lapse for the concentration of zooplankton to increase. For this reason, the abundance of zooplankton is the lowest in spring. Howbeit, during the summer season the high turbidity in estuarine waters (wind and tide induced resuspension) might affect the phytoplankton growth and restrain light availability; which may be the causative factor in recording the second-lowest zooplankton abundance in the study area. In agreement with our study, similar observations have also been reported from Kakinada Bay (Rakhesh et al., 2008) and Quinzhou Bay (Wang et al., 2014).

In our study salinity seemed to be an important factor in explaining the dynamics of the zooplankton, especially at a spatial scale. Marques et al. (2009) ascribed that salinity of different water masses is closely related to the distribution pattern of zooplankton. In the present study, spatial variation of salinity followed a similar pattern during four seasons. An increasing trend was observed from head to mouth of the estuary. The cluster analysis of four study seasons depicted a clear spatial distribution pattern of zooplankton population along the salinity gradient. During summer and monsoon seasons the upstream stations form a separate cluster apart from the middle and downstream stations. The major contribution of Bivalvia and Gastropoda clustered the upstream stations (station 1—3) during summer, indicating their seasonal recruitment during this time in SES. The upstream to downstream connectivity and directionality influence the passive distribution of zooplankton community. In SES, the significant spatial distribution of zooplankton during wet season could be explained by high river runoffs that create typical north-south river continuum environmental gradient patterns as described by Vannote et al. (1980) in the Ying river. Furthermore, the low runoff during dry season (spring) turned the river into numerous interconnected pools in SES, which resulted in a nondirectional spatial distribution of zooplankton (personal observation). Low flows during the dry period partially interrupted the upstream-downstream connection and limited the passive migration of organisms. Similarly to present observation, many researchers documented environmental-changes induced high temporal variation of zooplankton population in estuarine systems around the globe (Biggs et al., 1998; Peterson, 1996), and robustly heterogeneous spatial distribution of zooplankton (Giller et al., 1994; Zhao et al., 2017). The significant spatial changes of zooplankton abundance and biomass in SES might be synchronized with the existence of the salinity gradient, as described in the Pearl river estuary by Li et al. (2006).

Shannon species diversity index is one of the broadly used ecological indices for measuring diversity for a particular community. It can vary spatially and seasonally with different ecological factors (e.g., competition, predation and succession) which might change the evenness index albeit any alteration in richness index (Stirling and Wilsey, 2001). The present study showed a similar pattern in the graphical representation of diversity and evenness indices, but the relation with richness was not clear. Furthermore, the higher values were observed for all diversity indices in upstream stations, indicating this part of the estuary is healthier than the downstream part in terms of zooplankton biodiversity. According to Wang et al. (2014) the diversity threshold of zooplankton in a tropical estuarine system can be divided into 5 stages, like bad (<0.6), average (0.6—1.5), good (1.6—2.5), better (2.6—3.5) and excellent (>3.5). In the present study, the Shannon diversity index of SES was recorded much higher than 1.6 throughout the study period, showing a good to better zooplankton diversity pattern in this area. Moreover, the evenness index exceeded 0.3 during four seasons, indicating a good diversity of zooplankton (Sun et al., 2004). The species diversity and species richness values were high during the pre-monsoon period (spring and summer), along with high values of the evenness index, suggesting an equal distribution of zooplankton species during these seasons. The present study showed the lowest diversity indices during the monsoon season, which gradually increased after this period. This is consistent with previous works where a similar observation was also reported by Bhattacharya et al. (2015) at different parts of the Sundarbans.

4.3. Zooplankton response to environmental changes

Our study revealed clear differences in zooplankton community between the different sampling seasons, which can be explained by a combination of environmental variables. From the CCA, the assemblages of zooplankton in the SES are closely related to temperature, salinity, DO and nutrients. It is indicated that the abundance and biomass are obviously related to environmental factors in monsoon and winter seasons. The low salinity, moderate temperature, normoxic water with sufficient nutrients triggered the zooplankton growth during this time in the SES. A similar type of observation has also been reported in Rushikulla Estuary by Srichandan et al. (2015), where zooplankton density showed a positive correlation with nitrate and DO but negatively correlated with salinity. In terms of zooplankton population, monsoon and winter seasons would be considered as the most productive season for this estuarine system. An elevated Chl-*a* was recorded during monsoon when nutrients were readily available and temperature increased, while a decrease in Chl-*a* was observed during winter. Such seasonal pattern of Chl-*a* has been reported by many researchers in different estuarine complexes around the world (Amin et al., 2011; Biancalana et al., 2014; Gil et al., 2011). The lower concentration of the phytopigments and higher zooplankton population during winter suggests a potential zooplankton (especially meroplankton) grazing in this season (Torres et al., 2009). Moreover, anoxic conditions (during spring and summer) and high turbidity (only during summer) related to organic enrichment could be a causative factor in decreasing zooplankton abundance and accelerating rate of copepod mortality (Drira et al., 2018; Gordina et al., 2001; Park and Marshall, 2000), though the total zooplankton biomass was found to be high during summer due to the dominance of large-sized Decapoda larvae. In the overall study, the predominance of low saline species of genus *Paracalanus, Acartia* and *Acrocalanus* clearly indicates the estuarine influence in the study area. Furthermore, subtle changes of detrimental pollutant such as NH_4-N plays a noteworthy role in the seasonal pattern of zooplankton communities. The higher concentration of ammonia-nitrogen during summer had a great impact on the abundance of zooplankton in the present study. Zhao et al. (2013) recognized that too high or low concentration of this parameter results in the reduction of zooplankton density in an estuarine system. The distinct clusters in both stations and species biplot of CCA analysis clearly revealed that the zooplankton spatio-temporal variation may be caused by different environmental variables, which can regulate the overall composition, diversity, distribution of Copepoda and abundance of meroplankton in the estuarine ecosystem. Among all the environmental variables salinity, pH, temperature and micronutrients accounted for the most of spatio-temporal variations of zooplankton population dynamics. As suggested by Dorak and Albay (2016) and Wooldridge (1999), the horizontal salinity and temperature gradients are known to have an important role in determining the spatial and seasonal distribution of zooplankton, respectively.

4.4. Zooplankton as a relevant bioindicator

Due to their short life cycles, drifting habitus and quick reactions to changes of the aquatic environment zooplankton are considered as an excellent bioindicator for investigating and documenting of the environmental influences in estuarine and/or brackish water system (Annabi-Trabelsi et al., 2019; Campos et al., 2017; Drira et al., 2018; Sipkay et al., 2009). In a tropical estuarine complex, dominant zooplankton taxa generally determine the structure of the community and the pathway of material circulation and energy transference into the ecosystem. If a dominant group dies out, the structure of the community will alter along with the ecological environment (Wang et al., 2014). In the present investigation, the seasonal occurrences of particular zooplankton with significant temporal variation implies that the variation of salinity and other environmental factors in the surface water exerts either a direct or an indirect effect in the appearance or disappearance of some taxa and replacement by others. Mean abundance of some indicator zooplankton taxa varied seasonally and acted as the responsible factor for significant ($p = 0.001$) dissimilarity among four sampling period.

Among zooplankton, Copepoda are considered as most sensitive to even subtle changes in the hydrological characteristics and regarded as suitable ecological indicators of different environmental oscillation and ecosystem functioning (Campos et al., 2017; Jyothibabu et al., 2018). During monsoon, 3 Calanoida (*P. parvus, Acartia* sp. and *A. longicornis*) and 3 Cyclopoida (*O. brevicornis, O. simplex* and *O. similis*) species showed high *IndVal* index. Cyclopoida can survive in a wide range of habitats and maintain their population in any adverse condition (Paffenhoffer, 1993). Moreover, their reproductive strategy was the main reason for their significantly high abundance during monsoon season (Keister and Tuttle, 2013). The high *IndVal* index (83.01) of *O. brevicornis* and presence of *O. nana* only during monsoon exhibit a clear indication of organic pollution and anthropogenically disturbed marine system in this period at the river Matla of SES (Drira et al., 2018; Serranito et al., 2016; Uye, 1994). These phenomena probably can be best explained by the fact that this area during monsoon season is under constant anthropogenic stress compared to other seasons. The dominance of meroplankton (especially the Mollusca veliger) during winter is a good indication of the most productive season for their recruitment in SES activated by low temperature and a moderate amount of nutrients and Chl-*a* concentration in the estuarine environment. The higher indicator value of copepod *A. clausi* during this time implies their euryhaline character and the high abundance in the dry season, as reported in earlier studies (Dorak and Albay, 2016; Vieira et al., 2003). During spring, the herbivorous zooplankton like Euphausiacea calyptopis, Echinodermata larvae, Hydrozoa, and Copepoda nauplii indicated their preferences to transparent high saline estuarine water. The peak abundance of Hydrozoa during spring was a very common phenomenon in Indian coasts. Santhakumari and Nair (1999) and Srichandan et al. (2015) also reported such higher population density of Hydrozoa during the premonsoon period. Furthermore, maximum *IndVal* index of *C. crassiusculus* (57.58) during spring indicates their feeding preference towards Copepoda nauplii (Turner, 1984), which is most abundant in SES during this period. The highest indicator value (87.5) recorded for the Decapoda larvae and *B. hanseni* during the summer season suggested that SES supports these decapods community during this time for their ingress, growth and reproduction. Similarly, Srichandan et al. (2015) and Venkataramana et al. (2017) have also mentioned that the coastal part of Bay of Bengal remains more productive and supports high decapods density by linear correlation with temperature during pre-monsoon season.

In the present study, the maximum water temperatures 32.5 and 33.4°C were recorded during the monsoon and summer season, respectively, in this part of the

Sundarbans. Mitra et al. (2009) suggested that the effects of global warming can been observed in the Indian Sundarbans as a significant rising trend of the surface water temperature has been detected over the past 27 years. The increment of water temperature is visibly reflected in the present study by perennial dominance of Calanoida (*B. similis, P. parvus, A. gracillis, Acrocalanus gibber* and *Temora turbinata*) in SES, which are considered warm water preferring species (Bhattacharya et al., 2015; Stephen, 1984; Tseng et al., 2012; Wong et al., 2000). The exclusive appearance of these warm-water species along with high *IndVal* index might be an indication of the climate change-mediated temperature rise in the Indian Sundarbans.

5. Conclusion

The present study provides an overview of the changes in abundance and community structure of zooplankton and strengthens their role as an indicator organism of hydrographical changes in the Sundarbans. A strong spatial, as well as seasonal variation, was observed in the zooplankton community influenced by different hydrological parameters at the river Matla in SES. This is the first in-depth study from the mangrove dominated estuary under a restricted biosphere reserve area in the SES. A clear seasonal compositional shift with the increased percentage of Copepoda during the monsoon season was documented. Copepoda have emerged as the dominant group contributing $>50\%$ of the total population. Presence of different larval forms dominated by Crustacea suggested that the Sundarbans estuarine complex acts as a breeding ground for benthos species. Water temperature, DO, salinity and nutrients were the principal factors in affecting spatio-temporal differentiation of zooplankton community structure at the present study area. A clear seasonal cycle was observed in terms of variability in Copepoda composition and recruitment of different meroplankton communities. Such biological changes in zooplankton assemblages are likely to have significant implications on the productivity and functioning of the pelagic ecosystem in SES. Additionally, the present study is a maiden approach, focused on identifying indicator species of different zooplankton taxa at different time-scales. The occurrence of warm water species indicated the area is under the threat of climate change-mediated temperature rise. The present data, based on spatio-temporal scale in the Sundarbans, may help monitor the potential ecological assessment of this estuarine system. Furthermore, the result contributes to a deeper understanding of zooplankton variability and their seasonal succession pattern in this dynamic estuarine environment. Future works should be focused on identifying the indicator species of different zooplankton group at a longer time scale, which may help assess ecological understanding in the climate change-driven hydrological regime.

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Supplementary materials

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References

Amin, O., Comoglio, L., Spetter, C., Duarte, C., Asteasuain, R., Freije, R.H., Marcovecchio, J., 2011. Assessment of land influence on a high-latitude marine coastal system: Tierra del Fuego, southernmost Argentina. Env. Monit. Assess. 175 (1—4), 63—73, https://doi.org/10.1007/s10661-010-1493-5.

Annabi-Trabelsi, N., El-Shabrawy, G., Goher, M.E., Subrahmanyam, M.N.V., Al- Enezi, Y., Ali, M., Ayadi, H., Belmonte, G., 2019. Key drivers for copepod assemblages in a eutrophic coastal brackish lake. Water (Switzerland) 11. art. no. 363, 20 pp., https://doi.org/10.3390/w11020363.

Ayon, P., Criales-Hernandez, M.I., Schwamborn, R., Hirche, H.J., 2008. Zooplankton research off Peru: A review. Prog. Oceanogr. 79 (2—4), 238—255, https://doi.org/10.1016/j.pocean.2008.10.020.

Balasubramanian, R., Kannan, L., 2005. Physico-chemical characteristics of the coral reef environs of the Gulf of Mannar biosphere reserve, India. International J. Eco. Env. Sci. 31 (3), 265—271.

Bhattacharya, B.D., Hwang, J.S., Sarkar, S.K., Rakhsit, D., Murugan, K., Li-Chun, T., 2015. Community structure of mesozooplankton in coastal waters of Sundarban mangrove wetland, India: A multivariate approach. J. Marine Syst, 141, 112—121, https://doi.org/10.1016/j.jmarsys.2014.08.018.

Biancalana, F., Dutto, M.S., Berasategui, A.A., Kopprio, G., Hoffmeyer, M.S., 2014. Mesozooplankton assemblages and their relationship with environmental variables: a study case in a disturbed bay (Beagle Channel, Argentina). Env. Monit. Assess. 186 (12), 8629—8647, https://doi.org/10.1007/s10661-014-4032-y.

Bianchi, F., Acri, F., Aubry, F.B., Berton, A., Boldrin, A., Camatti, E., Cassin, D., Comaschi, A., 2003. Can plankton communities be considered as bio-indicators of water quality in the Lagoon of

Venice? Mar. Pollut. Bull. 46 (8), 964—971, https://doi.org/10.1016/S0025-326X(03)00111-5.

Biggs, B.J.F., Goring, D.G., Nikora, V.I., 1998. Subsidy and stress responses of stream periphyton to gradients in water velocity as a function of community growth form. J. Phycology 34 (4), 598—607, https://doi.org/10.1046/j.1529-8817.1998.340598.x.

Biswas, H., Mukhopadhyay, S.K., De, T.K., Sen, S., Jana, T.K., 2004. Biogenic Controls on the air-water carbon dioxide exchange in the Sundarban mangrove environment, northeast coast of Bay of Bengal, India. Limnol. Oceanogr. 49 (1), 95—101, https://doi.org/10.4319/lo.2004.49.1.0095.

Campos, C.C., Garcia, T.M., Neumann-Leitao, S., Soares, M.O., 2017. Ecological indicators and functional groups of copepod assemblages. Ecol. Indic. 83, 416—426, https://doi.org/10.1016/j.ecolind.2017.08.018.

Chatterjee, M., Shankar, D., Sen, G.K., Sanyal, P., Sundar, D., Michael, G.S., Chatterjee, A., Amol, P., Mukherjee, D., Suprit, K., Mukherjee, A., Vijith, V., Chatterjee, S., Basu, A., Das, M., Chakraborti, S., Kalla, A., Misra, S.K., Mukhopadhyay, S., Mandal, G., Sarkar, K., 2013. Tidal variations in the Sundarbans Estuarine System, India. J. Earth Syst. Sci. 4, 899—933, https://doi.org/10.1007/s12040-013-0314-y.

Clarke, K.R., Gorley, R.N., 2006. PRIMERv6: user manual/tutorial. PRIMER-E, Plymouth, UK, 192 pp.

Clarke, K.R., Warwick, R.M., 2001. Change in marine communities: an approach to statistical analysis and interpretation, 2nd edn. PRIMER-E, Plymouth, UK, 176 pp.

Conway, D.V.P., White, R.G., Hugues-Dit-Ciles, J., Gallienne, C.P., Robins, D.B., 2003. Guide to the coastal and surface zooplankton of the south western Indian Ocean. Occasional Publication of the Marine Biological Association of the United Kingdom, Plymouth, UK, 354 pp.

Das, J., Das, S.N., Sahoo, R.K., 1997. Semidiurnal variation of some physico-chemical parameters in the Mahanadi estuary, east coast of India. Indian J. Mar. Sci. 26 (3), 323—326.

David, V., Selleslagh, J., Nowaczyk, A., Dubois, S., Bachelet, G., Blanchet, H., Gouillieux, B., Lavesque, N., Leconte, M., Savoye, N., Sautour, B., Lobry, J., 2016. Estuarine habitats structure zooplankton communities: Implications for the pelagic trophic pathways. Estuar. Coast. Shelf Sci. 179, 99—111, https://doi.org/10.1016/j.ecss.2016.01.022.

De Young, B., Heath, M., Werner, F., Chai, F., Megrey, B., Monfray, P., 2004. Challenges of modeling ocean basin ecosystems. Science 304 (5676), 1463—1466.

Degerman, R., Lefebure, R., Bystrom, P., Bamstedt, U., Larsson, S., Andersson, A., 2018. Food web interactions determine energy transfer efficiency and top consumer responses to inputs of dissolved organic carbon. Hydrobiologia 805 (1), 131—146.

Dorak, Z., Albay, M., 2016. Effects of environmental factors on seasonal and spatial changes in surface zooplankton in Golden Horn Estuary (Istanbul, Turkey). Lakes Reserv. Res. Manage. 21 (2), 67—81.

Drira, Z., Kmiha-Megdiche, S., Sahnoun, H., Tedetti, M., Pagano, M., Ayadi, H., 2018. Copepod assemblages as a bioindicator of environmental quality in three coastal areas under contrasted anthropogenic inputs (Gulf of Gabes, Tunisia). J. Mar. Biol. Assoc. U.K. 98 (8), 1889—1905, https://doi.org/10.1017/S0025315417001515.

Dufrene, M., Legendre, P., 1997. Species assemblages and indicator species: The need for a flexible asymmetrical approach. Ecol. Monogr. 67 (3), 345—366.

Fernandez De Puelles, M.L., Lopaz-Urrutia, A., Morillas, A., Molinero, J.C., 2009. Seasonal variability of copepod abundance in the Balearic region (Western Mediterranean) as an indicator of basin scale hydrological changes. Hydrobiologia 617 (1), 3—16.

Field, J.G., Clarke, K.R., Warwick, R.M., 1982. A Practical Strategy for Analysing Multispecies Distribution Patterns. Mar. Ecol. Prog. Ser. 8, 37—52.

Gaonkar, C.A., Krishnamurthy, V., Anil, A.C., 2010. Changes in the abundance and composition of zooplankton from the ports of Mumbai, India. Environ. Monit. Assess. 168 (1—4), 179—194, https://doi.org/10.1007/s10661-009-1102-7.

Giering, S.L.C., Sanders, R., Lampitt, R.S., Anderson, T.R., Tamburini, C., Boutrif, M., Zubkov, M.V., Marsay, C.M., Henson, S.A., Saw, K., Cook, K., Mayor, D.J., 2014. Reconciliation of the carbon budget in the ocean's twilight zone. Nature 507 (7493), 480—483.

Gil, M.N., Torres, A.I., Amin, O., Esteves, J.L., 2011. Assessment of recent sediment influence in an urban polluted subantarctic coastal ecosystem. Beagle Channel (Southern Argentina). Mar. Pollut. Bull. 62 (1), 201—207, https://doi.org/10.1016/j.marpolbul.2010.10.004.

Giller, P.S., Hildrew, A.G., Rafaelli, D.G., 1994. Proceedings of British Ecological Society and American Society of Limnology and Oceanography Symposium. Blackwell Sci. Publ., Oxford, 649 pp.

Gordina, A.D., Pavlova, E.V., Ovsyany, E.I., Wilson, J.G., Kemp, R.B., Romanov, A.S., 2001. Long-term changes in Sevastopol Bay (the Black Sea) with particular reference to the ichthyoplankton and zooplankton. Estuar. Coast. Shelf Sci. 52 (1), 1—13, https://doi.org/10.1006/ecss.2000.0662.

Gorokhova, E., Lehtiniemi, M., Postel, L., Rubene, G., Amid, C., Lesutiene, J., Uusitalo, L., Strake, S., Demereckiene, N., 2016. Indicator properties of Baltic zooplankton for classification of environmental status within marine strategy framework directive. PLoS ONE 11 (7). art. no. e0158326, 26 pp., https://doi.org/10.1371/journal.pone.0158326.

Govindasamy, C., Kannan, L., Azariah, J., 2000. Seasonal variation in physico-chemical properties and primary production in the coastal water biotopes of Coromandel Coast, India. J. Environ. Biol. 21 (1), 1—7.

Grasshoff, K., Kremling, K., Ehrhardt, M., 1999. Methods of seawater analysis. Verlag Chemie, Weinheim Germany, 634 pp.

Hays, G.C., Richardson, A.J., Robinson, C., 2005. Climate change and marine plankton. Trends Ecol. Evol. 20 (6 Sp. Is.), 337—344.

Hunt, B.P.V., Hosie, G.W., 2006. The seasonal succession of zooplankton in the Southern Ocean south of Australia, part I: The seasonal ice zone. Deep-Sea Res. Pt. I Oceanogr. 53 (7), 1182—1202.

Hunt, B.P.V., Pakhomov, E.A., Trotsenko, B.G., 2007. The macrozooplankton of the Cosmonaut Sea, east Antarctica (30°E—60°E), 1987—1990. Deep-Sea Res. Pt. I Oceanogr. 54 (7), 1042—1069.

Jagadeesan, L., Jyothibabu, R., Arunpandi, N., Karnan, C., Balachandran, K.K., 2017. Dominance of coastal upwelling over Mud Bank in shaping the mesozooplankton along the southwest coast of India during the Southwest Monsoon. Prog. Oceanogr. 56, 252—275, https://doi.org/10.1016/j.pocean.2017.07.004.

Jyothibabu, R., Jagadeesan, L., Karnan, C., Arunpandi, N., Pandiyarajan, R.S., Balachandran, K.K., 2018. Ecological indications of copepods to oxygen-deficient near-shore waters. Ecol. Indic. 93, 76—90.

Kannan, R., Kannan, L., 1996. Physico-chemical characteristics of seaweed beds of the Palk Bay, southeast coast of India. Indian J. Mar. Sci. 25 (4), 358—362.

Karuppasamy, P.K., Perumal, P., 2000. Biodiversity of zooplankton at Pichavaram mangroves, South India. Adv. Biosci. 19, 23—32.

Kasturirangan, L.R., 1963. A key for the identification of the more common planktonic copepoda of Indian coastal waters. In: Pannikar, N.K. (Ed.), New Delhi: Council of Scientific and Industrial Research, 87 pp.

Keister, J.E., Tuttle, L.B., 2013. Effects of bottom-layer hypoxia on spatial distributions and community structure of mesozooplankton in a sub-estuary of Puget sound, Washington, USA. Limnol. Oceanogr. 58 (2), 667—680.

Kovach, W.L., 1998. MVSP—multi-variate statistical package for windows, version 3.0. Kovach Computing Services, Pentraeth, Wales, UK, 127 pp.

Kruskal, J.B., Wish, M., 1978. Multidimensional scaling. Sage Univ. Paper Ser., Quantitative Applications in the Social Sciences, No. 07011, Sage Publications, Newbury Park, http://dx.doi.org/10.4135/9781412985130.

Li, K.Z., Yin, J.Q., Huang, L.M., Tan, Y.H., 2006. Spatial and temporal variations of mesozooplankton in the Pearl River estuary, China. Estuar. Coast. Shelf Sci. 67 (4), 543—552, https://doi.org/10.1016/j.ecss.2005.12.008.

Longhurst, A.R., 2007. Ecological Geography of the Sea, 2nd edn., Acad. Press, Amsterdam, Boston, MA, 560 pp.

MacIntyre, H.L., Geider, R.J., Miller, D.C., 1996. Microphytobenthos: The ecological role of the 'secret garden' of unvegetated, shallow-water marine habitats. I. Distribution, abundance and primary production. Estuaries 19 (2 A), 186—201.

Margalef, R., 1967. Some concepts relative to the organization of plankton. Oceanogr. Mar. Biol. Annu. Rev 5, 257—289.

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.

Marques, S.C., Azeiteiro, U.M., Martinho, F., Viegas, I., Pardal, M.A., 2009. Evaluation of estuarine mesozooplankton dynamics at a fine temporal scale: The role of seasonal, lunar and diel cycles. J. Plankton Res. 31 (10), 1249—1263.

Mathew, L., Pillai, N., 1990. Chemical characteristics of the waters around Andamans during late winter. In: Proc. First Workshop Scientist Resul. FORV. Sagar, Sampada, 15—18.

Mialet, B., Gouzou, J., Azamar, F., Maris, T., Sossou, C., Toumi, N., Van Damme, S., Meire, P., Tackx, M., 2011. Response of zooplankton to improving water quality in the Scheldt estuary (Belgium). Estuar. Coast. Shelf Sci. 93 (1), 47—57.

Mishra, S., Panda, D., Panigrahy, R.C., 1993. Physico-chemical characteristics of the bahuda estuary (Orissa), East coast of India. Indian J. Mar. Sci. 22, 75—77.

Mitra, A., Gastellani, C., Gentleman, W.C., 2014. Bridging the gap between marine biogeochemical and fisheries sciences; configuring the zooplankton link. Prog. Oceanogr 129 (PB), 176—199.

Mitra, A., Gangopadhyay, A., Dube, A., Schmidt, A.C.K., Banerjee, K., 2009. Observed changes in water mass properties in the Indian Sundarbans (northwestern Bay of Bengal) during 1980—2007. Curr. Sci. 97 (10), 1445—1452.

Moderan, J., Bouvais, P., David, V., Le Noc, S., Simon-Bouhet, B., Niquil, N., Miramand, P., Fichet, D., 2010. Zooplankton community structure in a highly turbid environment (Charente estuary, France): Spatio-temporal patterns and environmental control. Estuar. Coast. Shelf Sci. 88 (2), 219—232, https://doi.org/10.1016/j.ecss.2010.04.002.

Morgan, S.G., 1995. The timing of larval release. In: McEdward, L. (Ed.), Ecology of marine invertebrate larvae. Florida. CRC Press, Boca Raton, 157—191.

Mouny, P., Dauvin, J.C., 2002. Environmental control of mesozooplankton community structure in the seine estuary (English Channel). Oceanol. Acta 25 (1), 13—22.

Mukhopadhyay, S.K., Biswas, H., De, T.K., Jana, T.K., 2006. Fluxes of nutrients from the tropical river Hooghly at land-ocean boundary of Sundarbans, NE coast of Bay of Bengal, India. J. Marine Syst. 62, 9—21, https://doi.org/10.1016/j.jmarsys.2006.03.004.

Nair, P.V.R., Gopinathan, C.P., Balachandran, V.K., Mathew, K.J., Regunathan, A., 1984. Ecology of mud banks: Phytoplankton productivity I. Alleppey mud-bank. CMFRI Bull 31, 28—34.

Nandy, T., Mandal, S., Chatterjee, M., 2018. Intra—monsoonal variation of zooplankton population in the Sundarbans Estuarine System, India. Environ. Monit. Assess. 190 (10), https://doi.org/10.1007/s10661-018-6969-8.

Nielsen, T.G., Sabatini, M., 1996. Role of cyclopoid copepods Oithona spp. in North Sea plankton communities. Mar. Ecol. Progr. Ser. 139 (1—3), 79—93.

O'Higgins, T.G., Ferraro, S.P., Dantin, D.D., Jordan, S.J., Chintala, M.M., 2010. Habitat scale mapping of fisheries ecosystem service values in estuaries. Ecol. Soc. 15 (4), art. no. 7, http://www.ecologyandsociety.org/vol15/iss4/art7/.

Paffenhoffer, G., 1993. On the ecology of marine cyclopoid copepods (Crustacea, Copepoda). J. Plankton Res. 15 (1), 37—55, https://doi.org/10.1093/plankt/15.1.37.

Pages, F., Gonzalez, H.E., Gonzalez, S.R., 1996. Diet of the gelatinous zooplankton in Hardangerfjord (Norway) and potential predatory impact by Aglantha digitale (trachymedusae). Mar. Ecol. Prog. Ser. 139 (1—3), 69—77.

Park, G.S., Marshall, H.G., 2000. Estuarine relationships between zooplankton community structure and trophic gradients. J. Plankton Res. 22 (1), 121—135.

Parsons, T.R., Maita, Y., Lalli, C.M., 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, Oxford, 173 pp.

Peterson, C.G., 1996. Response of benthic algal communities to natural physical disturbance. In: Stevenson, R.J., Bothwell, M.L., Lowe, R.L. (Eds.), Algal ecology: Freshwater benthic ecosystems. Acad. Press, San Diego, CA, 375—402.

Peterson, W.T., Bellantoni, D.C., 1987. Relationships between water-column stratification, phytoplankton cell size and copepod fecundity in long island sound and off central Chile. South Afr. J. Mar. Sci. 5 (1), 411—421.

Pielou, E.C., 1966. The measurement of diversity in different types of biological collections. J. Theoretical Biol. 13 (C), 131—144.

Rakhesh, M., Raman, A.V., Kalavati, C., Subramanian, B.R., Sharma, V.S., Sunitha Babu, E., Sateesh, N., 2008. Zooplankton community structure across an eddy-generated upwelling band close to a tropical bay-mangrove ecosystem. Mar. Biol. 154 (6), 953—972, https://doi.org/10.1007/s00227-008-0991-2.

Ramakrishnan, R., Perumal, P., Santhanam, P., 1999. Spatio-temporal variations of hydrographical features in the Pichavaram mangroves and Mohi aqua farm, Southeast coast of India. In: Proc. International Seminar for Application in Hydro geochemistry. Annamalai University, Chidambaram, Tamil Nadu, India, 197—203.

Resmi, S., Reddy, R.V., Venkatesha Moorthy, K.S., Chethan, N., 2011. Zooplankton dynamics in the coastal waters of adubidri, Karnataka. Indian J. Mar. Sci. 40 (1), 134—141.

Sampey, A., McKinnon, A.D., Meekan, M.G., McCormick, M.I., 2007. Glimpse into guts: Overview of the feeding of larvae of tropical shorefishes. Mar. Ecol. Prog. Ser. 339, 243—257.

Santhakumari, V., Nair, V.R., 1999. Distribution of hydromedusae from the exclusive economic zone of the west and east coasts of India. Indian J. Mar. Sci. 28 (2), 150—157.

Santhanam, P., Perumal, P., 2003. Diversity of zooplankton in Parangipettai coastal waters, Southeast Coast of India. J. Mar. Biol. Assoc. India. 45, 144—151.

Santhosh Kumar, C., Perumal, P., 2011. Hydrobiological Investigations in Ayyampattinam Coast (Southeast Coast of India) with Special Reference to Zooplankton. Asian J. Biol. Sci. 4 (1), 25—34.

Sarkar, S.K., Saha, M., Takada, H., Bhattacharya, A., Mishra, P., Bhattacharya, B., 2007. Water quality management in the lower stretch of the river Ganges, east coast of India: an approach through environmental education. J. Clean. Prod. 15 (16), 1559—1567.

Segar, K., Hariharan, V., 1989. Seasonal distribution of nitrate, nitrite, ammonia and plankton in effluent discharge area of Mangalore, West coast of India. Indian J. Mar. Sci. 18, 170—173.

Senthilkumar, S., Santhanam, P., Perumal, P., 2002. Diversity of phytoplankton in vellar estuary, southeast coast of India. In: Proc. 5th Indian Fisheries Forum, Bhubaneswar. Orissa, India, 145—248.

Serranito, B., Aubert, A., Stemmann, L., Rossi, N., Jamet, J.L., 2016. Proposition of indicators of anthropogenic pressure in the Bay of Toulon (Mediterranean Sea) based on zooplankton time-series. Cont. Shelf Res. 121, 3—12.

Shanks, A.L., 1995. Mechanisms of cross-shelf dispersal of larval invertebrates and fish. In: McEdward, L. (Ed.), Ecology of marine invertebrate larvae. Florida. CRC Press, Boca Raton, 323—367.

Shannon, C.E., 1948. A Mathematical Theory of Communication. Bell Sys. Tech. J. 27 (4), 623—656.

Sipkay, C., Kiss, K.T., Vadadi-Fjilop, C., Hufnagel, L., 2009. Trends in research on the possible effects of climate change concerning aquatic ecosystems with special emphasis on the modelling approach. Appl. Ecol. Environ. Res. 17 (2), 171—198.

Srichandan, S., Sahu, B.K., Panda, R., Baliarsingh, S.K., Sahu, K.C., Panigrahy, R.C., 2015. Zooplankton distribution in coastal water of the north-western Bay of Bengal, off Rushikulya estuary, east coast of India. Indian J. Geo-Mar. Sci. 44 (4), 546—561.

Sridhar, R., Thangaradjou, T., Senthil Kumar, S., Kannan, L., 2006. Water quality and phytoplankton characteristics in the Palk Bay, southeast coast of India. J. Environ. Biol. 27 (3), 561—566.

Stephen, R., 1984. Distribution of calanoid copepods in the Arabian Sea and Bay of Bengal. Mahasagar Bull. Natl. Inst. Oceanogr. 17, 161—171.

Stirling, G., Wilsey, B., 2001. Empirical relationships between species richness, evenness, and proportional diversity. Am. Nat. 158 (3), 286—299.

Strickland, J.D.H., Parsons, T.R., 1972. A practical handbook of seawater analysis. Fish. Res. Canada, Ottawa, 328 pp.

Sun, J., Liu, D.Y., Bai, J., Gao, H.W., Han, X.T., 2004. Phytoplankton community of the Bohai Sea in winter 2001. J. Ocean Univ. China 34 (3), 403—422.

Telesh, I.V., 2004. Plankton of the Baltic estuarine ecosystems with emphasis on Neva Estuary: A review of present knowledge and research perspectives. Mar. Pollut. Bull. 49 (3), 206—219, https://doi.org/10.1016/j.marpolbul.2004.02.009.

Torres, A.I., Gil, M.N., Aman, O.A., Esteves, J.L., 2009. Environmental characterization of a eutrophicated semi-enclosed system: Nutrient budget (Encerrada Bay, Tierra Del Fuego Island, Patagonia, Argentina). Water Air Soil Pollut. 204 (1—4), 259—270.

Tseng, L.C., Dahms, H.U., Chen, Q.C., Hwang, J.S., 2012. Mesozooplankton and copepod community structures in the southern East China Sea: The status during the monsoonal transition period in September. Helgoland Mar. Res. 66 (4), 621—634.

Turner, J.T., 1984. The feeding ecology of some zooplankters that are important prey items of larval fish. US Dept. Comm. NOAA, Natl. Mar. Fish. Serv. 28 pp.

Uriarte, I., Villate, F., 2004. Effects of pollution on zooplankton abundance and distribution in two estuaries of the Basque coast (Bay of Biscay). Mar. Pollut. Bull. 49 (3), 220—228, https://doi.org/10.1016/j.marpolbul.2004.02.010.

Uye, S.I., 1994. Replacement of large copepods by small ones with eutrophication of embayments: cause and consequence. Hydrobiologia 292—293 (1), 513—519.

Van der Marrel, E., 1990. Ecotones and ecoclines are different. J. Veg. Sci. 1, 135—138.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37 (1), 130—137.

Venkataramana, V., Sarma, V.V.S.S., Reddy, A.M., 2017. Impact of river discharge on distribution of zooplankton biomass, community structure and food web dynamics in the Western coastal Bay of Bengal. Reg. Stud. Mar. Sci. 16, 267—278.

Vieira, L., Azeiteiro, U., Re, P., Pastorinho, R., Marques, J.C., Morgado, F., 2003. Zooplankton distribution in a temperate estuary (Mondego estuary southern arm: Western Portugal). Acta Oecol. 24 (Suppl. 1), S163—S173, https://doi.org/10.1016/S1146-609X(03)00038-9.

Wang, D., Lu, J., Chen, P., Ma, Y., 2014. Community characteristics and of zooplankton in Qinzhou Bay. Acta Ecol. Sinica 34 (3), 141—147, https://doi.org/10.1016/j.chnaes.2014.03.002.

Wong, C.K., Tam, P.F., Fu, Y.Y., Chen, Q.C., 2000. Seasonal succession and spatial segregation of planktonic copepoda in the Zhujiang Estuary in relation to temperature and salinity. Crustacean Issues 12, 363—375.

Wooldridge, T., 1999. Estuarine zooplankton community structure and dynamics. In: Allanson, B.R., Baird, D. (Eds.), Estuaries of South Africa. Cambridge Univ. Press, Cambridge, UK, 141—166.

Yousif Al-Yamani, F., Skyrabin, V., Gubanova, A., Khvorov, S., Prusova, I., 2011. Marine zooplankton practical guide for the Northwestren Arabian Gulf. Kuwait Inst. Sci. Res., Kuwait, 197 pp.

Zhao, C., Liu, C., Zhao, J., Xia, J., Yu, Q., Eamus, D., 2013. Zooplankton in highly regulated rivers: Changing with water environment. Ecol. Eng. 58, 323—334.

Zhao, K., Songa, K., Pan, Y., Wang, L., Da, L., Wang, Q., 2017. Metacommunity structure of zooplankton in river networks: Roles of environmental and spatial factors. Ecol. Indic. 73, 96—104.

Zhou, S., Jin, B., Guo, L., Qin, H., Chu, T., Wu, J., 2009. Spatial distribution of zooplankton in the intertidal marsh creeks of the Yangtze River Estuary. China. Estuar. Coast. Shelf Sci. 85 (3), 399—406.

Ziadi, B., Dhib, A., Turki, S., Aleya, L., 2015. Factors driving the seasonal distribution of zooplankton in a eutrophicated Mediterranean Lagoon. Mar. Pollut. Bull. 97 (1—2), 224—233, https://doi.org/10.1016/j.marpolbul.2015.06.012.