Variability in the zooplankton assemblages in relation to environmental variables in the tidal creeks of Sundarban estuarine system, India

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Abstract

The present study illustrates a holistic account of zooplankton community dynamics in relation to physico – chemical variables in the tidal creeks of Indian Sundarbans estuarine system. Out of 11 water parameters, seven parameters (Temp., salinity, DO, turbidity, PO_4 – P, NO_3 – N and NO_2 – N) differed significantly ($p \leq 0.05$) among seasons. A total of 63 zooplankton taxa were recorded with the predominance of Copepoda, varying in ranges from 59.55 to 73.13% of the total zooplankton population. PERMANOVA design depicted the significant variations of zooplankton population both spatially (F = 2.313; p = 0.001) and temporally (F = 6.107; p = 0.001). Out of 41 species of Copepoda recorded, 14 species (*Paracalanous parvus, Parvocalanous dubia, Bestiolina similis, Acrocalanous gibber, A. gracilis, Acartia erythraea, A. spinicauda, Pseudodiaptomus serricaudatus, P. annandalei, P. aurivilli, Oithona brevicornis, O. similis, Longipedia weberi* and *Microsetella norvegica*) indicated as *'characterizing species'* in the creek environment, and highlighted the euryhaline nature as well as broad range of thermal tolerance of these species. β – diversity index (Index of Multivariate dispersion) reflected higher values (β = >1) in the creeks (S4, S2 and S6), those are experienced with high anthropogenic pressure. On the whole, the calculated mean value of α – diversity (d'=4.07; H'=2.31) indicated *'good'* zooplankton diversity. Water parameters *viz*., Temp., salinity, DO, turbidity, PO_4 – P and NO_3 – N were found to have influence on the distribution, abundance and diversity of zooplankton in the creeks. More specifically, the linear model (DistLM) exhibited two variables *viz*., temperature and salinity were the primary controlling factors in shaping the zooplankton community compositions in the creek environment.

Introduction

Tropical and sub-tropical regions of the world are home to diverse assemblage of species (Cornils et al. 2007). Plankton are cosmopolitan; distributed across all ecosystems such as lakes, pools, reservoirs, hill streams, rivers, estuaries and the oceanic compartments (Cloern et al. 2014). Ecological studies emphasizing on phytoplankton and zooplankton communities has been exhaustively studied at recent times since there is a vivid environmental influence on the planktonic communities (Thabet et al. 2018). Tropical estuarine ecosystems in this respect are fascinating for studying the dynamics of zooplankton, due to its frequently changing hydrological conditions and rigorous biological processes (Islam et al. 2006). Zooplankton communities play a pivotal role in the functioning of aquatic ecosystems as it provides crucial linkages in the aquatic food web (Capriulo et al. 2002; Sotton et al. 2014). The information regarding the abundance and composition, and its relationship with the environmental parameters is indispensable for understanding the ecological processes of a particular area (Sousa et al. 2008). Monitoring and understanding the alterations in the dynamics of the zooplankton community over time can also provide a deep insight about the ecosystem functioning, which forms the basis for developing predictive models based on natural and anthropogenic alterations in the environment, especially those induced by climate variations (Tommasi et al. 2013). Therefore, it is imperative to study spatial and temporal structure of the zooplankton community to comprehend the state of ecosystem health.

Tidal creeks are a pre-eminent part of the estuarine ecosystem. These are extensive, bountiful and home to enormous biodiversity (Mallin 2004). They are highly fecund coastal environments in terms of aquatic biodiversity (Wiegert and Freeman 1990), acting as a support system to complex food webs (Posey et al. 2002). They also serve as feeding and nursery grounds, providing food and habitat to numerous fish, and other species of commercial importance (Lawal-Are et al. 2010). Several estuaries across the world have numerous tidal creeks with diverse water quality characteristics which pilot the ecosystem functions (Lerberg et al. 2000). Off late, the increased efforts to develop coastal areas for various economic purposes have resulted in the tidal creeks losing their ecological value (Vernberg and Vernberg 2001). Anthropogenic effluents such as nutrients, pesticides, heavy metals and other chemical pollutants contaminate the creek waters to a dangerous level (DeLorenzo et al. 2001). The net result is that many of these productive and ecologically significant ecosystems are degraded to various extents. Thus, these ecosystems are highly susceptible to environmental changes and human induced changes; nevertheless, their ecological significance is underestimated which is reflected by the fact that significantly a smaller number of studies have been conducted on these systems as compared to other known estuarine systems (Mallin 2004).

The Delta of Hooghly – Matla estuarine system is traversed by seven major rivers along with their tributaries and creeks. This deltaic system harbours luxuriant mangroves, and constitutes Sundarban mangrove ecosystem, which is one of the most biologically productive ecosystems. The Indian Sundarban Delta (ISD) is experiencing the adverse impacts of climate change, such as sea level rise, changes in temperature, precipitation regime, and cyclone activity since last three decades (Danda et al. 2011). As per the Delta Vision document of WWF – I, Sagar Island is one of the most vulnerable areas of ISD archipelago (Danda et al. 2011). The estimated sea level rise along the coast of Sagar Island was found to be 3.14 mm/year which was attributed to global warming and other local factors (Hazra et al. 2002). The Sagar island is bestowed with 12 major creeks and numerous minor creeks forming a web of intertidal creeks with luxuriant vegetation, and biodiversity that includes various planktonic, nektonic forms (Sarkar 1983). Among these, the zooplankton community structure encountered in the Hooghly estuary is of considerable interest, because it has direct cascading impact on the higher trophic levels in the aquatic trophic guild (Sarkar 1983). Information with respect to the zooplankton in Indian Sundarbans is mostly limited to rivers (Nandy et al. 2018; Nandy and Mandal 2020; Paul et al. 2019), and north east part of the Indian Sundarbans (Bhattacharyya et al. 2015), whereas the studies on zooplankton from the tidal creeks of Indian Sundarban as well as other tropical creek systems are scarce (Sarkar et al. 1985 and 1986). Hence, the present study was undertaken to analyze the zooplankton community assemblage and its distribution concerning environmental variables in the tidal creeks of Indian Sundarban ecoregion. The alternate hypothesis is that the different environmental parameters along the tidal creeks have influence on the structure and compositions of the zooplankton community assemblage over a seasonal period.

Materials And Methods

Study area

Sagar Island is the largest inhabited island in the Indian Sundarbans ecoregion, lying between latitude 21º37' and 21º52″ N and longitude 88º03' and 88º11' E in the western part of the Hooghly-Matlah estuarine system. The island is traversed by large and small tidal creeks which are connected with the open estuarine water. In the present study, the sampling sites were chosen based on the varying hydrographical conditions and anthropogenic interference, which includes fishing, agriculture and other commercial activities etc. Six sampling sites *viz.,* Sikarpur (SIK), Sagar (SAG), Hatipeta (HAT), Chemaguri (CHE), Phooldubi (PHO) and Kachuberia (KAC) (hereafter referred to as S1, S2, S3, S4, S5 and S6, respectively) were selected on the six major creeks. Station S1 and S4 opens into Mooriganga river, and S3, S5 and S6 opens into river Hooghly, whereas S2 opens into the Bay of Bengal. The study period is considered as post–monsoon (November to February), characterized by low to negligible rainfall and low temperature; pre–monsoon (March to June) characterized by squalls and convectional rainfall and high temperature, and Monsoon (July to October) characterised by torrential rains with sultry weather conditions (Chaudhuri et al. 2012). The geographical locations of the sampling sites and study area are shown in Fig. 1.

Sampling methodology

Monthly sampling was carried out from six sampling stations between July 2016 and June 2018. For determination of water quality, sub-surface water samples (0.5 m depth) were collected using Niskin water sampler and transferred immediately to pre–rinsed polyethylene bottle (1.0 L). Water samples were brought to the laboratory in cold condition for further nutrients analysis. We obtained in situ measurements of water temperature (Temp.) by a mercury thermometer (P–601466), pH with a digital pH meter (pH 620, Eutech Instruments, Singapore) and turbidity (Nephelometric turbidity unit) was measured by a Turbidity meter (Model No. EI331E). The salinity, dissolved oxygen (DO) and total alkalinity (TA) were estimated on board by following titrimetric methods (APHA, 2012). The water samples collected for dissolved nutrient analysis were filtered through GF/F filter paper (mesh size– 0.7 µm) for removing the particulate matter and the filtrate was stored at –20°C until further analysis. Nutrients such as nitrite (NO_2–N), nitrate (NO_3–N), phosphate (PO_4–P) and silicate (SiO_4–Si) were analysed following standard spectrophotometric procedures described in Strickland and Parsons (1972). For analysis of bio-chemical oxygen demand (BOD), water samples were collected separately in 500 ml polyethylene bottles (HDPE, Tarson). BOD was estimated by 5–day BOD test (APHA 2005). All the methods were standardized as per ambient conditions, and blank measurements were taken into consideration for the procedures.

Zooplankton samples were collected by filtering 100 L of water through 50 µm plankton net (mouth diameter: 75cm) from the sampling sites. To avoid the large-scale variation in zooplankton and dial vertical migration, all the samples were collected during morning hours between 6.00 am to 10.00 am. The collected samples were preserved in 4% buffered formalin and transported to the laboratory at the earliest for qualitative and quantitative analysis. A total of 144 zooplankton samples were analysed in the present study. The Sedgewick-Rafter counting cell method was applied for enumeration of zooplankton by employing trinocular light microscope (Axioster plus – Carl Zeiss). The taxonomic composition of the samples was analysed to the lowest possible taxa following standard taxonomic identification keys (Kasturirangan 1963; Conway et al. 2003; Al–Yamani et al. 2011; Shiel 1995). The abundance of zooplankton was expressed as number of individuals per cubic meter (ind.m^{-3}).

Data analysis

The water quality parameters were normalized by transforming log(x+1) except pH prior to analyses. The water quality parameters in different stations were subjected to one-way analysis of variance (ANOVA), and Post hoc test (Duncan's multiple range tests) using SPSS v.21. The statistical significance of spatio-temporal differences of water variables were tested with a Permutational Multivariate Analysis of Variance (PERMANOVA), a non-parametric multivariate statistical test. Pearson’s correlations (2–tailed) between water variables and zooplankton groups, and between the copepod families were also computed. ANOVA (post hoc) was performed to understand the significant variations of copepod families in seasons. Further, we performed the PERMANOVA to test the differences ($p \leq 0.05$) between the zooplankton samples (abundance) in terms of seasons and stations. Alpha diversity (α-diversity) based on species richness per sample (*SRp*), Shannon diversity (*H*′) (Shannon-Weiner 1949), richness (*d*′) (Margalef 1958), Simpson diversity index *(1-λ*′*)* (Simpson 1949) and Evenness index (Pielou 1977) were measured. Additionally, one-way ANOVA was performed to identify the significant ($p \leq 0.05$) differences of the richness of zooplankton taxa across stations. Beta (*β*) diversity was measured using two multivariate approach *viz.,* index of multivariate dispersion (MVDISP; Warwick and Clarke 1993), and *β*–dissimilarity index based on Bray curtis dissimilarity (Bray Curtis 1957). The index of multivariate dispersion (IMD) was also applied as a multivariate stability index to evaluate the stability changes in the zooplankton community (Warwick and Clarke 1993). The graphical representation of *k*-dominance curve in both the year was employed to investigate the dominance pattern of zooplankton taxa across seasons. A Bray-Curtis similarity matrix was then calculated in the six stations sampled during the different phases. Cluster analysis (group averaged) and multi-dimensional scaling (MDS) were used to assess the similarity of community structure among samples; which were then tested using analysis of similarity (ANOSIM) to understand the significant differences between stations with respect to zooplankton species composition.

Similarity percentage (SIMPER) routine was performed to categorize species responsible for similarity (*characterizing species*) and dissimilarity (*discriminating species*) between the groups, and also the relative contribution of individual species to the total zooplankton community. RELATE test, a non-parametric type of Mantel test, was performed to comprehend the significant pattern of the change of the zooplankton species assemblage between the two years (2016–17 and 2017–18). Pre-treatment of all the biological data was done by square root transformation to achieve the normality of the zooplankton abundance data. To identify and quantify the environmental variables that influenced the zooplankton community variability, BIO-ENV (Biota and/or Environment matching) and the distance – based linear model (DistLM) were conducted. BIO–ENV procedure reflected the best set of environmental variables that explained the patterns of zooplankton communities. A marginal test (non-parametric significance test), was used to determine the variation in biological data, and each environmental variable that can explain. Further, sequential test was done to examine whether any particular variable contributed significantly to the explained variation in biological (zooplankton) data (Clarke et al. 2014). The fitted DistLM was visualized using the distance-based redundancy analysis (dbRDA). Then we obtained the model using the Akaike information criterion (AICc), and the stepwise selection procedure. The above stated analyses were performed by using PRIMER v 6.0 (Clarke and Gorley 2006).

Results

Variations of water quality parameters

The variations of water quality variables in different seasons of the study sites are shown in Table 1. No significant spatial differences ($p \geq 0.05$) in water variables were found, while the temporal differences exhibited significant heterogeneity (ANOVA post hoc test, $p \leq 0.05$). Out of 11 water parameters, seven parameters (Temp., salinity, DO, turbidity, PO_4–P, NO_3–N and NO_2–N) differed significantly ($p \leq 0.05$) among seasons. The creeks water remained alkaline throughout the study period. Lowest pH was observed at S1 (6.51), and highest at S6 (8.2) throughout the sampling period. Seasonal mean surface water temperature ranged from 20.06±3.48 ºC to 31.0±2.41 ºC. The highest (32.70 ºC) and lowest (16.9 ºC) value was recorded at S1 in June and S6 in January, respectively. A wide variation of salinity was observed during the study period. The maximum salinity was recorded at S2 in June (27.2 ppt), and lowest at S5 in September (0.60 ppt). The salinity values varied at the different sampling stations according to their distance from the sea. Differences in dissolved oxygen concentration of the stations were found to be no significant. The higher magnitude of dissolved oxygen was obtained during post-monsoon (7.20±0.27 mgl^{-1}), and it decreased from monsoon (6.35±0.15) to pre-monsoon (5.80±0.20). Turbidity was recorded in the expected level with its peak during monsoon and lowest in pre-monsoon. Mean seasonal turbidity varied from 23.35±14.48 to 88.63±16.25 NTU with its maximum (104.0 NTU) at S6 in October, and minimum (12.0 NTU) at S3 in January.

The seasonal trend of nutrients was not uniform in the studied stations. NO_3–N contents were comparatively higher during monsoon, and its concentrations were recorded maximum at S6 and minimum at S1. A similar type of seasonal trend was noticed for dissolved PO_4–P and NO_2–N in the sampling sites. The mean concentrations of PO_4–P and NO_2–N were found to be decreasing from monsoon to post-monsoon, and again it started showing reverse trend during pre-monsoon. Dissolved SiO_4–Si exhibited wide variation across seasons; however, post hoc analysis portrayed no significant difference ($p \geq 0.05$) among stations. Though ANOVA (post hoc test) portrayed no significant variations of water variables across the stations; PERMANOVA analysis reflected the significant spatial (F=1.459, p = 0.046) and temporal (F=7.923, p=0.001) differences in water variables in the studies creeks. Intra-relationship among various water quality parameters is described in Table 2. Water temperature exhibited significant positive correlation with turbidity (r = 0.682; $p \leq 0.01$), PO_4–P (r = 0.535; $p \leq 0.05$) and NO_3–N (r = 0.575; $p \leq 0.05$). Salinity in turn, was found to have a correlation with nutrient parameters *viz.,* PO_4–P (r = 0.443), NO_3–N (r = – 0.50; $p \leq 0.05$) and SiO_4–Si (r = 0.75; $p \leq 0.01$). DO also had significant negative correlation with turbidity (r = – 0.601; $p \leq 0.01$), PO_4–P (r = – 0.723; $p \leq 0.01$) and SiO_4–Si (r = – 0.591; $p \leq 0.01$) during the study period.

Zooplankton abundance, composition and distribution

The mean abundance of total zooplankton and copepod population in the studied stations are given in Table 3. A total of sixty three zooplankton taxa were recorded throughout the study period. Among zooplankton major groups, Copepoda was most prominent in terms of species richness and numerical abundance, varying in ranges from 59.55 to 73.13% of the total zooplankton. Among zooplankton Calanoida alone contributed 46% followed by Cyclopoida (15%) and Harpacticoida (6%). The other groups contributing significantly were larvae (13%), crustacean nauplii (9%) and Mysids (4%) (Fig. 2). The mean seasonal abundance was maximum during the pre-monsoon (50,861.11±23,702.63 ind.m^{-3}) and lowest in the monsoon (29,805.56±17,571.72 ind.m^{-3}). On the whole, the quantitative spectrum of total zooplankton ranged from 10,000 to 1,10,000 ind.m^{-3} with its maximum abundance at S1 and minimum at S5 during February and October, respectively. The station-wise average numerical abundance of zooplankton in different seasons is illustrated in Fig. 3. As a whole, holoplankters dominated throughout the study period in all the stations contributing 71.4–87.9% to the total zooplankton community with the highest in monsoon and lowest in pre–monsoon. The meroplankters contributed 11.2– 34.62% to the total zooplankton density with the highest in pre–monsoon and lowest in monsoon. The abundance of holoplankters and meroplankters in the different stations are shown in Fig. 4 (a & b).

A total of 41 species of Copepoda were recorded throughout the study comprising 30 species of Calanoida (14 genera), 5 species of Cyclopoida (3 genera) and 6 species of Harpecticoida (5 genera). The family Paracalanidae and Oithonidae invariably constituted the bulk of the total copepod population, and accounted for 41% and 17% respectively. Maximum species diversity that was recorded belonged to the families of Paracalanidae (7) followed by Acartiidae (5) and Pseudodiaptomidae (4). Out of 41 species of Copepoda recorded, 14 species (*Paracalanous parvus, Parvocalanous dubia, Bestiolina similis, Acrocalanous gibber, A. gracilis, Acartia erythrea, A. spinicauda, Psudodiaptomus serricaudatus, P. annandalei, P. aurivilli, Oithona brevicornis, O. similis, Longipedia weberi* and *Microsetella norvegica*) were perennially present in the creeks. That in turn, clearly highlights the euryhaline nature, and broad range of thermal tolerance of these species. The average numerical abundance of Copepoda was maximum during pre-monsoon (31,791±7,012 ind.m^{-3}) followed by post–monsoon (29,152±5,597 ind.m^{-3}) and monsoon (19,236±5,912 ind. m^{-3}). The mean percentage contribution of Copepoda was highest at S5 (73%) and lowest at S2 (65%), whereas month-wise, it accounted maximum during May (74%). The correlation coefficient values of the family Paracalanidae, Acartiidae, Eucalanidae, Temoridae and Calanidae showed positive correlation between them, explaining the possible formation of groups by themselves (Table 4). Out of 17 copepod families, six families (Paracalanidae, Acartiidae, Temoridae, Calanidae, Oithonidae and Oncaeidae) differed significantly (ANOVA; $p \leq 0.05$) between seasons, while rest of the families did not portray significant temporal variations.

Albeit, Copepoda can be considered as the major group, which comprised of a large proportion of total zooplankton population in all the months, the occasional co–dominance of larvae (comprising of the polychaete, cirripede, isopod, amphipod, gastropod and fish larvae) and mysids were also documented. The mean abundance of larvae was maximum during pre–monsoon (6,222 ind.m^{-3}) and minimum in monsoon (2,500 ind.m^{-3}). Throughout the study period, the numerical abundance of larvae was maximum in October and minimum in July. Rotifera and Cladocera contributed 1% each to the total zooplankton throughout the study period. The temporal abundance of Rotifera exhibited two peaks (bi-modal pattern) in August and November. There was significant increase in average numerical abundance of Rotifera from pre–monsoon (55 ind.m^{-3}) to post–monsoon (430 ind.m^{-3}). Cladocera did not vary significantly across the seasons. Chaetognatha was represented by a single species, *Zonosagitta bedoti* with an average numerical abundance of 386 ind.m^{-3}, and exhibited its maximum (1,505 ind.m^{-3}) in January. Its abundance exhibited unimodal pattern across the seasons. Among the others, Mysids contributed significantly to the total zooplankton density, whereas Hydromedusae were spotted sporadically during the study period. Results of ANOVA (post hoc test) showed, no significant spatial differences in zooplankton (groups), while temporal differences exhibited significant heterogeneity ($p \leq 0.05$) among the zooplankton groups such as Copepoda (F= 4.061; p = 0.039), Cladocera (F= 7.046; p = 0.007), Chaetognatha (F=3.902; p= 0.05), crustacean nauplii (F=13.442; p= 0.001) and larvae (F=7.902; p= 0.005). Other three major groups *viz.* Rotifera (F=1.214; p=0.324), Eggs (F=1.220; p=0.323) and Mysids (F=1.73; p=0.930) did not show statistically significant variations across seasons.

Species similarity

The Cluster analysis on the similarity of zooplankton species abundance in the studied stations are shown in Fig. 5. The species abundance resulted in three clusters. The maximum similarity (83.9%) was observed between the stations S1 and S2 during post–monsoon, and lowest similarity (73%) between S3 and S6 during pre–monsoon. On the whole, the species composition in the samples exhibited >65% similarity between the stations. The grouping of species composition was further substantiated by the NMDS, and the plot also gave similar compositional pattern among samples. The assemblage of pre–monsoon differed substantially from that of the other two seasons, with regard to the zooplankton composition (Fig. 6). Results of ANOSIM reflected the significant (Global R = 0.101; significance level 0.1%) spatial differences of zooplankton species composition. The zooplankton community also depicted the significant temporal variation (R= 0.565; P 0.1%). The *k*-dominance curve extracted for the period 2016–17 reflected that the species abundance and diversity was noticeably higher during the pre–monsoon as compared to the other seasons (Fig. 7a), whereas in the following year (2017–18) the curves overlapped indicating no differences in the species diversity, illustrating the similar dominance patterns (Fig.7b). RELATE routine analysis further substantiated the significant (ρ = 0.399; P 0.1%) inter annual differences of the zooplankton community compositions between 1st and 2nd year study period. Though, one-way ANOVA (post hoc) results portrayed no significant variation of the zooplankton groups spatially (p>0.05), PERMANOVA design depicted the significant variations of zooplankton population both spatially (F=2.313; p = 0.001) and seasonally (F = 6.107; p = 0.001). On the whole, the spatio–temporal variations of zooplankton were found to be significant (F = 2.0; p = 0.001) in the study area.

SIMPER routine was analysed based on the abundance of zooplankton described the *characterizing species* (within the group similarity), and *discriminating species* (between the group dissimilarity). The average similarity percentage varied between 44.69 and 51.1% with the highest at S3 and lowest at S6. Table 5 summarizes the information on characterizing species and their percentage contribution to the total zooplankton abundance in each group. At S3, *P. parvus* (12.4%), *B. similis* (10.9%), *O. brevicornis* (9.76%) and *P. dubia* (9.70%) were most prominent. Similarly, *B. similis* (20.34%), *O. brevicornis* (9.84%), *P. parvus* (8.55%) and *A. spinicauda* (7.07%) were the main contributors at the station S6. The dissimilarity percentage calculated ranged from 50.34 to 56.81% with the highest percentage found to be between S2 and S6 (56.81%). *Paracalanous parvus* (6.20%), crustacean nauplii (5.65%), polychaete larvae (5.60%), *O. brevicornis* (5.34%), *B. similis* (3.89%), *P. dubia* (3.28%), *Longipedia weberi* (3.23%) and *Acrocalanous gibber* (3%) were the major contributors to this group. With that of percentage contribution (β–dissimilarity) in the different assemblages, these species exhibited as key zooplankton species that differentiated between the assemblage, and their variability makes them *discriminating species* in the different zooplankton assemblages.

Diversity indices

α–diversity

The occurrence of Copepoda species varied considerably in seasons. Maximum species richness (36 species) was recorded at the station S3 during pre–monsoon followed by S2 (34 species) and S5 (32 species) during post–monsoon and pre–monsoon, respectively. The average species richness of the Copepoda was 28±4 species across the stations. On the whole, the seasonal species richness was highest during pre–monsoon (41 species) followed by monsoon (37 species) and post–monsoon (31species) throughout the study period. In respect of total zooplankton, maximum richness was accounted for 53 taxa at S2 during post–monsoon, whereas it was minimum at S4 (34 taxa) during monsoon. Significant spatial variations in the zooplankton taxa during monsoon (F = 5.667; p = 0.000) and post–monsoon (F = 9.634; p = 0.000) was observed, whereas the variation was not significant during pre–monsoon (F = 1.474; p = 0.219).

The Shannon-Wiener diversity *(H'),* Margalef's species richness *(d')* and Pielou's evenness index *(J')* in the studied stations for both the year is shown in Fig. 8. As with total zooplankton population, the d' was highest at S1 during post–monsoon (5.47) and lowest at S5 during monsoon (2.55). The H' values also depicted similar trend with the maximum at S1 during post–monsoon (2.71) and minimum at S2 during monsoon (1.66). The stations S1 and S6 showed similar assemblage pattern with regard to the richness, evenness and diversity of zooplankton. Throughout the study period, the zooplankton assemblage was not uniformly distributed in the studied stations and fluctuated greatly. The zooplankton species evenness *(J')* depicted that, it was relatively higher at S4 during pre–monsoon (0.86) and lower at S5 during monsoon (0.55). Results of ANOVA (post hoc test) showed significant variations ($p \leq 0.05$) of diversity indices (d', H' and $1-\lambda'$) across seasons except J'. The correlation matrix exhibited a significant positive correlation between d' and H' (r=0.923; $p \leq 0.01$), and also d' with $1-\lambda'$ (r = 0.83; $p \leq 0.05$). Similarly, J' had positive correlation with H' (r = 0.42; $p \leq 0.05$) and $1-\lambda'$ (r = 0.61; $p \leq 0.01$). All the correlation coefficient values of the indices showed positive correlation between them, implying similar pattern of species interaction in the zooplankton assemblage throughout the study.

***β* – diversity**

The relative dispersion (inter stations β–dissimilarity) value calculated using the multivariate dispersion index. The stations S4 (=1.11), S2 (=1.13) and S6 (=1.16) showed higher values (>1) indicating high β–diversity compared to S3 (=0.72) and S5 (=0.77). The zooplankton species turnover was registered in the impacted stations (S4, S2 and S6) as the values reached β =1. However, the pair-wise comparison (stations compared) of IMD depicted lower values (<1.0) indicating community variability (stability) during the study period. The β–dissimilarity index revealed the inter-stations differences in the species distribution patterns in the study area. The highest β–dissimilarity percentage was found to be between S2 and S6 with 56.81% and lowest between S3 and S5 (50.34%).

Influence of physico-chemical parameters on zooplankton distribution

The correlation matrix showed that, Copepoda was positively correlated with salinity (r = 0.557; $p \leq 0.05$), DO (r = 0.46), and negatively correlated with NO_3–N (r = −0.479; $p \leq 0.05$). Cladocera had positive correlation with salinity (r = 0.367), and significant negative correlation with turbidity (r = −0.60; $p \leq 0.01$). Crustacean nauplii and larvae also portrayed significant positive correlation with the salinity, PO_4–P and SiO_4–Si, and negative correlation with DO, turbidity and NO_3–N (Table 2). By and large, total zooplankton displayed the significant positive correlation with salinity (r = 0.617; $p \leq 0.05$), and negative correlation with NO_3–N (r = −0.575; $p \leq 0.05$).

For all the sampling stations, the correlation between zooplankton abundances and environmental variables were established by multivariate BIOENV analysis. The analysis confirms a set of environmental parameters that is related to spatial variations of zooplankton. BIO-ENV analysis (employing Spearman rank correlation method) reflected that the water quality parameters *viz.,* pH, salinity, DO, turbidity, PO_4–P, NO_3–N were correlated with the zooplankton community (Table 6). The best set of correlation between zooplankton and the individual environmental variable obtained in the combination of salinity and PO_4–P with the maximum coefficient of 0.210, whereas the minimum correlation coefficient (0.170) was recorded only with salinity. The correlation coefficient (ρ = 0.21) with the significance level 1.6% indicated that, two variables *i. e.* salinity and PO_4–P were the controlling factors for the distribution of zooplankton in the studied stations. To quantify the additional explained variables, Marginal tests (distance based linear model, DistLM) was performed to obtain a significant correlation between the zooplankton and each of the environmental variables. The results showed that, the significance correlation ($p \leq 0.05$) has been observed, with the variables such as Temp., salinity, DO, turbidity, PO_4–P and NO_3–N. The Sequential tests also revealed similar results with the former having significant correlation ($p \leq 0.05$) with three variables *viz.,* Temp., salinity and turbidity (Table 7). The fitted model (DistLM) explained that the two variables; Temp. and salinity were the deterministic parameters to explain the zooplankton community compositions in the studied stations (Table 8).

Discussion

Zooplankton community structure and its distribution pattern

The density and taxonomic diversity of the organisms in samples is primarily dependent upon the mesh size of sampling nets (Turner and Dagg 1983). The abundance of zooplankton, particularly the copepod nauplii and small copepods (*Oithona* spp.) were undervalued by the use of large mesh nets for sampling. For example, a mesh size of >150 µm is fairly large to sample quantitatively the small copepods and meroplankters, that sometimes dominate the estuarine zooplankton community (Fulton 1984). In our study, overall, the copepod nauplii and juvenile stages of copepods accounted great majority in the samples. While profiling the zooplankton taxa in the creeks of Sagar Island, Sundarbans, a total of 63 zooplankton taxa were documented. Bhattachajee et al. (2015) reported 41 meso-zooplankton taxa from the northern part of Sundarban mangrove wetland; 56 zooplankton taxa from the river Saptamukhi, Sundarban estuarine system (SES) (Nandy et al. 2018), and 47 taxa of zooplankton from Mooriganga river estuary reported by Paul et al. (2019). Recently, Nandy and Mandal (2020) documented 56 zooplankton taxa from river Matlah, Sundarban estuarine system, primarily dominated by Copepoda.

The dominance of Copepoda in the zooplankton community was well documented in various estuaries across the world in both tropical and temperate regions (Mwaluma et al. 2003; Gao et al. 2008; Bhattacharyya et al. 2015; Srichandan et al. 2015; Abdul et al. 2016; Paturej et al. 2017; Nandy et al. 2018). During the present study, Copepoda contribution to the total zooplankton population was ranging from 59.5 to 73.13%, which was in line with the findings of Nandy and Mandal (2020) from Matlah river system, where the authors reported the dominance of Copepoda (59 to 87%) to the total zooplankton population with the monsoon maxima (87%). However, in the present context, a pre–monsoon maximum was evident, which was contrast to the observations made by Nandy and Mandal (2020), but in agreement with the other workers (Ramaiah et al. 1996; Bhattacharya et al. 2015). The recruitment of neritic species through tidal influenced massive ingress of seawater into the creeks also could be one of the plausible causes for higher abundance of Copepoda in pre–monsoon (Mishra and Panigrahy 1996). Sarkar et al. (1986) found predominance of Copepoda (73–96%) in the total zooplankton population with highest values in pre–monsoon, and lowest during late monsoon period in the creeks of Sagar Island which supports the findings of the present study. Calanoid copepods being the dominant group followed by Cyclopoids and Harpacticoids during pre–monsoon in the present study was in line with Bhattacharya et al. (2015). Sai Sastry and Chandramohan (1995) also reported similar kind of Copepods contribution *viz.,* Calanoid > Cyclopoid > Harpacticoid during pre–monsoon with herbivorous and omnivorous copepods being the principal trophic components in the Cochin backwaters (Madhu et al. 2007). The abundance of Copepoda steadily increased from post–monsoon to pre–monsoon with rising trend of the salinity in the present study. The recorded low zooplankton abundance during monsoon could be attributed to heavy influx of freshwater coupled with abrupt hydrological changes, which in turn decreased the zooplankton density (Mwaluma et al. 2003; Santhanam et al. 2012).

Community structure of zooplankton in the present study was in conformity with the Varghese and Krishnan (2009); Bhattacharya et al. (2015) and Rakesh et al. (2013), where the authors noted higher zooplankton species composition during pre-monsoon as compared to other seasons. The ubiquitous dominance of Copepod species *viz. B. similis, P. parvus, P. dubia, A. spinicauda, P. serricaudatus, O. brevicornis* and *O. similis* in the creeks habitat signifies their broad trophic spectrum (Nandy and Mandal 2020) with high adaptability to the environmental conditions. In the present study, 14 Copepod species has been documented as having perennial existence in the studied creeks, which may be due to their continuous breeding nature, high reproductive capacity coupled with suitable environmental conditions and food availability in the ecosystem (Ramaiah and Nair 1997; Santhanam and Perumal 2003). Similar type of species dominance has been reported from Mandovi and Zuari estuarine system and Godavari estuary by Padmavathi and Goswami (1996) and Sai Sastry and Chandramohan (1995), respectively. The dominance of Copepod families *viz.,* Oithonidae, Paracalanidae, Acartiidae and Pseudodiaptomidae in the present study were at par with the findings of Neumann-Leitao et al. (1992); McKinnon and Klumpp (1998). The higher abundance of species *Acartia sewelli, Eucalanus crassus, Candacia bradyi, Acrocalanous longicornis* during pre–monsoon, and *A. plumosa*, *Centropages dorsipinnatus* during post–monsoon, probably explains the limited period of existence, and highlighting the temporal shift in species abundance in the creeks of Sundarbans. The prevalence of high numbers of *Oithona* spp. among other copepods in the present results was similar to the reports of Gallienne and Robins (2001), which described them as the most abundant and ubiquitous copepod in the world. High abundance of *Oithona* spp. in the zooplankton population could be attributed to their smaller body size, omnivorous feeding habit (Kumar 2003), and high reproductive capacity (Santhanam and Perumal 2003). Almeda et al. (2010) suggested that the lower metabolic requirements of Oithonids compared to Calanoids might explain the high abundance of the former group, both in coastal eutrophic waters and in oligotrophic oceanic environment.

Formation of groups and co-existence

In the present study, the copepod families such as Paracalanidae, Candacidae, Oithonodae, Onceidae, Ectinosomatidae and Longipedidae showed positive correlation amongst themselves (Table 4) indicating that there is a close association between the families and species under these families can increase or decrease in conjunction with one another. Thus, it provides evidence that these families coexisted and combined to form their own group in the zooplankton assemblage. The coexistence of these copepods reveals their advantageous life history traits in the local environment (site-specific) which made them a successful inhabitant (Dur et al. 2007) in these creeks habitat. The families Candacidae and Tortanidae may have formed their own separate group, as they were both negatively correlated with most of the other families. Similar finding was also reported by Bhattacharya et al. (2015) from Sundarban waters, where the authors speculated that there is congeneric association of five and six species of family Acartiidae and Paracalanide, respectively, from Jambu Island, Indian Sundarbans. These coexisting species exhibited high adaptability and opportunistic nature, by means of shifting their feeding habit to adopt in a highly variable estuarine environment (Bhattacharya et al. 2015; Mwaluma et al. 2003).

Holoplankters predominated throughout the year in all the stations with slightly higher numbers in monsoon months, whereas meroplankters were highest during post–monsoon, which indicates a key role of salinity in controlling the zooplankton community (Jyothibabu and Madhu 2007). The co-dominance of meroplankters (polychaete larvae, decapod larvae, crab zoea, bivalvia, gastropod veliger, isopod larvae and cirripede larvae) is suggestive of the fact that these organisms take an important role in the coupling of bentho-pelagic food webs (Rakesh et al. 2008; Nandy and Mandal 2020). Another characteristic feature of the present observation was the relatively large occurrence of copepod nauplii, which could be attributed to high density of older copepods (Uye et al. 2000) round the year. Chaetognatha, *Zonosagitta bedoti* was found to be maximum during post–monsoon which was in consistent with the findings made by Nandy and Mandal (2020). Bhattacharya et al. (2015) reported higher percentage contribution of developing stages of *Z. bedoti* in their study from Sundarban mangrove wetland, and inferred that the species prefer estuarine environment for its development. In the present study, the mean abundance of *Z. bedoti* (386 ind.m^3) was higher than the former study (55 ind. m^3), which may be due to its salinity, geographic heterogeneity and sampling strategy. The gradual increase in the abundance of Chaetognaths from the post–monsoon to pre–monsoon season corresponding to the increase in salinity which was also reported by Sarkar et al. (1985) from Hooghly–Matlah estuarine system.

Significantly less contribution was made by Rotifera and Cladocera, which was often more specific to low saline water environment (Godhantaraman 2001), where they prevailed only during monsoon and late monsoon period. The occurrence of genera *Brachionus* and *Ceriodaphnia* during monsoon months indicates they are least tolerant to higher salinity, and transported passively by river run-off. In agreement to our study, similar observations have been made earlier by Govindasamy and Kannan (1991), where low abundance of Rotifera and Cladocera in the zooplankton community in Pichavaram mangroves was observed. The accumulation of meroplanktonic larval forms indicated the availability of rich food supply (planktonic forms) in the mangrove dominated creeks, low predation pressure (Kimmerer 1991), high growth rate (Turner 2004), and a balanced food concentration. In addition, these larval forms are also flushed by the sea during the spring tide, which also partially explains the neretic larval supply in the creeks. According to (Morgan 1995), the avoidance of predators may also influence the larval release and dispersal in the estuary, which could also be the reason for higher abundance of larvae, resting eggs and nauplii in the mangrove dominated creeks. The muddy substrate of the inner estuary supports a rich polychaete community, whose larvae were also more evident in the studied creeks.

5. 3. Creeks ecosystem health

Creeks ecosystem health

Margalef's species richness *(d')* and Shannon-Wiener diversity *(H')* exceeding 2.50 indicates healthy environment of an aquatic ecosystem (Magurran 1988). Similarly, Chao et al. (2009) categorized the threshold values of diversity index *(H')* for zooplankton in the tropical estuarine system as *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 investigation, the calculated mean value of d' and H' were found to be 4.07±0.45 and 2.31±0.15 indicating *'good'* zooplankton diversity in the creeks which was in conformity with Nandy and Mondal (2020) and Rakshit et al. (2015). The Index of multivariate dispersion showed higher values (β =>1) in the creeks (S2, S4 and S6), those are experiencing high anthropogenic pressure coupled with other local factors (boat trafficking, dredging, tourism) in the present study. Seasonal mean diversity (H' = 2.46) and richness (d' = 4.44) values were maximum during post–monsoon along with high value of evenness index (J' = 0.76). Similar results were also reported by Bhattacharya et al. (2015) where higher values of species diversity and richness during post–monsoon and lowest during monsoon were documented. Contrary to the present findings, Nandy and Mandal (2020) reported higher species diversity (H' = >1.6) and richness during pre–monsoon, but was of same view in reference to the monsoon minima. The species diversity decreases when a community become uneven, and is dominated by single species or fewer species (Rakshit et al. 2015). The value of J' was 0.75±0.04 for all the seasons, which implied evenly distribution of zooplankton population with the healthier diversity (Sun et al. 2001) in the system. A similar study by Rakesh et al. (2013) calculated somewhat lower value in the Gautami–Godavari estuary (H' = 1.87±0.19 and J' = 0.59±0.01), and higher values (H' = 2.62±0.25 and J' = 0.79±0.008 bits.ind. l^{-1}) in coastal immediate waters.

Correlation between zooplankton assemblage pattern and environmental traits

The factors determining the seasonal and interannual variations of zooplankton assemblages are salinity, temperature, sediment type and origin of the fauna previously reported by Selifonovo (2008). The variations in the zooplankton community were significantly correlated to the physico-chemical factors (especially the water temperature, salinity, DO, turbidity and PO_4–P) in the studied creeks. Abdul et al. (2016) ascribed that water variables (temperature, salinity, transparency and DO) significantly explain the principal variations in the zooplankton species composition in a Nigerian tropical coastal estuary, which was in line with the present observation. In estuarine environments, the salinity gradient has control over the overall species composition (Bollens et al. 2011). Therefore, a substantial positive correlation between salinity and various groups of zooplankton (Copepoda, Cladocera, Chaetognatha, crustacean nauplii, larvae, mysids and total zooplankton) were seen in the present study. This was at par with many other previous findings that emphasized the influence of salinity on zooplankton community (Paturej et al. 2009; Dube et al. 2010). However, the inversely proportional relationship between zooplankton density and salinity has been described from the Matlah system (Nandy and Mandal 2020), with a note that the predominance of low saline species of genus *Paracalanus, Acartia* and *Acrocalanous* are indicating the estuarine influence in their studies. In aquatic ecosystems the rise in temperature has been associated with elevated abundance and zooplankton species diversity (Buyurgan et al. 2010). The maximum density and diversity of zooplankton were recorded during pre–monsoon in the present study, which supports the notion. Furthermore, previous studies (Salvador and Bersano 2017; Du et al. 2020) noted that the increasing temperature promoted the abundance of small bodied copepods (*P. parvus* and copepod nauplii in particular), which are frequently associated with the increase in temperature and eutrophic condition in the coastal environment. Our results also corroborated with the former findings where there was maximum abundance of small-bodied copepods (especially *P. parvus, B. similis, P. dubia* and *O. brevicornis*) during pre–monsoon season. This probably hinted towards the affinity for temperature, and increase in numerical abundance of zooplankton that could be directly proportional to the increasing temperature in the creek habitats. The relationship between zooplankton taxa, temperature and high concentrations of nutrients (NO_3–N, PO_4–P and SiO_4–Si) has been revealed by many studies (Park and Marshall 2000; Biancalana et al. 2014). It is consensus that an increase in the concentration of nutrients influences the top levels of a food web through a cascade of interactions (Anderson et al. 2002). The negative influence of NO_3–N on the zooplankton community in the vistula lagoon (Paturej et al. 2017) was in agreement with the present observation.

Aquatic turbidity is also a causative factor in decreasing zooplankton and it accelerates copepod mortality, which was evident in Sundarban estuarine system (Nandy and Mandal 2020), and many other estuaries (Gordina et al. 2001; Park and Marshall 2000). In the present study too, turbidity negatively influenced on the zooplankton community. The mechanisms driving zooplankton community compositions are difficult to distinguish, but it is clear from the above discussion that water variables such as temperature, salinity, DO, turbidity and PO_4–P have profound influence on the zooplankton community structure in the creeks water, which was evident from the BIOENV and marginal test. Furthermore, the fitted model (DistLM) also depicted two variables *viz.,* water temperature and salinity were the deterministic variables that could explain the distribution of zooplankton community. This is in agreement with previous studies which emphasized the impact of salinity and temperature on zooplankton distribution (Paturej et al. 2006; Gao et al. 2008; Sebastian et al. 2012). Additionally, the recruitment of zoobenthos populations in the creeks was largely ensured by the local populations, and their distributions and settlements are related to the tidal flow.

Conclusion

The present study reveals the spatio-temporal dynamics of zooplankton at various geographical locations stands unique, and provides a comprehensive information on the status of the ecological interaction with the zooplankton community in the creek environment. In the present investigation, the calculated mean value of d and H' (4.07 and 2.31, respectively) indicating *'good'* zooplankton diversity in the creeks system. The Index of multivariate dispersion reflected higher values (β = >1) in the creeks (S4, S2 and S6) that implied the systems are in stress due to varying anthropogenic pressure. Strong seasonal and spatial variations were recorded in the zooplankton community influenced by varying environmental variables. Temperature and salinity were positively correlated to the increase in zooplankton abundance. On the whole, water parameters such as temperature, salinity, DO, turbidity and PO_4 – P and NO_3 – N were found to have influence on the distribution, abundance and diversity of zooplankton in the creeks. More specifically, among these variables, our fitted distance based linear model (DistLM) exhibited two variables *viz.*, temperature and salinity were the principal factors in controlling the zooplankton community compositions in the creek environment. Overall, the study highlights the necessity of incorporating different approaches for a better understanding of zooplankton community structure in mangrove environment including Indian Sundarban ecoregion. The present work shall help in the ecological assessment of the creek ecosystem as well as providing the baseline information on tidal creek ecosystem.

Declarations

Ethical Statement: The authors declare that they have strictly followed all the rules and principles of ethical and professional conduct while completing the research work. No specific permission was required to collect the zooplankton samples at the study sites.

Consent to participate: Not applicable

Consent to publish: Not applicable

Conflict of Interest: The authors declare that they have no conflict of interest.

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Authors Contributions

Sanghamitra Basu: Sample collection, taxonomic identification, statistical analysis, interpretation of data, manuscript preparation; **Pranab Gogoi**: taxonomic identification, statistical analysis and manuscript preparation; **Subarna Bhattacharyya**: Guidance, manuscript corrections; **Lohith Kumar K.:** Preparation of the map of the study area and manuscript preparation; **Sanjoy Kumar Das:** Manuscript preparation and corrections; **Basanta Kumar Das**: Overall guidance and correction.

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Tables

Table 1 Variations of physico-chemical parameters of studied locations of Sagar island, Sundarbans

Stations	Seasons	pH	Temp. (ºC)	Salinity (ppt)	DO (mgl^{-1})	Turbidity (NTU)	COD (mgl^{-1})	BOD (mgl^{-1})	PO_4-P (mgl^{-1})	NO_3-N (mgl^{-1})	SiO_4-Si (mgl^{-1})	NO_2-N (mgl^{-1})
SIK	MON	7.26±0.24	27.55±0.65	6.91±7.91	6.44±0.97	74.38±9.33	83.75±37.65	2.41±1.31	6.11±2.55	8.57±5.57	4.47±2.01	0.52±0.28
(S1)	POM	7.165±0.23	20.15±3.53	13.45±3.45	7.26±0.47	26.79±19.34	70.25±58.86	6.02±3.92	3.40±1.97	2.58±1.11	3.16±0.41	0.36±0.21
	PRM	7.17±0.38	31.00±2.41	17.89±4.60	5.80±0.63	64.01±26.37	86.63±46.47	3.12±1.47	13.17±4.04	5.35±3.17	10.32±5.54	0.90±0.63
SAG	MON	7.43±0.20	27.66±0.97	6.53±6.44	6.40±0.59	61.54±13.03	77.38±15.45	2.38±1.07	3.13±2.58	10.28±6.45	3.29±1.21	0.54±0.38
(S2)	POM	7.43±0.33	20.89±3.19	17.14±6.42	7.20±0.40	37.05±36.40	52.38±41.03	3.80±0.85	1.71±0.65	3.51±2.65	6.55±5.28	0.34±0.29
	PRM	7.23±0.46	29.70±2.18	22.91±4.39	5.81±0.92	55.08±30.13	84.38±41.87	2.99±1.96	6.90±3.48	3.26±1.26	11.34±6.84	1.02±0.72
HAT	MON	7.44±0.25	28.03±0.60	7.74±7.75	6.08±0.83	77.70±8.37	76.88±17.86	2.11±0.96	6.58±2.33	8.95±4.18	4.70±2.45	0.85±0.53
(S3)	POM	7.47±0.46	20.99±3.38	13.80±2.76	7.58±0.27	23.35±14.48	61.25±38.34	2.24±1.59	2.78±2.03	5.77±2.80	6.19±3.33	0.31±0.24
	PRM	7.17±0.43	30.70±2.23	19.81±4.90	5.79±0.91	58.50±18.61	89.50±53.51	3.89±2.06	10.28±4.50	7.33±2.74	7.97±4.65	0.60±0.39
CHE	MON	7.50±0.10	28.15±0.95	6.57±7.10	6.48±0.49	64.38±8.34	82.75±30.77	1.31±0.99	5.94±3.10	7.64±4.62	4.71±0.62	1.09±0.86
(S4)	POM	7.33±0.52	20.7±3.12	12.99±4.19	7.10±0.87	23.78±19.38	62.50±49.68	1.73±0.88	2.34±1.48	2.57±1.39	5.83±3.57	0.31±0.25
	PRM	7.44±0.45	30.90±2.22	20.14±1.55	5.51±0.33	64.88±31	61.88±30.77	3.54±2.07	10.18±4.64	8.44±6.04	8.61±2.69	0.79±0.55
PHO	MON	7.33±0.19	28.35±0.82	3.82±4.34	6.46±0.52	67.63±6.81	90.88±14.34	3.66±2.6	6.21±2.87	8.70±3.16	4.95±2.14	0.79±0.60
(S5)	POM	7.44±0.29	20.13±3.21	10.05±1.36	7.32±0.64	23.20±16.31	64.75±46.39	2.20±1.41	4.85±1.87	4.33±1.56	9.60±4.84	0.53±0.31
	PRM	7.44±0.26	29.35±2.12	16.86±2.64	6.14±0.81	39.39±13.82	70.00±47.48	2.90±1.57	5.77±1.50	5.29±3.02	5.93±1.12	0.67±0.58
KAC	MON	7.51±0.31	27.80±0.82	5.21±5.71	6.29±0.57	88.63±16.25	90.00±12.88	2.82±1.04	4.72±2.83	10.37±6.35	3.66±2.60	0.81±0.48
(S6)	POM	7.53±0.33	20.06±3.48	10.34±1.04	6.75±0.26	31.10±15.71	67.75±53.37	2.23±1.35	3.41±0.54	3.57±2.10	9.76±5.35	0.59±0.27
	PRM	7.43±0.26	30.29±2.47	16.68±3.44	5.76±0.70	62.90±27.11	49.00±31.14	2.97±2.45	8.19±2.33	6.89±4.01	11.32±6.33	1.02±0.68

(MON=monsoon; POM=Post-monsoon; PRM=Pre-monsoon and the '± values' denotes the standard deviation; n=8)

Table 2 Intra-relationship of water quality parameters and major groups of zooplankton

:	pH	Temp.	Sal	DO	Tur	BOD	PO_4-P	NO_3-N	NO_2-N	SiO_4-Si	COPE	CLAD	ROTI	CHAE	NAUP	LARV	EGGS	MYSI	TZP
	1																		
np.	0.039	1																	
inity	-0.214	0.44	1																
	0.148	**-.877****	-0.331	1															
bidity	0.156	**.682****	-0.37	**-.601****	1														
D	0.333	-0.13	-0.12	0.182	0.101	1													
$_4-P$	-0.13	**.535***	0.443	**-.723****	0.435	-0.221	1												
$_3-N$	0.432	**.575***	**-.503***	-0.371	**.771****	0.049	0.192	1											
$_2-N$	-0.053	**0.573***	-0.15	-0.473*	**0.612****	0.009	0.423	0.224	1										
$_4-Si$	-0.167	0.387	**.751****	**-.591****	0.127	-0.108	**.667****	-0.251	0.218	1									
PE	-0.207	-0.385	**0.557***	0.306	-0.421	0.447	-0.165	**-.479***	0.052	0.152	1								
AD	0.178	-0.143	0.367	-0.086	**-0.60****	-0.005	0.031	-0.128	**0.548***	0.224	0.235	1							
TI	0.323	-0.089	-0.332	0.138	0.201	-0.011	-0.307	0.216	0.26	-0.307	0.103	0.466	1						
AE	0.035	**-0.542***	0.048	0.246	-0.312	0.320	-0.315	-0.299	-0.07	-0.136	0.102	**.558***	0.467	1					
UP	-0.379	0.227	**.657****	-0.429	-0.101	0.329	**.549***	-0.262	0.007	**.552***	0.259	-0.17	-0.344	-0.113	1				
RV	-0.195	-0.186	**.652****	-0.033	-0.318	0.419	0.254	**-.612****	0.062	**.614****	**.549***	0.136	-0.195	0.037	**.541***	1			
GS	-0.307	**-.570***	0.159	0.448	**-.508***	**0.579***	**-.478***	**-.627****	-0.14	-0.043	**.580***	0.151	0.069	0.39	0.091	**.556***	1		
SI	-0.083	-0.179	0.075	0.135	-0.154	0.025	-0.044	-0.085	0.117	-0.07	0.127	0.109	-0.31	0.117	0.064	-0.214	0.177	1	
	-0.288	-0.336	**.617****	0.173	-0.43	**0.508***	0.006	**-.575***	0.093	0.342	**.959****	0.247	0.002	0.136	**.473***	**.705****	**.613****	0.155	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Note: COPE: Copepoda; CLAD: Cladocera; ROTI: Rotifera; CHAE: Chaetognatha; NAUP: Nauplii; LARV: Larvae (polychaete, comprising polychaete, cirripede, isopod, amphipod, gastropod and fish larvae); Eggs: Resting eggs (copepods, rotifers, fish); MYSI: Mysids; TZP: Total zooplankton

Table 3 Numeric abundance (mean and standard deviation; n=24) of total zooplankton and copepod population with the diversity indices measures in the studied stations

Stations	Total zooplankton abundance ($ind.m^{-3}$)	Total Copepod abundance ($ind.m^{-3}$)	Copepod contribution (%)	Richness *(d′)*	Shannon Diversity *(H′)*	Simpson diversity *(1-λ′)*	Evenness *(J′)*
S1	42.33±27.43	26.63±20.41	69.92	4.48±1.53	2.43±0.65	0.88±0.17	0.78±0.19
S2	41.86±25.01	27.58±15.56	65.89	3.93±1.29	2.27±0.55	0.86±0.15	0.75±0.16
S3	43.66±16.16	29.72±10.71	68.06	4.47±1.23	2.48±0.53	0.89±0.15	0.78±0.16
S4	28.50±14.42	16.97±7.70	59.55	3.46±1.22	2.04±0.62	0.82±0.18	0.76±0.18
S5	45.55±20.68	29.33±17.32	73.13	4.09±0.81	2.29±0.47	0.85±0.16	0.73±0.22
S6	40.88±14.64	27.11±16.34	66.30	4.39±0.94	2.44±0.51	0.88±0.16	0.77±0.19

The abundance of total zooplankton and total copepods are expressed in thousands

Table 4 Correlation matrix showing the intra−relationship of copepod families

Family	PARA	ACAR	EUCAL	PSEU	TEMO	CAND	CALA	CENT	PONT	TORT	OITH	ONCE	CYCL	MIRA	ECTI	LONG	CLYT
PARA	1																
ACAR	-0.064	1															
EUCAL	0.09	-0.15	1														
PSEU	0.189	0.426	-0.385	1													
TEMO	0.262	-0.192	**.728****	-0.172	1												
CAND	**.554***	0.042	-0.158	0.356	0.070	1											
CALA	-0.131	**.614****	-0.219	**.546***	0.050	-0.168	1										
CENT	0.037	**.578***	-0.406	0.315	-0.294	-0.032	**.567***	1									
PONT	0.130	0.227	0.086	0.369	0.331	-0.168	0.457	0.189	1								
TORT	0.105	-0.223	0.461	-0.097	**.655****	-0.173	0.202	-0.193	0.151	1							
OITH	**.489***	**.670****	-0.023	**.609****	0.130	0.396	**.508***	0.357	0.438	0.1	1						
ONCE	**.752****	0.011	0.175	0.046	0.182	**.472***	-0.186	-0.112	-0.123	-0.087	0.232	1					
CYCL	0.132	0.066	-0.092	0.189	-0.195	-0.28	0.218	0.362	0.121	-0.201	-0.102	0.232	1				
MIRA	0.243	0.218	0.324	0.184	0.201	0.312	-0.019	0.204	0.158	-0.129	0.160	0.334	**.473***	1			
ECTI	**.594****	0.123	0.137	0.434	0.066	**.566***	0.071	0.161	-0.012	-0.096	0.357	**.663****	0.444	**.625****	1		
LONG	**.520***	0.153	-0.052	0.353	0.072	**.483***	0.131	-0.046	0.027	-0.110	0.338	**.789****	0.062	0.125	**.637****	1	
CLYT	0.128	**.484***	0.327	**.504***	0.129	0.180	0.207	0.042	0.088	0.230	0.435	0.081	0.048	0.435	0.377	0.106	1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Note: PARA: Paracalanidae; ACAR: Acartiidae; EUCAL: Eucalanidae; PSEU: Pseudodiaptomidae; TEMO: Temoridae; CAND: Candacidae; CALA: Calanidae; CENT: Centuridae: PONT: Pontellidae; TORT: Tortanidae; OITH: Oithonidae; ONCE: Onceidae; CYCL: Cyclopidae; MIRA: Miraciidae; ECTI: Ectinosomatiidae; LONG: Longipadidae; CLYT: Clytemnesteridae

Table 5 SIMPER analysis depicted the '*characterizing species'* and their percentage contribution to the average similarity and the '*discriminating species'* that contribute to the maximum dissimilarity between the assemblages (stations)

Stations	Major species contribution to similarity within the assemblage (*Characterizing species)*
(Avg. sim: 69%)	*Oithona brevicornis* (12.17%), *P. parvus* (11.40%), Crus. nauplii (9.66%), *B. similis* (9.01%), *P. dubia* (7.35%), *P. serricaudatus* (5.15%), Polychaete larvae (4.34%), *O. similis* (4.18%), *A. spinicauda* (4.10%), *A. erythraea* (3.8%), *A. gibber* (3.66%)
(Avg. sim: 63%)	*Paracalanous parvus* (15.32%), Crus. nauplii (14.17%), *B. similis* (12.05%), *O. brevicornis* (10.83%), *P. dubia* (5.59%), *L. weberi* (4.61%), *P. annadalei* (4.12%), *A. spinicauda* (4.10), *O. venusta* (4.02%), *A. gracilis* (3.2%)
(Avg. sim: 97%)	*C. naulii* (12.4%), *P. parvus* (11.87%), *B. similis* (10.92%), Mysids (9.76%), *O. brevicornis* (9.70%), *P. dubia* (5.49%), *P. serricaudatus* (4.04%)
(avg. sim: 19%)	*Bestiolina similis* (17.82%), Crus. nauplii (15.42%), *P. parvus* (13.89%), *O. brevicornis* (11.43%), Polychaete larvae (7.27%), *L. weberi* (4.15%), *P. dubia* (4.07%), *P. serricaudatus* (3.7%), *P. aurivilli* (3.42%), *Microsetella norvegica* (3.1%)
(Avg. sim: 01%)	*Bestiolina similis* (15.56%), *O. brevicornis* (11.13%), Crus. nauplii (10.77%), *P. parvus* (8.49%), *A. spinicauda* (7.10%), *L. weberi* (4.90%), *P. dubia* (4.75%), *P. serricaudatus* (4.7%), *A. erythraea* (4.1%), *Acrocalanous gracilis* (3.7%)
(Avg. sim: 73%)	*Bestiolina similis* (20.34%), Crus. nauplii (9.82%), *O. brevicornis* (8.55%), *P. parvus* (7.07%), *A. spinicauda* (5.42%), Polychaete larvae (5.24%), *L. weberi* (4.57%), *P. dubia* (3.34%), *Pseudodiaptomus aurivilli* (3.1%), *Microsetella norvegica* (2.86%)

Avg. dissimilarity	*Discriminating* species
2 (55.34%)	*Paracalanous parvus* (5.85%), Crus. nauplii (5.44%), *O. brevicornis* (5.29%), *B. similis* (4.71%), *A. plumosa* (4.41%), *A. gibber* (4.11%)
& 55.34%)	Crus. nauplii (6.23%), Mysids (5.93%), *P. parvus* (5.37%), *B. similis* (5.12%), *O. brevicornis* (4.94%), *P. dubia* (4.94%)
& S3 .58%)	Mysids (7.36%), Crus. nauplii (6.335%), *P. parvus* (5.71%), *O. brevicornis* (5.13%), *P. dubia* (4.50%)
& S4 .84%)	Crus. nauplii (6.89%), *B. similis* (6.34%), *O. brevicornis* (5.39%), Polychaete larvae (4.78%), *P. parvus* (4.66%), Mysids (4.62%), *P. dubia* (4.38%), *A. plumosa* (4.33%)
&S 4 .27%)	Crus. nauplii (7.57%), *P. parvus* (6.35%), *O. brevicornis* (5.61%), *B. similis* (5.32%), Mysids (4.76%), Polychaete larvae (4.60%)
& S4 .91%)	Mysids (8.04%), Crus. nauplii (8.02%), *P. parvus* (5.59%), *O. brevicornis* (5.28%), *B. similis* (5.19%), *P. dubia* (5.17%)
& S5 .93%)	*Bestiolina similis* (7.92%), *O. brevicornis* (6.08%), *P. parvus* (5.73%), Crus. nauplii (4.80%), *P. dubia* (4.18%)
& S5 .25%)	*Bestiolina similis* (6.85%), *P. parvus* (6.75%), *O. brevicornis* (6.32%), Crus. nauplii (5.50%)
& S5 .34%)	*Bestiolina similis* (8.04%), Crus. nauplii (8.02%), *P. parvus* (5.5%), Mysids (5.2%), *O. brevicornis* (5.1%), *P. dubia* (5.1%)
& S5 .15%)	*Bestiolina similis* (7.98%), Crus. nauplii (7.18%), *O. brevicornis* (6.68%), *P. parvus* (5.76%), Mysids (4.64%), Polychaete larvae (4.25%)
& S6 .48%)	Polychaete larvae (5.75%), *O. brevicornis* (5.29%), *B. similis* (5.19%), Crus. nauplii (4.86%), *P. parvus* (4.79%)
& S6 .81%)	*Paracalanous parvus* (6.20%), Crus. nauplii (5.65%), Polychaete larvae (5.60%), *O. brevicornis* (5.34%)
& S6 .06%)	Crus. nauplii (6.51%), Mysids (6.0%), *P. parvus* (5.74%), *O. brevicornis* (5.23%), Polychaete larvae (4.85%), *P. dubia* (4.58%)
& S6 .21%)	Crus. nauplii (7.32%), Polychaete larvae (7.03%), *O. brevicornis* (5.14%), *P. parvus* (4.92%), *B. similis* (4.58%), Mysids (4.51%)
& S6 .01%)	*Oithona brevicornis* (6.37%), *P. parvus* (5.65%), *B. similis* (5.63%), Polychaete larvae (5.56%), Crus. nauplii (5.23%)

Table 6 BIO−ENV analysis observed in the zooplankton community compared with environmental variables

No. of variables	Parameters	Spearman correlation
2	Salinity, PO_4−P	**0.210**
3	Salinity, PO_4−P, NO_3−N	0.203
3	pH, Salinity, PO_4−P	0.202
4	pH, Salinity, PO_4−P, NO_3−N	0.197
4	Salinity, BOD, PO_4−P, NO_3−N	0.184
2	Salinity, NO_3−N	0.177
5	pH, Salinity, BOD, PO_4−P, NO_3−N	0.174
3	Salinity, Turbidity, PO_4−P	0.173
1	Salinity	**0.170**

Table 7 Marginal and sequential tests of environmental variables and the abundance of zooplankton

MARGINAL TESTS			
Variable	SS	Pseudo-F	P
pH	979.65	0.90426	0.592
Temp.	2465.1	2.3208	**0.007**
Salinity	3936.3	3.7807	**0.001**
DO	1864.7	1.7415	**0.033**
Turbidity	1765.6	1.6467	**0.046**
BOD	801.59	0.73817	0.77
PO_4-P	2196.7	2.0607	**0.016**
NO_3-N	1817.2	1.6961	**0.03**
SiO_4-Si	2486	2.3412	0.053
SEQUENTIAL TESTS			
Variable	SS	Pseudo-F	P
Temp.	3936.3	3.7807	**0.001**
Salinity	2757.8	2.7137	**0.001**

Table 8 Distance-based linear model (DistLM) that fitted for the relationship between zooplankton abundance and environmental variables

	Axis	% Explained variation out of fitted model		% Explained variation out of total variation	
		Individual	Cumulative	Individual	Cumulative
1	Salinity	69.75	69.75	6.08	6.08
2	Temp.	30.25	100	2.64	8.71

Figures

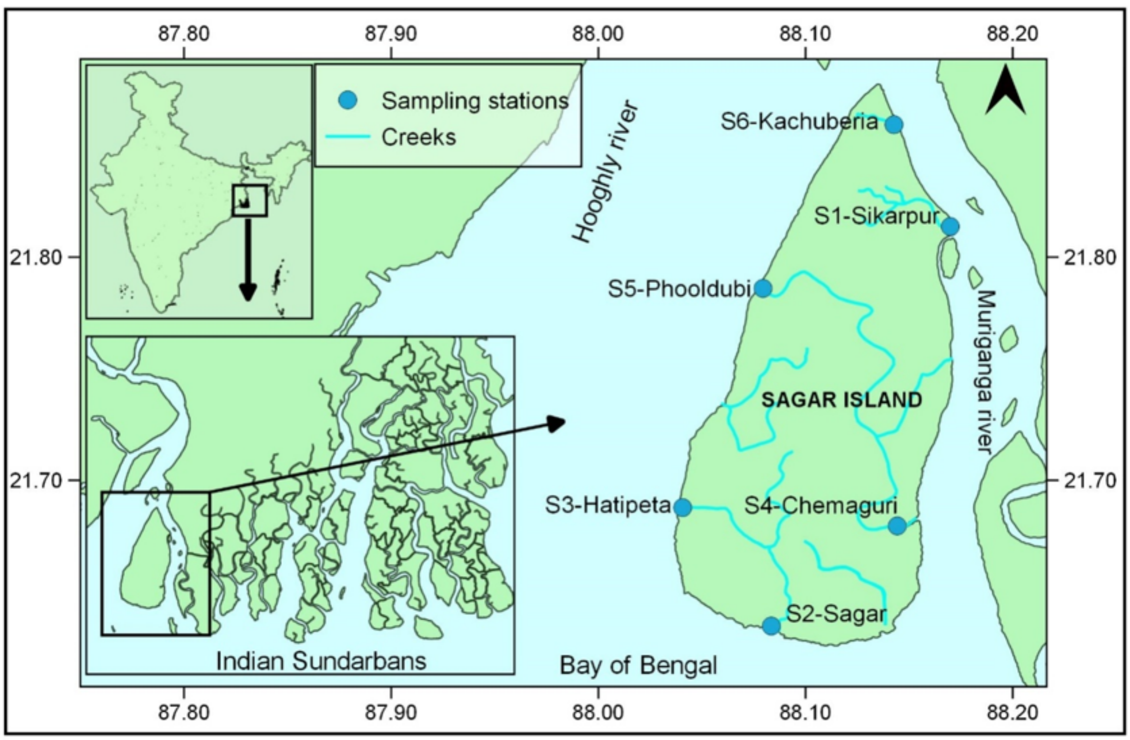


Figure 1

The geographical locations of the sampling sites and study area of Sagar Island, Sundarbans Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

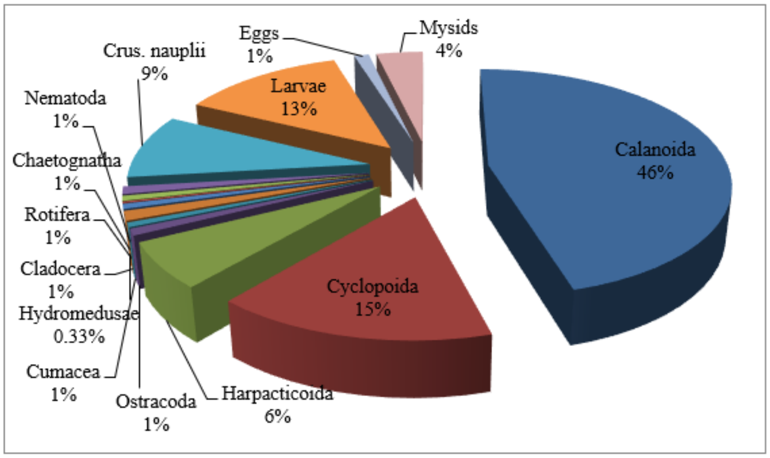


Figure 2

Percentage composition of zooplankton in the studied stations

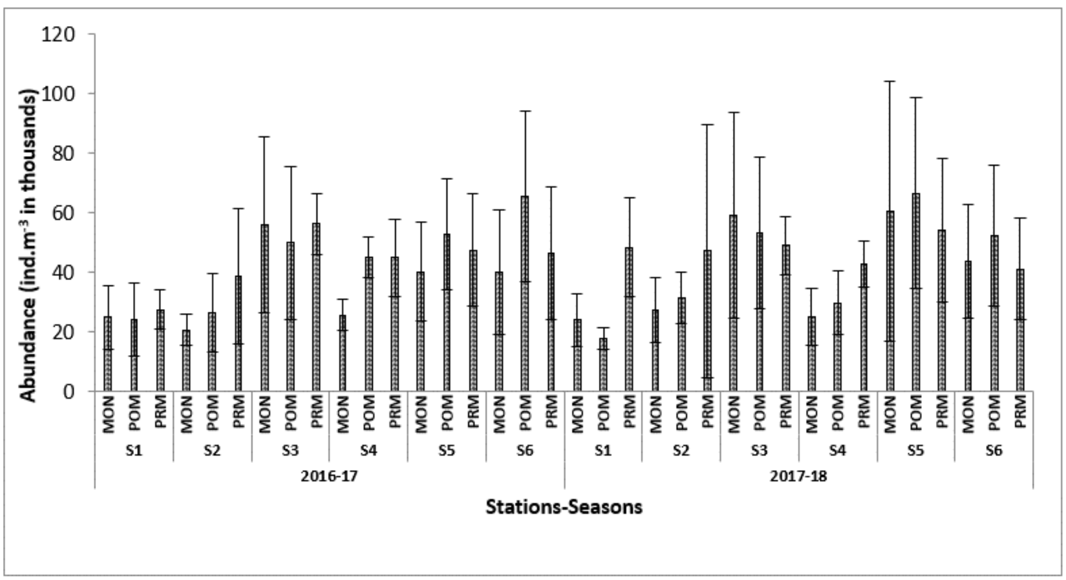
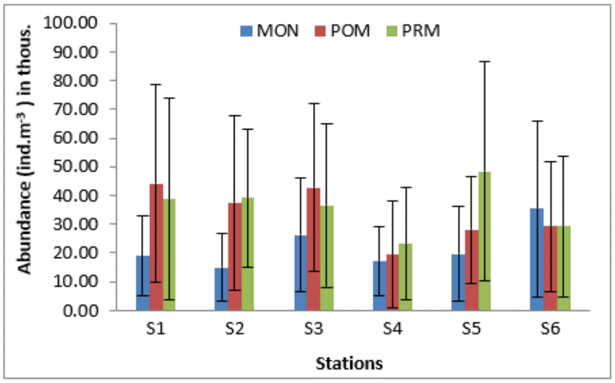


Figure 3

Mean abundance of total zooplankton in studied stations with seasons



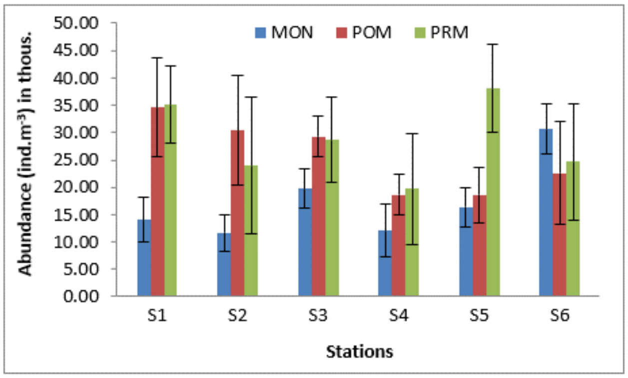


Figure 4

Top panel: a & Bottom panel:b Spatio-temporal variations in abundance of (a) Holoplankters (top panel) and (b) Meroplankters (bottom panel); MON: Monsoon; POM: Post-monsoon; PRM: Pre-monsoon

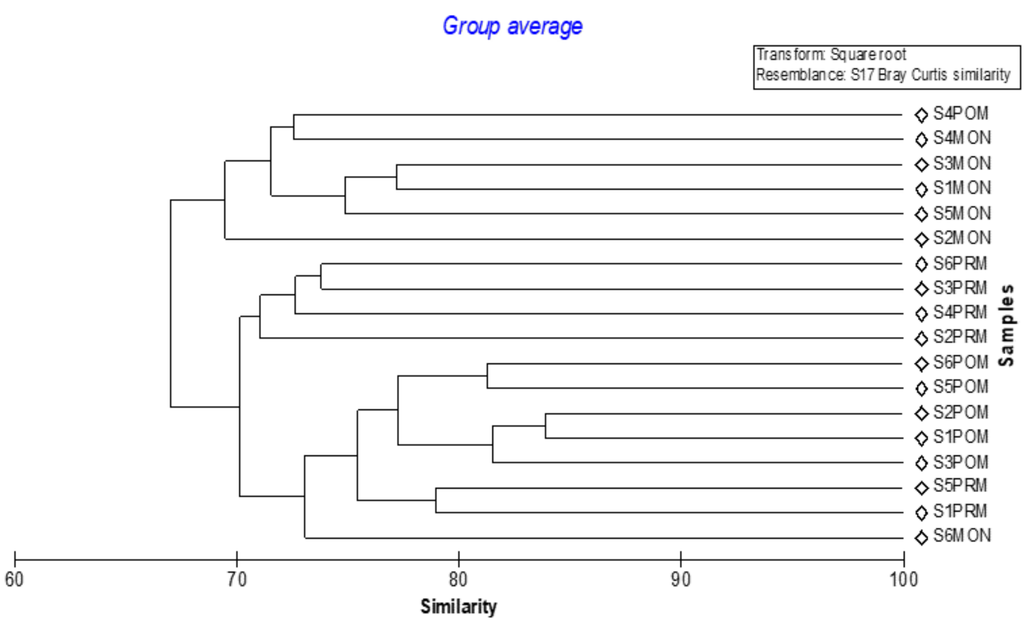


Figure 5

Dendogram showing the similarity of the stations in different seasons

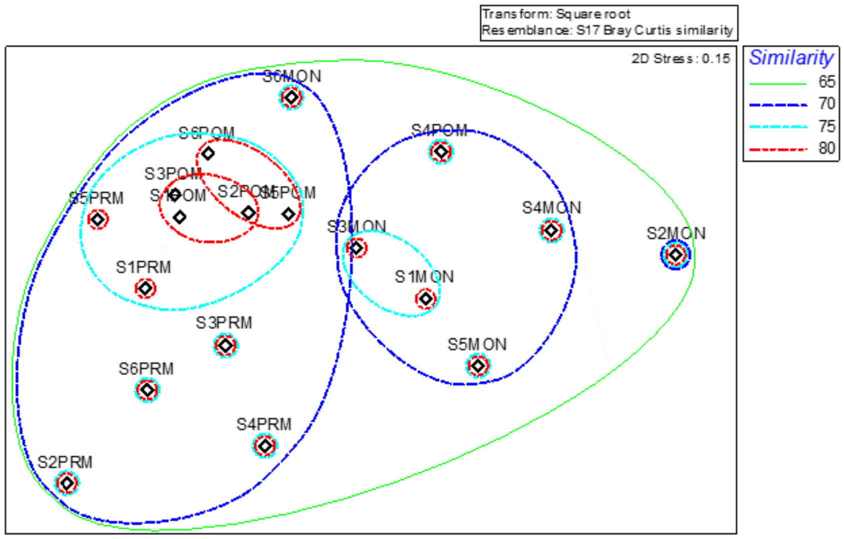


Figure 6

Non metric dimensional scaling map of the zooplankton community in the studied stations

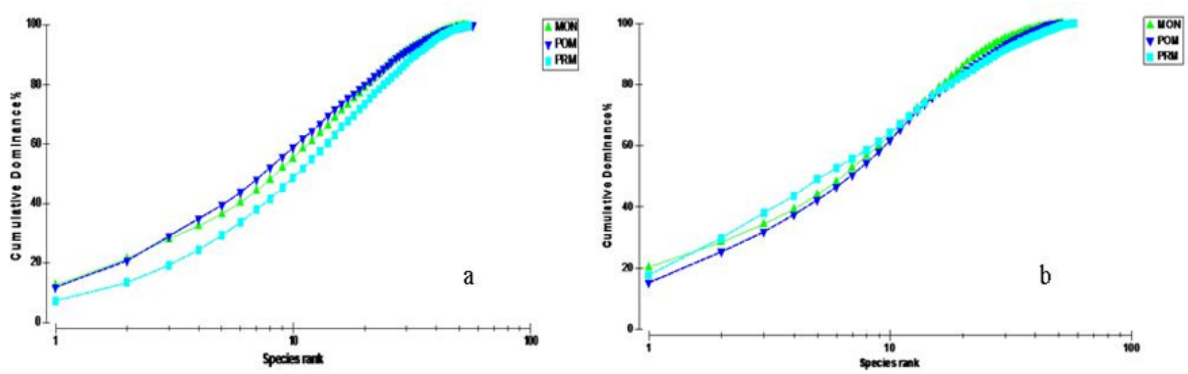


Figure 7

a & b k-dominance curve plotted in different seasons during the period of 2016-17 and 17-18

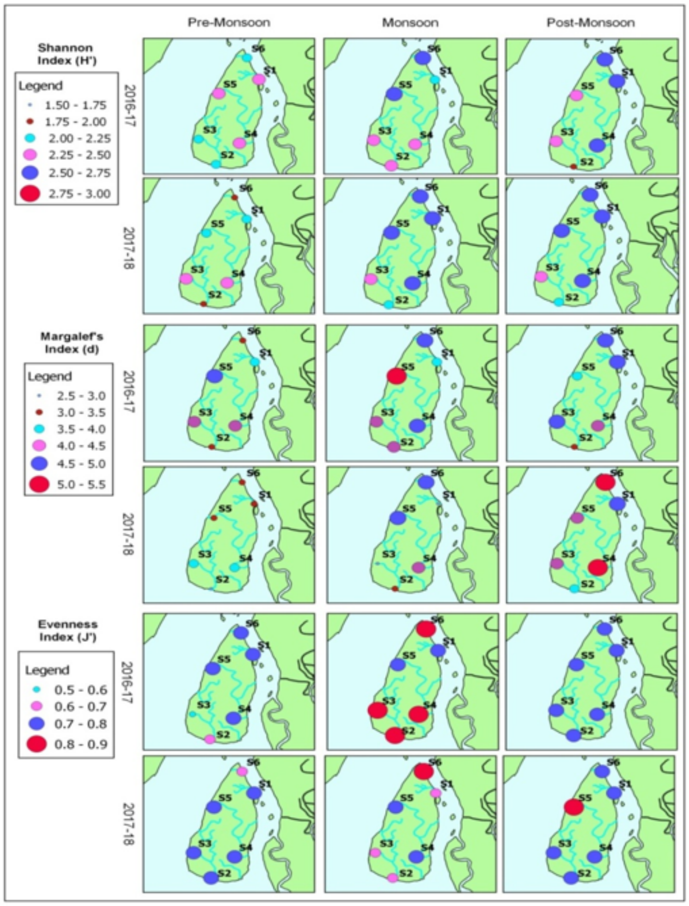


Figure 8

Univariate measures of diversity indices at the sampling stations in different seasons, with superimposed bubbles of the values of diversity indices. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.