Proceedings of the Zoological Society
https://doi.org/10.1007/s12595-024-00543-3

RESEARCH ARTICLE

Ecology of the Copepods at a Low Salinity Zone of the Ganges Estuary, India

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Received: 5 February 2024 / Revised: 31 May 2024 / Accepted: 15 July 2024

Abstract

Low salinity (below 5 PSU) zone (LSZ) acts as an ecocline and limits species distribution within an estuary. After Farakka barrage (1975) the Diamond Harbour (DH) of the Ganges estuary turned to a LSZ from meso- to poly-haline zone, which might have affected estuarine inhabitants including plankton (e.g., copepods). The objectives were to study diversity, dominance of the copepods and their associations with environmental variability of the DH. The present study and a review of the previous literature were used for an assessment of the structural changes of the copepod community over time. Copepod assemblages were sampled seasonally (four times per season) from a sampling site (22.10.59° N; 88.11.22° E) of the DH. Water temperature (°C), salinity and pH were recorded *in situ* and Total Nitrogen (TN), Nitrate-nitrogen (NO_3-N) and Phosphate (P) levels were measured at the laboratory following the spectrophotometric methods. Seasonal variations of the salinity, pH, NO_3-N and P were not significant but water temperature and TN levels were significant. Copepod richness at DH was the highest in the monsoon (13) followed by the postmonsoon (11) and premonsoon (10). The species richness of the copepods at DH declined from the levels of the 1970s. Presently, *Paracalanus parvus* is the most abundant copepod at DH followed by *B. similis*. During the pre-Farakka time; *P. parvus* and *B. similis* were rare and species such as *Cyclops* sp., *Bryocamptus* sp., *Ergasilus* sp. which were not found in the present study were abundant. Multivariate analysis suggested significant seasonal variations of the copepod community structure. Salinity, water temperature, pH, P and NO_3-N levels of DH may limit the distribution of a few species. The DH is experiencing a sea level rise at a rate of 5.3 mm/year; therefore, environmental variability may change, which may draw more eurihaline and neritic copepod species towards the DH so a regular monitoring of the LSZ of the estuary is recommended.

Keywords Plankton diversity · Environmental variability · Diamond Harbour · Farakka barrage

Introduction

Ecotones such as estuaries have ecoclines based on the gradients of salinity (Elliot and McLusky 2002). A few studies have subdivided different zones within an estuary based on the observation that estuarine species are not evenly distributed across salinity gradients of an estuary (Remane and Schlieper 1972; Bulger et al. 1993). Describing and summarizing distribution patterns of estuarine biota along the gradients of salinity, are one important and practical function of those studies; another is to help understand the linkages between ecological processes and species distributions (Remane and Schlieper 1972; Bulger et al. 1993; Telesh and Khlebovich 2010). According to Bulger et al. (1993) among various estuarine zonation schemes the 'Venice System' is the leading one. The 'Venice System' has gained its wide application in describing the patterns of distribution among estuarine organisms (Remane and Schlieper 1972). The 'Artenminimum zone' (i.e., area with minimum species number) of an estuary is a narrow salinity range of 5–8 PSU where the relative number of the true brackish water species generally reach the maximum but the freshwater and marine

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Published online: 23 August 2024

origin species slope to the minimum (Remane 1934). In that zone of an estuary two major types of fauna (marine and freshwater) meet and co-exist wherever the smooth water salinity gradient is present and the zone itself acts as an ecological, physiological and evolutionary barrier (Telesh and Khlebovich 2010). Estuarine zones where salinity remains between 0.5 and 5 (practical salinity scale) are low salinity zones (LSZ) (Kimmerer et al. 2013). The LSZs are generally dominated more by species which are of freshwater origin (e.g., plankton and fish) than the brackish and/or salt-water species (Kimmerer et al. 2013). The diversity, dominance, and distribution of species at the LSZ are often limited by salt tolerance (Kimmerer et al. 2013; Nagarathinam et al. 2021). At times estuaries are affected by the human interventions including construction of a barrage or the freshwater abstraction schemes on the upstream of the estuary that impact the natural course of freshwater flow over time and not only change the salinity profile of the estuary but also many of its physical–chemical variabilities (Nagarathinam et al. 2021; Hassrick et al. 2023). Those changes impact the ecology of the inhabitant communities including plankton (Nagarathinam et al. 2021). It is; therefore, important to monitor the structural changes of the communities at the LSZs of an estuary (Nagarathinam et al. 2021).

The Ganges estuary (GE) of India runs through the lower Ganges delta. Presently, above the Diamond Harbour (DH) (about 70 K.M. from the estuary mouth) the GE generally remains salt free, below the DH a meso- to polyhaline and near the mouth of the GE polyhaline conditions could be observed (Sinha et al. 1996; Mukhopadhyay et al. 2006; Nandy and Bandyopadhyay 2011). The lower course of the Ganges River in India is connected to the larger Ganges system through the Farakka barrage scheme which is situated about 426 K.M. upstream from where the estuary meets the Bay of Bengal (Nandy and Bandyopadhyay 2011). After the commission of the Farakka barrage in 1975 freshwater inflow in the estuarine stretch of the Ganges river has improved as a consequence a significant section of the estuary has become salt free (although this section receives regular tides), the estuarine section has shrunk and at present it is mostly restricted near the mouth section (e.g., Kakdwip and Namkhana regions of the Indian Sundarbans) of the GE (Sinha et al. 1996; Banerjee et al. 2017). In recent times, DH has a salinity between 0.03 and 4.29 (Sinha et al. 1996); therefore, it could be considered as the LSZ of the GE. The DH used to have a salinity profile of trace to 23.19 between 1959 and 1967 i.e., before the construction of the Farakka barrage (Sinha et al. 1996). It is; therefore, evident from the previous research that the GE has gone through a desalination process over the last few decades which might have affected the diversity, distribution and ecology of its inhabitants including the plankton (e.g., copepods) (Sinha et al. 1996).

Copepods are the dominant zooplankton of the GE and are natural food resources of commercially exploited macroinvertebrates and fish species of the GE and other estuaries of Indian Sundarbans (Bhattacharya et al. 2015; Paul et al. 2024). Previous studies conducted on the copepod community of the GE suggested salinity as the limiting factor for species richness, diversity and distribution (Sarkar et al. 1986; Sinha et al. 1996; Bhattacharya et al. 2015; Paul et al. 2019, 2024) but most of the studies concentrate on the meso- to polyhaline zones of the GE. Those studies reported up to 36 species of the copepods in the GE (Sarkar et al. 1986; Bhattacharya et al. 2015). During monsoon, diversity of the copepods generally declines, which otherwise shows two peaks every year first when premonsoon (March to June) transits to monsoon and then in the late postmonsoon (October to February) (Sarkar et al. 1986; Bhattacharya et al. 2015). The abundances of the copepods are generally higher in the premonsoon and the postmonsoon seasons (average > 2000 ind.m^{-3}) than the monsoon season (average < 800 ind.m^{-3}) (Bhattacharya et al. 2015). Copepods *Acartiella tortaniformis*, *Pseudodiaptomus serricaudatus*, *Paracalanus parvus* and *Bestiolina similis* persist throughout the year in the meso- to polyhaline zone of the GE (Sarkar et al. 1986; Bhattacharya et al. 2015). Any specific study focused on the copepods of the LSZ of the GE is rare. Considering that a seasonal study was conducted in 2021 on the copepod community of the DH. The objectives were to i) study diversity, dominance of the copepods and their associations with environment of DH and ii) assess the structural changes of the copepod community over time through the combination of the present study and the previous literature. Those objectives would help in better understanding of the ecological processes of the LSZ of the GE.

Materials and Methods

Study Site

The study was conducted from a site at the DH (22.10.59° N; 88.11.22° E) (Fig. 1). The DH is about 6 K.M. wide and has an average depth of 12.5 m and a tidal range of 5.04 m (Mukhopadhyay et al. 2006; Nandy and Bandyopadhyay 2011). The DH has a warm and humid climate and the seasons could broadly be classified as premonsoon (originally February to May but off late extended even to June), monsoon (i.e. June to September but at times delayed and off late extended to middle of October) and postmonsoon (i.e. originally October to January but recently shifting towards November to February). Air temperature of the DH generally ranges between 15 and 40 °C and the annual average rainfall is about 1600 mm out of which 75–80% rainfall occurs in monsoon.

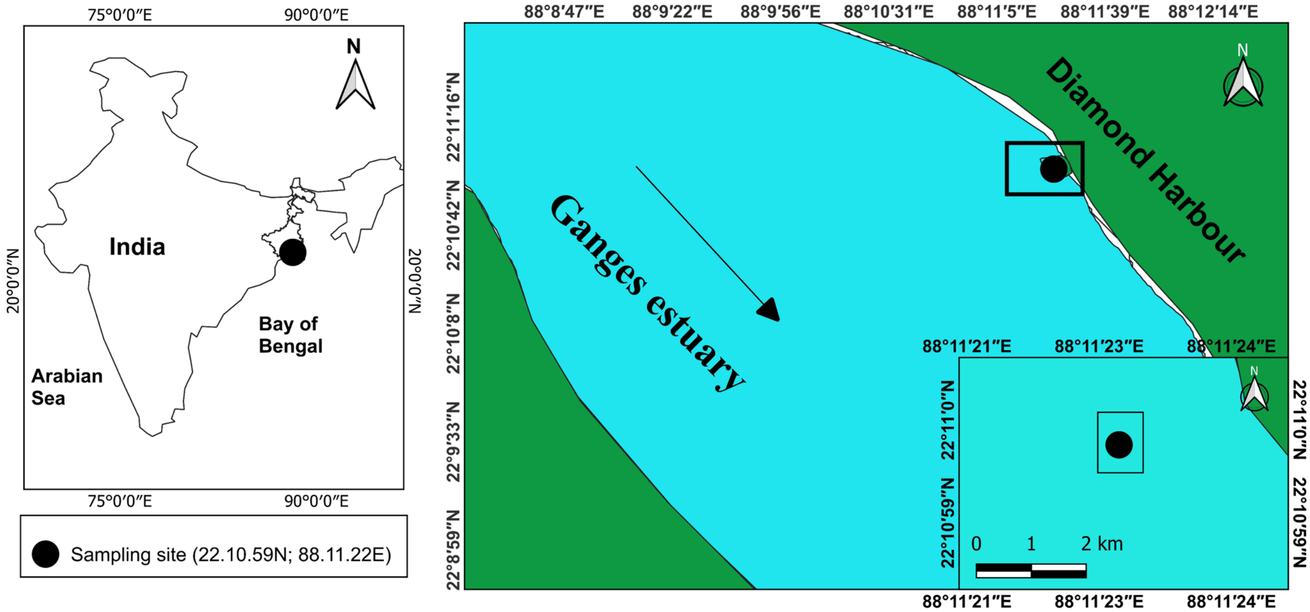

Fig. 1 Study site on the low salinity zone of the Ganges (Hooghly) estuary, India

Study of the Copepod Community

During 2021 copepod assemblages were sampled (at least four times in premonsoon, monsoon and postmonsoon) seasonally at dark on the high tide by deploying a plankton net (200 µm mesh size, 60 cm diameter and 3 feet long) which was equipped with a horizontally placed mechanical flow meter (Make: Hydrobios, Germany) and towed horizontally for 3 min from a dinghy boat. After collection the samples were preserved in 4% neutral buffered formalin. In the laboratory, the copepod assemblages were then identified and enumerated to the species level under a stereo microscope (Make: Bestscope 3020 T, China) fitted with a Sedgwick Rafter counting chamber following the taxonomic literatures of Kasturirangan (1963). For that multiple aliquots of 1 ml were drawn from each sample (at least 1% of each sample was analysed), The abundance (i.e., adults only) of each copepod species was expressed as individuals per cubic meter (ind.m^{-3}).

Study of the Environmental variability

On each occasion of the copepod sampling, salinity (in practical salinity unit), water temperature (°C) and pH were measured from subsurface water by a handheld multiparameter probe (Pro-1030, Make: YSI, USA). Water samples (2L) were also collected from the study site for measurements of the Total Nitrogen (TN) (i.e., dissolved organic and inorganic fractions), Nitrate-Nitrogen (NO_3-N) and Phosphate (P) levels. Water samples were filtered on boat through GF/F filter paper (pore size: 0.70 µm) and put inside the 2L sterilised plastic containers and transported in the ice. Nutrient concentrations (µM) were measured at the laboratory following the standard spectrophotometric (by using UV–VIS Spectrophotometer, Model: 119, Make: Systronics, India) procedures described by the Kremling (1999).

Statistical Analysis

The environmental dataset was small in nature so all the data were assumed to be non-parametric. Seasonal variability of the environmental variables collected during the study was evaluated by conducting multiple Kruskal–Wallis tests followed by post-hoc tests if required. Copepod abundance database was square-root transformed (after transformation ranged 0–10.28) for reducing the data dispersion (original scale 0 to 11,169). To explore dissimilarity of the copepod assemblages collected in different seasons a Non-metric Multidimensional Scaling (NMDS) was conducted considering the Bray–Curtis measure of dissimilarity ('Vegan' package version 2.5.7). Inference of dimensionality of the NMDS (i.e. K = 2) was taken after examining the stress-score (i.e. 0.19), Shepard diagram (see annexure 1), and by judging the values of the non-metric fit R^2 (i.e. 0.964) and the linear fit R^2 (i.e. 0.734), respectively. For drawing NMDS biplots 'ggplot2' package version 3.3.5) was used. The copepod assemblages sampled in the different seasons were compared (i.e. centroids) through a permutational multivariate analysis of variance (PERMANOVAs) (Adonis test, permutations = 999, method = Bray–Curtis, package: 'Vegan' version: 2.5.7) and the assumption of the homogeneity of multivariate dispersion was tested through an Analysis of Variance. A similarity percentage analysis (SIMPER) (package: 'Vegan' version: 2.5.7) was carried out to evaluate the major component species that caused the dissimilarity in the copepod assemblages based on different seasons. Copepod and environmental datasets of different seasons were pooled and a Canonical Correspondence Analysis (CCA) was conducted to evaluate the relationships between copepod assemblages and environmental variables. For statistical analysis all data replicates were considered. Level of statistical significance was set at 95%. Values of K-W chi-square, Pseudo-F, R^2, F, Degrees of Freedom (df) and p were reported. Data analysis was conducted using the CRAN R 4.1.1. (R Core Team 2021).

Results

Seasonal Variability of Environment

Salinity levels (annual range 0.3 to 2.2) of the DH during the premonsoon (1.90 ± 0.34 SE), monsoon (1.25 ± 0.17 SE) and postmonsoon (1.10 ± 0.31 SE) of 2021 did not vary significantly (K-W chi-squared = 3.14, df = 2, $p = 0.21$) from each other (Fig. 2). Water temperature levels (annual range 19.70–30.20 °C) of the DH were 29.60 ± 0.26 °C, 29.15 ± 0.25 °C and 20.90 ± 0.61 °C in the premonsoon, monsoon and postmonsoon of 2021, respectively (Fig. 2) and those levels varied significantly (K-W chi-squared = 8.11, df = 2, $p = 0.02$). Post-hoc results suggested that water temperature of the estuary during the premonsoon was significantly ($p < 0.001$) higher than postmonsoon and the postmonsoon temperature was significantly ($p < 0.001$) lower than monsoon but significant variation was not observed between premonsoon and monsoon temperatures. During the premonsoon (7.31 ± 0.33 SE), monsoon (7.87 ± 0.02 SE) and postmonsoon (7.39 ± 0.05 SE) of 2021 pH levels (annual range 7.20 to 7.89) of the DH were not significantly (K-W chi-squared = 4.17, df = 2, $p = 0.12$) different from each other (Fig. 2). The TN levels (annual range 49.35 to 68.32 µM) of the DH were 63.79 ± 1.80 µM, 55.14 ± 1.46 µM, 50.81 ± 2.03 µM during the premonsoon, monsoon and postmonsoon of 2021, respectively (Fig. 2). Their seasonal variation was significant (K-W chi-squared = 7.88, df = 2, $p = 0.01$). Post-hoc results suggested that TN levels during the premonsoon was significantly higher than both monsoon ($p = 0.012$) and postmonsoon ($p = 0.003$) but no significant variation was observed between postmonsoon and monsoon seasons. The NO_3–N levels (annual range 13.95–21.25 µM) during premonsoon, monsoon and postmonsoon were 17.35 ± 1.81, 18.84 ± 0.54, 15.30 ± 0.94, respectively (Fig. 2) and did not vary significantly (K-W chi-squared = 2.80, df = 2, $p = 0.24$) among the seasons. During the premonsoon (1.08 ± 0.19 SE), monsoon (0.66 ± 0.17 SE) and postmonsoon (1.17 ± 0.07 SE) of 2021 the P levels (annual range 0.49 to 1.65 µM) of the DH did not vary significantly (K-W chi-squared = 2.80, df = 2, $p = 0.24$).

Seasonal Variability of the Copepod Community

Species richness during premonsoon, monsoon and postmonsoon was 10, 13 and 11, respectively (Table 1). Table 1 further shows the differences in the seasonal abundances of the different copepod species sampled from the DH section of the GE. The NMDS biplot hints the variability of the copepod community in different season (Fig. 3). PERMANOVA results suggested that the copepod community significantly varied between seasons (PERMANOVA: DF = 2, Sum of Square = 0.22, Pseudo-F = 2.30, $R^2 = 0.33$, P = 0.013; the assumption of the homogeneity of multivariate dispersion was not violated (ANOVA: DF = 2, F = 0.22, P = 0.80)). Among

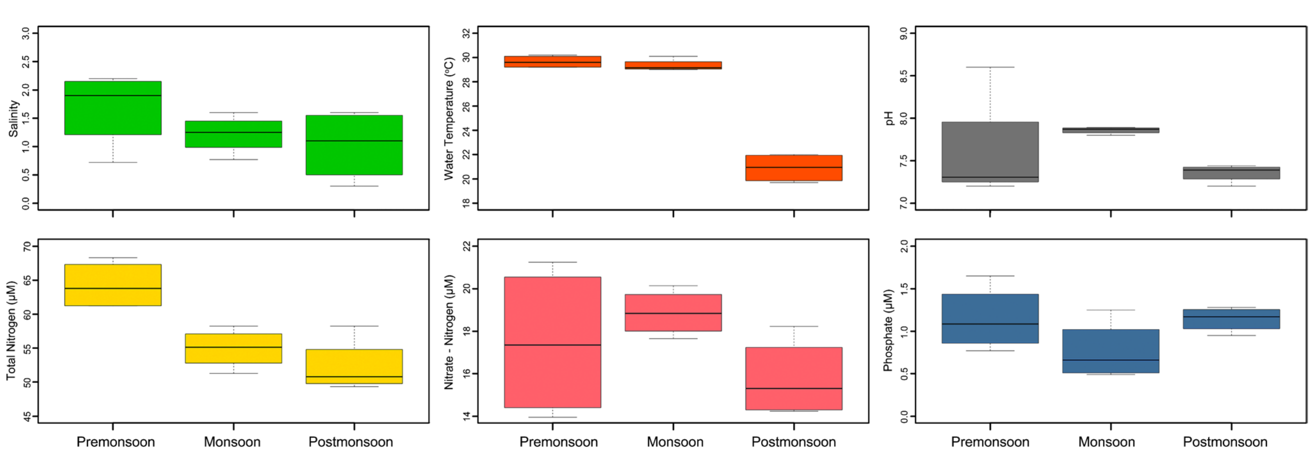

Fig. 2 Temporal variability of the environmental variables sampled from the low salinity zone of the Ganges estuary, India

Table 1 Seasonal variability (i.e., minimum—maximum) in the abundance (ind.m-3) of copepods sampled from the low salinity zone of the Ganges estuary, India

Species	Premonsoon	Monsoon	Postmonsoon
Paracalanus parvus	668–4470	1290–11169	625–4379
Bestiolina similis	406–1275	349–3200	866–4066
Acartiella tortaniformis	0–524	575–3839	596–1967
Pseudodiaptomus serricaudatus	87–406	117–1200	192–1475
Acartia tonsa	0–813	200–2443	0–384
Oithona nana	87–813	0–2792	0–48
Paracalanus aculeatus	0–813	0–698	144–1251
Acrocalanus gibber	0–0	0–1047	0–0
Oithona similis	0–813	0–117	0– 0
Acartia tropica	0–406	0–0	0–492
Oithona brevicornis	0–638	0–172	0–9
Acartia spinicauda	0–0	0–117	0–337
Acrocalanus gracilis	0–0	0–117	0–170
Paracalanus dubia	0–0	0–235	0–0

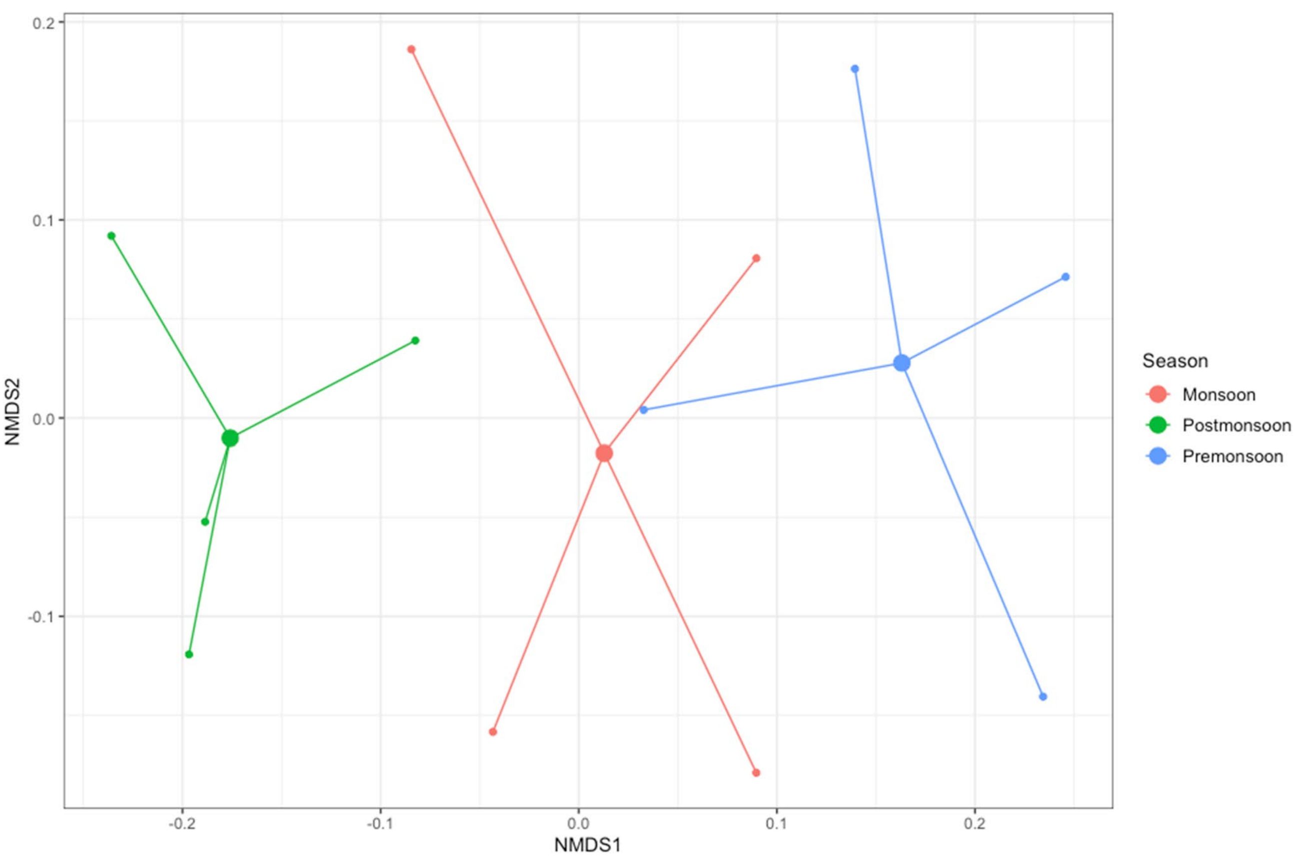

Fig. 3 Seasonal variability of the copepod assemblages sampled from the low salinity zone of the Ganges estuary, India

premonsoon samples the similarity of the community was 66.79%, which was primarily driven by *P. parvus*, *B. similis*, *P. serricaudatus* and *O. nana* (Table 2). Similarity of the community was 66.81% and 74.47% during monsoon and postmonsoon, respectively and that was primarily driven by *P. parvus*, *B. similis*, *A. tortaniformis* and *P. serricaudatus* (Table 2). The dissimilarity between the premonsoon and monsoon the copepod community was 34.17%, which was mainly contributed by *A. tonsa*, *A. tortaniformis*, *A. gibber* (Table 3). The postmonsoon

Table 2 Results of SIMPER analysis showing similarity (%) in seasonal copepod assemblages sampled from the low salinity zone of the Ganges estuary, India

PRM Average similarity: 66.79		MON Average similarity: 66.81		POM Average similarity: 74.47	
Species	Contribution	Species	Contribution	Species	Contribution
Paracalanus parvus	26.07	*Paracalanus parvus*	21.86	*Bestiolina similis*	21.86
Bestiolina similis	20.93	*Acartiella tortaniformis*	21.65	*Paracalanus parvus*	21.65
Paracalanus serricaudatus	16.40	*Bestiolina similis*	20.00	*Acartiella tortaniformis*	20.00
Oithona nana	16.40	*Paracalanus serricaudatus*	15.52	*Paracalanus serricaudatus*	15.52

PRM, premonsoon; MON, monsoon; POM, postmonsoon

Table 3 Results of SIMPER analysis showing dissimilarity (%) in seasonal copepod assemblages sampled from the low salinity zone of the Ganges estuary, India

PRM & MON				PSM & PRM				PSM & MON			
Average dissimilarity: 34.17				Average dissimilarity: 36.59				Average dissimilarity: 34.78			
Species	PRM	MON	Contribution	Species	PSM	PRM	Contribution	Species	PSM	MON	Contribution
A. tonsa	2.53	5.27	12.41	*O. nana*	0.66	4.22	14.10	*A. tonsa*	1.11	5.27	15.67
A. tortaniformis	3.15	5.93	10.02	*P. aculeatus*	4.66	2.10	12.37	*O. nana*	0.66	3.87	12.74
A. gibber	0.00	2.54	09.79	*A. spinicauda*	2.77	0.00	11.16	*P. aculeatus*	4.66	2.11	11.83
O. similis	2.40	0.82	09.17	*A. tonsa*	1.11	2.53	09.90	*A. gibber*	0.00	2.54	09.36

PRM, premonsoon; MON, monsoon; POM, postmonsoon

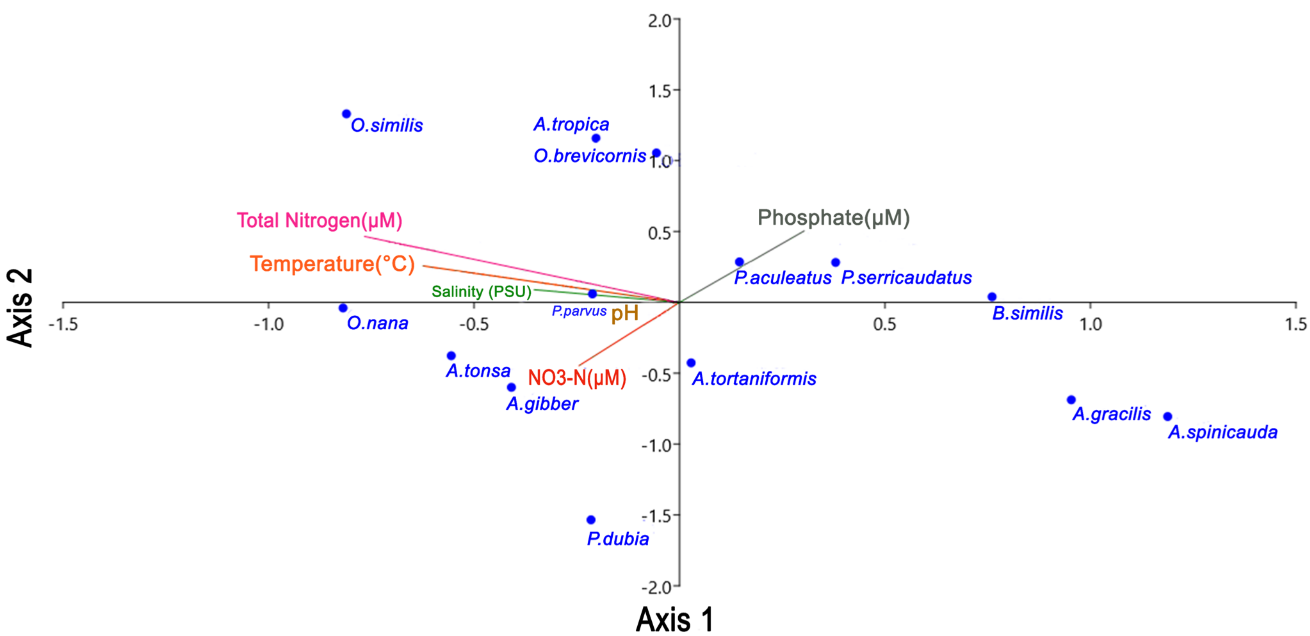

Fig. 4 Relationship between environmental variables and the copepod assemblages sampled from the low salinity zone of the Ganges estuary, India

and monsoon communities were 34.78% dissimilar from each other and such a dissimilarity was primarily driven by *A. tonsa*, *O. nana*, *P. aculeatus* (Table 3). Dissimilarity between premonsoon and postmonsoon groups was 36.59% and that was mainly due to the species such as *O. nana*, *P. aculeatus*, *A. spinicauda* (Table 3).

Correlation Between Environment and the Copepod Community

The Canonical Correspondence Analysis (CCA) ordination diagram (Fig. 4) suggested that *P. parvus* was positively associated with salinity and water temperature. *Paracalanus aculeatus*, *P. serricaudatus* and *B. similis* were positively associated with the levels of the P at the DH. *Acartia tonsa* and *A. gibber* were negatively associated with nitrate concentrations whereas *A. tortaniformis* was positively associated. *Acartia tonsa* and *A. gibber* along with *O. nana* also showed negative affinity towards the pH levels of the DH. The copepods *O. similis*, *A. tropica*, *O. brevicornis*, *A. gracilis*, *A. spinicauda* and *P. dubia* did not show prominent associations with the environmental variables.

Discussion

Environmental Variability of the Diamond Harbour

Results of salinity, pH, NO_3-N and *P* levels did not show significant seasonal variability but the seasonal variability of the water temperature and TN levels were significant. The present salinity levels of the DH and its seasonal fluctuations were found consistent with the studies conducted on the DH after the commissioning of the Farakka barrage; however, when the results of salinity were compared to the records of the pre-Farakka time, considerable desalinization of the DH is evident (Nandy et al. 1983; Sinha et al. 1996). Typical to the most tropical estuaries the water temperature of the DH showed significant seasonal variation which is at par with the recent studies conducted on the meso- to polyhaline sections of the GE and other estuaries of the region (Tiwari et al. 2022; Chakraborty et al. 2022; Paul et al. 2024). The results hint at an overall shift to higher water temperature of the DH when compared with the water temperature recorded in the pre-Farakka time (Nandy et al. 1983; Nath 1998; Manna et al. 2013). The results related to pH are consistent with the previous studies conducted at the DH (Sinha et al. 1996; Tiwari et al. 2022) and it corroborates with the modest alkaline characteristics of the GE (Nandy et al. 1983; Lal 1990; Nath 1998; Mitra et al. 2018; Paul et al. 2019). Owing to the semi-urban nature of the estuary, the DH receives organic and inorganic nutrient loads of sewage discharge, industrial drainage, agricultural runoffs, pisciculture effluents (Sarkar et al. 2007; Manna et al. 2013; Bhattacharya et al. 2015). In the present study nutrient levels of the GE were high in the premonsoon compared to monsoon and postmonsoon seasons. The observed levels of the nutrients and their seasonal variabilities are consistent with the previous works on conducted on the GE (Bhattacharya et al. 2015; Mitra et al. 2018).

Seasonal Variability of the Copepod Community

The DH is now dominated by species such as *P. parvus*, *B. similis* and *A. tortaniformis*. Presently *P. parvus* is the most abundant copepod species. The DH was dominated earlier by copepods species such as the *Cyclops* sp., *Bryocamptus* sp., *Ergasilus* sp (Sinha et al. 1996). During the pre-Farakka barrage period species of *Paracalanus* genus were rare at DH (Sinha et al. 1996). The highest cumulative abundance of *P. parvus* was observed during the warmer (29.00–30.10 °C) and salinity-limited (0.77–1.66) monsoon. Studies in the Jangmok Bay of Korea suggested that the seasonal dynamics of *P. parvus* is significantly influenced by water temperature (Jang et al. 2013). The copepod *B. similis* found to show similar prevalence irrespective of seasonal and environmental variability of the tropical estuaries including the GE (Hani and Jayalakshmi 2023; Paul et al. 2019). The copepods *A. gibber* and *P. dubia* (least abundant) were present exclusively during the monsoon but species such as *A. tropica* was absent. The copepods *A. spinicauda* and *A. gracilis* showed low abundances overall and those species were absent during the premonsoon. Among the three recorded *Oithona* species, *O. nana* showed the highest numerical abundance with the maximum being sampled in the monsoon. *Oithona nana* and *O. brevicornis* showed low abundances and *O. similis* was absent in the postmonsoon. The prevalence of small sized copepods of the Oithonidae family suggested their high adaptability to the trophic and hydrological conditions of the local estuaries (Bhattacharya et al. 2015; Nandy and Mondal 2020).

Relationship Between Environment and Copepod Community

Paracalanus parvus showed strong associations with salinity and water temperature levels of the DH. Euryhaline nature of *P. parvus* is reflected by its dominance in both low to intermediate salinities in the mangrove estuaries of Indian Sundarbans (Bhattacharya et al. 2015; Nandy and Mandal 2020). Contrary to that, Paul et al. (2017) did not find any correlation between the *P. parvus* and salinity regime of the sub-tropical Rio de la Plata estuary of Uruguay. *Acartiella tortaniformis*, *Acartia spinicauda*, *Bestiolina similis* and *Acrocalanus gracilis* were not significantly impacted by the varying environment of the DH section of the GE, that may demonstrate their higher adaptability which was observed by Paul et al. (2019, 2020, 2023, 2024) both under the normal and the stochastic conditions of the GE. The frequency of occurrence of the herbivorous calanoids *Paracalanus aculeatus* and *Pseudodiaptomus serricaudatus* are positively associated with P levels. Nagarathinam et al. (2021) reported higher *P* levels in the mesohaline regions of Kochi backwaters during premonsoon and the positively associated with abundance of *P. serricaudatus*. Similarly, the copepod *P.aculeatus* was found to exhibit positive association with the higher premonsoon P levels of the estuarine region of Yangtze River (Wang et al. 2016). The omnivorous copepod *Bestiolina similis* also showed positive association with the P level. It has nutrient requirements similar to *P. aculeatus* in the estuaries of Indian Sundarbans (Bhattacharya et al. 2015; Nandy and Mandal 2020). Eco-physiological work on plankton considering the environmental variability of the local estuaries is rare. In future, it would be interesting to assess the impacts of the chronic changes of the physical–chemical properties of the DH on the survival, life history and reproduction of both the abundant and rare copepod species of the DH.

Changes in the Copepod Community of the Diamond Harbour

Previous to the commissioning of the Farakka Barrage the DH section of the GE was not a LSZ rather it was a meso- to polyhaline zone of the GE (Sinha et al. 1996). Shrivastava (2011) suggested that the true estuarine environment is restricted up to 60-70 K.M. from the seaface and the estuarine-brackish environment extends 25 to 35 K.M. inside the shore line in the premonsoon period and during the monsoon the freshwater zone extends towards estuarine-brackish zone as result of the monsoon run-off. The plankton of the lower reach of the GE experienced several changes in their diversity, distribution and ecology after the commission of the Farakka barrage (Sinha et al. 1996). Productivity and the plankton status followed the pattern of successive spatial-temporal modification in salinity and nutrient status of the GE (Nandy et al. 1983).That is because the previously recognized LSZ of the GE had turned into a limnetic zone, the previously gradient zone turned into LSZ to euryhaline zone, and the marine zone of the GE is now restricted near the mouth (Nandy et al. 1983; Sinha et al. 1996). After the commission of the Farakka barrage on the Ganges river, density of the plankton increased by 33.7% within 1975-1977 and successively by 27.8% in a span of 10 to 15 years and further by 36.5% over a period of two and half decades (Bhaumik et al. 2015). This sudden increase plankton population immediately after the Farakka barrage scheme could be the outcome of the inundation of previously exposed and organically rich river beds mainly used for agriculture or covered with natural vegetation in the lower research of the GE (Sinha et al. 1996) The species richness of the copepod community of the DH section; however, has declined from species richness observed in 1970s (Sinha et al. 1996). At present the copepod species which reside at the DH are mostly brackish in nature or estuarine specialists, and the neritic species are far less in comparison to the Namkhana section (meso- to polyhaline zone) of the GE (Bhattacharya et al. 2015; Paul et al. 2019, 2024). Decadal changes (e.g., size, feeding guilds, composition) in the copepod community structure were observed by Bhattacharya (2015) while working on the mesozooplankton (dominated by copepods) of Indian Sundarbans (including the GE) and compared

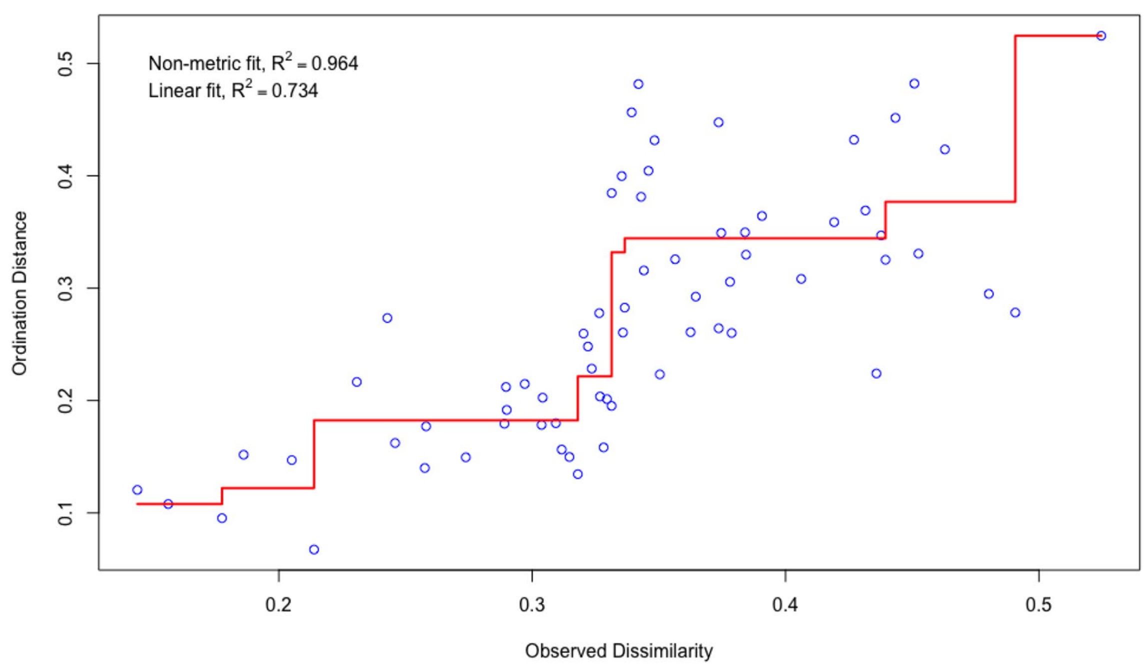

Fig. 5 Fig 5. Shepard diagram for drawing inference of dimensions of the NMDS plot and non-metric fit R^2 and the linear fitR^2

the results with the previous literature e.g., Sarkar et al. (1986). The freshwater discharge data of the GE's lower stretch is less accessible to scientific communities. The DH is experiencing sea level rise at a rate of 5.3 mm/year (MoEFCC, India); therefore, in future it would be more saline than its current status. That may draw copepods that are more neritic in nature; therefore, the existing community structure is likely to change. Recommendations include regular monitoring of those changes and to make the freshwater data available for better prediction of the ecological processes of the LSZ of the GE.

Appendix

See Fig. 5.

Acknowledgements Dr. BD. Bhattacharya, Ms. P. Bhattacharya and Mr. Samya Karan acknowledge the financial assistance received from the Estuarine and Coastal Studies Foundation during the course of the study. Authors are thankful to the Estuarine and Coastal Studies Foundation, India for funding the research and providing the research and administrative facilities during the course of the study.

Author Contributions Dr. Paul contributed to the study conception and design. Material preparation, data collection and analysis were performed by Dr. Bhattacharya, Ms. Bhattacharya,Ms. Mitra, Mr. Karan and Dr. Paul. The manuscript was written jointly by Ms. Bhattacharya, Ms. Mitra and Dr. Paul. Dr.Bhattacharya and Mr. Karan had edited the final manuscript.

Data Availability The datasets generated during and/or analyzed during the study are not publicly accessible but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest All the authors declare that they have no conflict of interest on connection with this study.

Ethical Approval No ethical approval is required to work with.

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