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ORIGINAL RESEARCH ARTICLE

Impact of human-altered hydrographical setting on the Copepod community structure in an extensive tropical estuary along the southwest coast of India

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Abstract This study presents how human-altered hydrographical settings (flow restrictions) impacts the natural distribution and community structure of copepods in the Kochi Backwaters (KBW), the largest monsoonal estuary along the southwest coast of India. This study is primarily based on an extensive seasonal sampling in the KBW and their comparison with a historical data set. Thannermukkom Barrage (TB) was built in the southern section of the KBW in the 1970s to prevent saline water intrusion to the upstream during the non-monsoon periods. Thirteen locations (1—4 in the downstream, 5—9 in the midstream, and 10—13 in the upstream) were sampled in this study over the entire stretch of the KBW during the Pre-Southwest Monsoon (PRM), Southwest Monsoon (SWM), and Post-Southwest Monsoon (PSWM). The overall effect of TB in the KBW is a seaward push of mesohaline conditions during all seasons with varying intensities. In response to the seaward push of mesohaline conditions, copepods *Acartiella keralensis, Acartia plumosa, Acartia* sp., *Pseudodiaptomus annandalei, Pseudodiaptomus serricaudatus, Euterpina acutifrons* and *Oithona brevicornis* showed a corresponding spatial shift for their highest abundance and diversity from midstream during PRM to the downstream during the SWM/PSWM. Multivariate and IndVal analysis demarcated many indicator species of cope-

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pods of different hydrographical settings in the KBW. A comparison with the historical data set showed that there is an apparent long-term change in hydrography, copepod composition and community structure in the upstream of the KBW due to TB.

1. Introduction

Mesozooplankton (>200 μm) play a vital role in the aquatic environment in transferring energy in the lower level (plankton) food web to higher trophic levels. The distribution of copepods, the most abundant component of the mesozooplankton (>60% in abundance), is mainly influenced by the salinity of the estuarine and coastal waters (Chen et al., 2011; Roman et al., 2000). During the Southwest Monsoon (SWM; June—September), the high precipitation and land runoff lead to freshwater dominance in Indian (monsoonal) estuaries (Arunpandi et al., 2020; Haridevan et al., 2015; Vijith et al., 2009). Soon after the SWM, the river flow decreases, and seawater intrusion becomes prominent in these estuaries. Kochi (Cochin) backwaters (KBW) is the largest estuary along the southwest coast of India (Kurup et al., 1990) sustaining estuarine, brackish and freshwater conditions extending from Azhikode in the north to Alleppey in the south (Figure 1a).

The KBW receives the seasonal highest amount of freshwater influx during the southwest monsoon (SWM — June to September) every year (Arunpandi et al., 2020; Jyothibabu et al., 2006; Kurup, 1990; Srinivas et al., 2003). Thannermukkom barrage (TB), is a saltwater regulator constructed in the south side of KBW in 1976 (Figure 1b—d). Four rivers (Manimala, Meenachil, Pamba and Achenkovil) enter the KBW from the south of TB and make a combined discharge of ~20000 × 10^6 m^3 per year (Qasim, 2003; Srinivas et al., 2003). TB was constructed in 1976 mainly to prevent saltwater intrusion to the Southern part (upstream) of the KBW during non-monsoon (Pre-Southwest Monsoon — SWM; Post-Southwest Monsoon — PSWM) period. The closing (PSWM to PRM) and opening (SWM) of the shutters of TB usually takes 3—4 days. TB has a length of 1250 m with 63 shutters (93 Vents 12.5 × 5.47 m). TB has also facilitated (Report on visit to Vembanad Kol, 2008) many of the livelihood activities of people involved in agriculture, fishing, tourism, inland navigation, coir retting, and lime shell collection. But over the years, the flow restrictions in the KBW by TB caused severe ecological deterioration, which leads to the eutrophication, massive distribution of exotic water weeds (*Eichornia, Monochoria* etc.) and dwindling of many endemic faunal resources (Gopalan, 1991).

The changing flow regime of KBW due to the closing of TB shutters causes several environmental issues (Qasim, 2003; Revichandran et al., 2011), which includes increased siltation (Gopalan, 1991), spread of aquatic weeds, eutrophication and oxygen depletion. Earlier studies have shown the disruption of the natural ecological balance, thereby imposing adverse effects on the migrating fauna of prawn, fish and clam (Kannan, 1979; Padmakumar et al., 2002). Some general aspects of TB impacts on the hydrography and the living resources in the KBW were investigated in the past (Achari, 1988; Arun, 2009; Buyukates and Roelke, 2005; Froneman, 2004; Haridevan et al., 2015; Kibirige and Perissinotto, 2003; Menon et al., 2000). However, still, there is no comprehensive data available on the extent to which TB influences the distribution of plankton in KBW, which is particularly crucial because plankton is globally considered as an excellent indicator of environmental change (Mackey et al., 1996; Millie et al., 1993; Pinckney et al., 2001). Therefore, in this seasonal study, we focused on the copepod composition and their community structure in different sections (downstream, midstream and upstream) of the KBW mainly to know what alteration TB has caused to the plankton composition and distribution. The following objectives were covered in this study (a) to understand the seasonal ecological differences in the KBW on a spatial scale and (b) assess the impact of TB on the copepods composition and community structure in the KBW and (c) to identify the indicator species of copepods to the different hydrographical settings in the KBW.

2. Material and methods

2.1. Sampling

The KBW (area 256 km^2 and volume 0.55 km^3) is situated between 09°00′N—10°40′N and 76°00′E—77°30′E. In general, TB is fully opened from June to September (Southwest Monsoon) and remains closed from March to May (Premonsoon/Pre-Southwest Monsoon). The present sampling was done during three seasons; August 2013 (Southwest Monsoon; SWM), December 2013 (Post-Southwest Monsoon; PSWM) and March 2015 (Pre-Southwest Monsoon; PRM). Samples were collected from 13 locations from the downstream (Kochi inlet) to the upstream (Alapuzha in the south of TB). A speed boat was used for sampling to cover the entire stretch of KBW almost at the same tidal phase. Nine stations were to the north of TB (1—9) and four stations to the south (10—13). Among these stations, 1—4 represent the downstream, 5—9 the middle stream and 10—13 the upstream. According to the salinity ranges suggested by McLusky (1993), KBW has several salinity levels such as euhaline (> 30), polyhaline (18—30), (c) mesohaline (5—18), oligohaline (0.5—5) and (e) limnetic (< 0.5).

2.2. Physico-chemical parameters

Vertical distribution of salinity was measured using a CTD (Sea CAT SBE 19 plusV2). Water samples were collected using Niskin sampler for measuring the chemical and biological parameters such as dissolved oxygen, nutrients, total

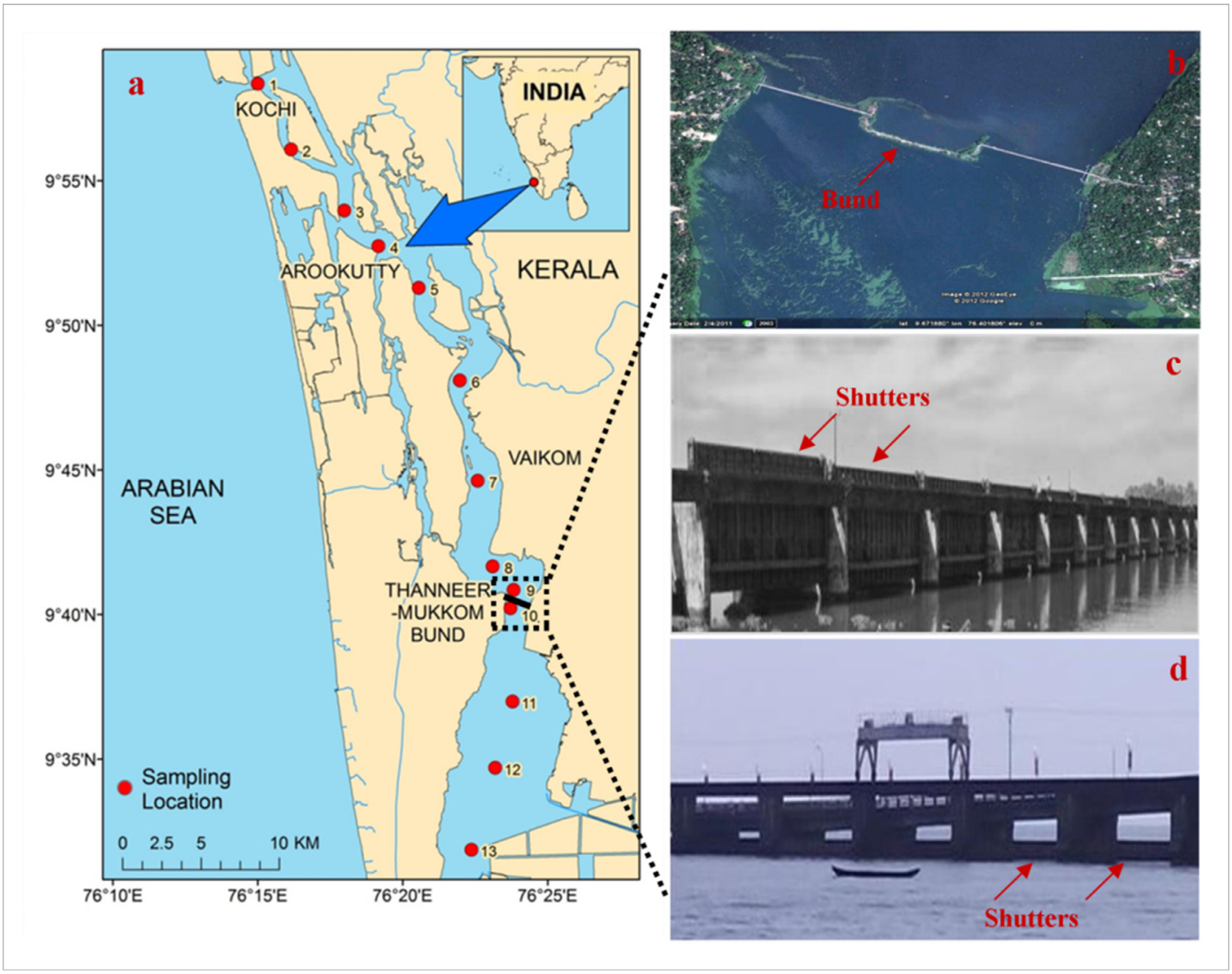

Figure 1 (a) Sampling locations in the Kochi backwaters (KBW), (b) Google Earth image of Thannermukkom barrage (TB), (c) open TB and (d) closed TB. Red arrows in (c) and (d) show the state of shutters (open/closed).

Chlorophyll *a* (Chl *a*) and mesozooplankton. Dissolved oxygen was measured using the modified Winkler method. For nutrient analysis, collected samples were kept in an icebox and transported to the laboratory where they were stored under −20°C till analysis. They were measured based on the standard procedure (Grasshoff et al., 1983). For turbidity, samples were measured by a calibrated turbidity meter (EUTECH TN-100) as per the nephelometric principles.

2.3. Biological components

Chlorophyll *a* (Chl *a*) was measured from 2 L water samples. For total Chl *a* analysis, 500 ml of water subsamples were filtered through 0.2 μm (Whatman GF/F filters). Phytoplankton concentrated on filter paper was extracted for Chl *a* using 10 ml of 90% acetone (in amber tubes) overnight (UNESCO, 1994) and measured through a calibrated Turner Fluorometer (Turner designs — 7200). Mesozooplankton was sampled using a WP net (mesh size 200 μm) with a mouth area of 0.25 m^2. The plankton net was towed horizontally at slow speed (2 knots), just below the water surface (~1 m depth). A flow meter (Hydro-bios) was attached across the mouth to calculate the volume of the water filtered. The samples collected were preserved in 4% formaldehyde for later enumeration and identification. Zooplankton group abundance was measured using the standard procedure of Postal et al. (2000). Among the sorted samples, cladocerans were identified up to genus level, whereas copepods were identified up to species levels using standard literature (Conway et al., 2003; Gardner and Szabo, 1982; Kasturirangan, 1963; Sewell, 1999; Tanaka, 1956).

2.4. Statistical analysis

2.4.1. Grouping of locations

A euclidian distance matrix type of cluster/NMDS analysis was performed for the grouping of locations based on their similarity for hydrographical parameters. Cluster/NMDS analysis was performed separately for three seasons. The locations within the cluster have more similarity, whereas the groups are dissimilar. Hydrographical parameters were normalised before the analysis of the cluster. SIMPROF permutation analysis was performed to test the significance of the clustering pattern.

2.4.2. Indicator species (IndVal) analysis

The representative species in each assemblage of copepods are identified based on Indicator value (IndVal) index (Dufrêne and Legendre, 1997). IndVal primarily reflects whether the species assemblages are symmetric or asymmetric between different groups of observations. IndVal index reaches the maximum (100%) when all the individuals of a species occur in a single group of observations (centre of distribution), which essentially represents the asymmetric distribution of that species between the groups. On the other hand, the IndVal index reaches the lowest when the species are symmetrically distributed between the groups (Hunt and Hosie, 2006). According to Dufrêne and Legendre (1997), a minimum of 25% IndVal can be considered as the threshold level to determine IndVal species in a group of observations. In the present study, $\geq$40% IndVal value was used as the threshold to demarcate the IndVal species.

2.4.3. Univariate and multivariate analysis

Differences in hydrographical and biological components were tested through ANOVA. Initially, datasets were tested for their distribution. The datasets in normal distribution parametric ANOVA with Tukey's HSD posthoc test was performed to compare the difference between the clusters, whereas the heterogeneity sample distribution non-parametric ANOVA (Kruskal-Wallis) with Dunns post hoc test was performed for comparing the differences between the clusters. The tests of normality, parametric and non-parametric ANOVA were carried out in XL stat pro-software pack up. The interrelationships within and between the environmental parameters and the biological parameters (Chlorophyll *a* and copepod species) were analysed using RDA (CANOCO 4.5). Primarily, the data was tested with Detrended Correspondence Analysis for finding a suitable ordination technique. The Detrended Correspondence Analysis results showed axis gradient length <2, suggesting the use of a linear multivariate RDA as the most appropriate method (Leps and Smilauer, 2003). The biological variables were log-transformed before the analysis. The ordination significance was tested with Monte Carlo permutation tests (499 unrestricted permutations) ($p < 0.05$). RDA was represented in the form of Triplots in which points display sampling stations (black circles), and biological (dotted green lines) and arrows showed environmental variables (blue lines); salinity was denoted with dotted pink colour.

3. Results

3.1. Physico-chemical parameters

3.1.1. Salinity

The distribution of salinity showed the dominance of salinity during the PRM period (Figure 2) wherein, polyhaline/euhaline (26.4 salinity) levels were found in the downstream, mesohaline (11—13.5 salinity) levels in the midstream, and oligohaline (0.9—4.9 salinity) in the upstream. Salinity gradients were evident from the downstream to the upstream with a marked difference (˜5 salinity) caused by TB. During the SWM, the surface waters were limnohaline (0.06 and 1.60 salinity) (Table 1), which extended over the entire stretch of the KBW except for the bar mouth. During the PSWM period, the mesohaline (16.4 salinity) condition prevailed over the downstream and in the midstream reaches oligohaline to mesohaline levels, whereas oligohaline (0.64 salinity) levels in the upstream of KBW. ~1.4 unit salinity difference was noticed between the downstream and upstream of KBW (Table 1).

3.1.2. Nutrients

Spatially, the distribution of nutrients showed varies pattern. In the present study, nitrate (NO_3) concentration ranged between 0.63 and 18.53 μM and did not show any clear trend in the distribution. However, during SWM, nitrate was relatively high (from 10.8 to 18.53 μM) and uniform over the entire KBW compared to PSWM (from 3.1 to 15.2 μM) and PRM (from 0.63 to 10.9 μM) (Table 1 and Figure 3c, 4c and 5c). Phosphate (PO_4) concentrations varied from 0.15 to 2.05 μM during the PRM period (Table 1 and Figure 3d); 0.13 to 0.37 μM during the SWM (Figure 4d) and from 0.28 to 1.02 μM during the PSWM (Figure 5d). The concentration was generally high in the downstream locations, which was lower during the SWM compared to the PRM and the PSWM period. Significantly high silicate concentration found in the KBW throughout the year. Silicate concentration varied from 13 to 49.1 μM during the PRM (Table 1 and Figure 3e); 92.77 to 126.29 μM during the SWM (Figure 4e) and 15.33 to 25.47 μM during the PSWM (Figure 5e). Silicate was five times higher in the downstream during the SWM compared to PRM (Table 1). Spatially, silicate concentration was higher in the upstream locations compared to downstream and midstream of the KBW (Table 1).

3.1.3. Dissolved oxygen, turbidity

Dissolved oxygen ranged between 3.98 and 5.92 mg/L during the PRM; 5.78 to 7.06 mg/L during the SWM, and 4.05 to 5.09 mg/L during the PSWM period. Spatially, DO was high in upstream locations. Seasonally, DO was high during the SWM period and found saturated levels in the entire study area (Table 1). Turbidity ranged between 1.1 and 4.3 NTU during the PRM (Table 1 and Figure 3f), 1.83 to 17.37 NTU during the SWM (Table 1 and Figure 4f) and 1.9 to 7.97 NTU during the PSWM (Table 1 and Figure 5f). Irrespective of the seasons, turbidity was found to be high in the downstream. In the entire stretch of the study area, turbidity was high during the SWM, followed by PSWM and the least during the PRM (Table 1). Phosphate concentration was relatively high in the downstream compared to the upstream during PRM and PSWM while silicate showed a reverse trend. During the SWM period, a variation in nutrients was low between the downstream, midstream and upstream of KBW (Table 1).

3.2. Clustering of locations based on the hydrographical features

Based on the distribution of the hydrographical parameters, the sampling locations grouped into four different groups during the PRM period *viz*., locations 1 and 2 in cluster I, locations 3 to 6 in cluster II, 7—9 in cluster III and 10—14 in cluster IV. The spatial distribution of hydrographical parameters and their mean values are presented in Figure 3. During the PRM, cluster I was formed in the extreme downstream locations, which was characterised as polyhaline

Table 1 Spatial and seasonal distribution of environmental and biological parameters.

Parameters		Stations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
PRM	Salinity	26.4	21.01	15.05	14.27	13.5	12.15	10.49	10.99	9.92	4.9	1.07	1.01	0.89
	DO (mg/L)	3.98	4.47	4.95	4.76	4.92	5.31	5.63	5.13	5.74	5.24	5.06	6.00	5.92
	NO_3 (μM)	2.81	1.95	0.63	0.81	1.37	3.46	5.68	9.06	9.73	10.93	11.21	9.55	7.43
	PO_4 (μM)	1.85	2.05	1.45	1.12	0.80	0.82	0.35	0.32	0.24	0.24	0.16	0.15	0.19
	SiO_4 (μM)	13.00	20.00	24.00	14.40	16.0	22.00	28.65	28.15	32.30	38.65	37.00	41.25	49.10
	Turbidity (NTU)	4.30	3.90	3.27	3.37	3.40	3.31	3.69	2.21	2.13	1.43	1.48	1.10	1.26
	Chl *a* (mg m^{-3})	2.3	4.62	4.28	3.64	3.86	6.42	1.95	2.89	1.55	2.1	9.22	2.35	3.05
	MSP (No. m^{-3})	394.9	340.51	654.01	596.1	501.1	318.7	285.1	192.4	99.53	96.8	73.34	67.97	100.7
SWM	Salinity	1.60	0.11	0.15	0.10	0.09	0.34	0.11	0.25	0.08	0.08	0.09	0.08	0.06
	DO (mg/L)	5.78	5.91	5.95	6.01	6.09	6.17	6.2	6.2	6.26	6.7	6.98	7.01	7.06
	NO_3 (μM)	16.96	11.73	12.36	10.80	14.61	12.77	13.32	15.10	18.53	12.20	13.14	10.45	10.36
	PO_4 (μM)	0.37	0.26	0.21	0.29	0.26	0.24	0.24	0.16	0.13	0.17	0.17	0.17	0.19
	SiO_4 (μM)	101.9	92.7	102.7	110.6	113.5	118.5	118.1	114.3	113.3	124.1	124.7	126.2	121.3
	Turbidity (NTU)	10.92	17.37	11.52	4.94	5.28	4.99	4.99	4.98	3.02	2.73	4.15	2.45	1.83
	Chl *a* (mg m^{-3})	2.9	3	3.17	1.68	2.6	3.5	3.47	2.39	3.41	4.2	2.66	1.63	1.11
	MSP (No. m^{-3})	85.85	73.69	143.17	74.86	76.72	47.82	72.19	91.19	63.42	55.63	16.07	13.22	36.56
PSWM	Salinity	16.4	14.4	12.2	7.58	6.80	6.35	5.65	4.63	2.02	0.64	0.16	0.12	0.12
	DO (mg/L)	4.05	5.09	5.08	4.8	4.09	4.05	4.16	4.85	4.47	4.87	4.92	4.72	4.36
	NO_3 (μM)	4.57	3.1	3.26	8.71	11.99	13.05	12.75	12.06	12.51	13.71	14.46	15.22	12.96
	PO_4 (μM)	1.02	0.99	0.86	0.68	0.64	0.46	0.46	0.43	0.38	0.37	0.28	0.28	0.30
	SiO_4 (μM)	17.80	16.31	16.03	16.56	17.26	19.43	18.88	15.33	16.79	21.04	25.47	21.65	25.41
	Turbidity (NTU)	7.97	7.80	4.79	2.75	2.90	2.72	2.38	2.10	1.90	2.50	2.99	2.06	2.23
	Chl *a* (mg m^{-3})	2.88	2.69	3.02	2	2.35	2.68	3.8	2.53	1.48	1.96	3.17	6.61	4.2
	MSP (No. m^{-3})	803.3	1866.7	1460.6	483.46	306.86	219.27	288.77	324.76	253.7	222.53	144.30	132.86	146.23

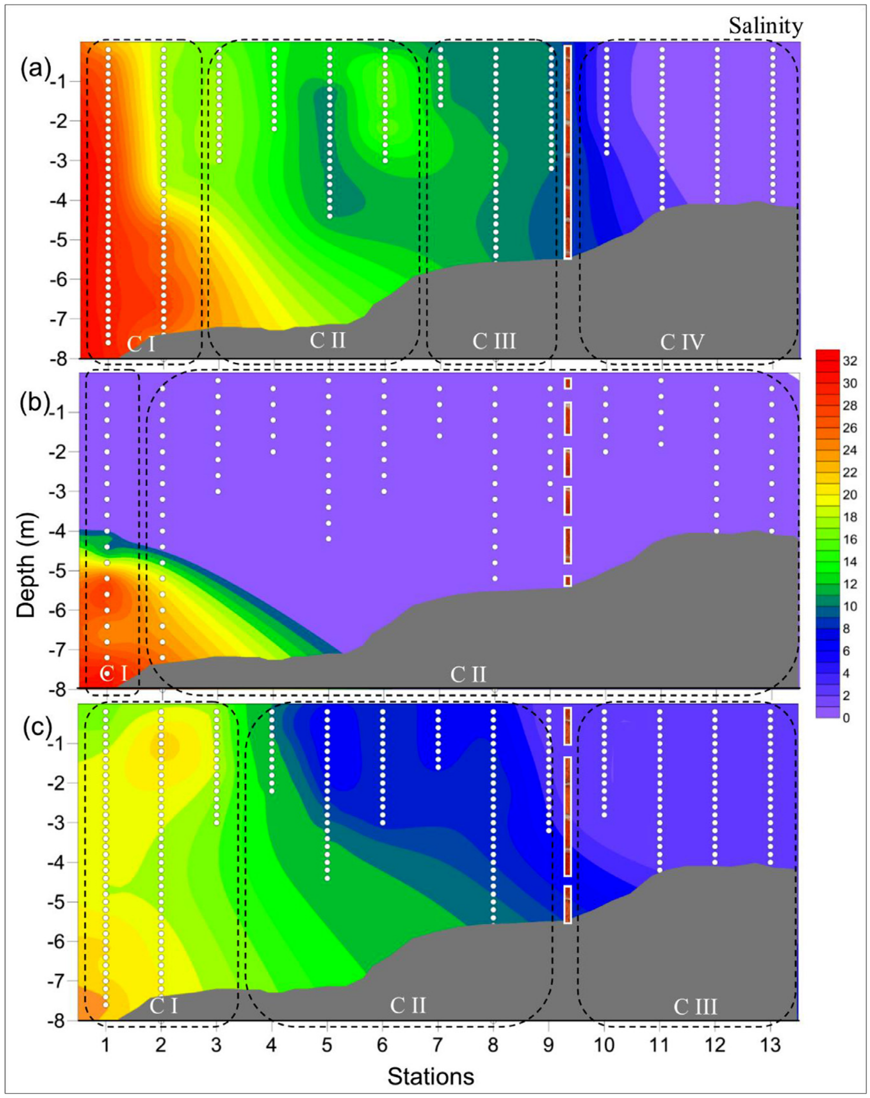

Figure 2 The distribution of salinity in the Kochi backwaters. Red coloured bricks indicate TB across the Kochi backwaters. (a) Pre-southwest monsoon (PRM): cluster I (C I) indicates downstream polyhaline locations, cluster II (C II) and cluster III (C III) midstream mesohaline locations, and cluster IV (C IV) upstream oligohaline locations. (b) Southwest Monsoon (SWM): cluster I (C I) extreme downstream and cluster II (C II) oligohaline/limnetic condition in the midstream and upstream. (c) Post-southwest monsoon (PSWM): cluster I (C I) was mesohaline downstream locations, cluster II (C II) was mesohaline to oligohaline midstream locations, and cluster III (C III) was limnetic upstream locations.

salinity (av. 23.7 $\pm$ 3.8), turbidity (av. 4.1 $\pm$ 0.28 NTU), rich in phosphate (av. 1.95 $\pm$ 0.14 μM) and low-silicate (av. 16.5 $\pm$ 4.9 μM). Cluster II represents the midstream locations with mesohaline salinity (av. 14.5 $\pm$ 2.1), moderate phosphate (av. 1.04 $\pm$ 0.3 μM) and turbidity (av. 3.3 $\pm$ 0.6 NTU). Cluster III represents the upstream region near to TB (locations 7—9) characterised by mesohaline salinity (av. 10.46 $\pm$ 0.53), rich in silicate (av. 29.7 $\pm$ 2.26) and low phosphate (av. 0.3 $\pm$ 0.05). Cluster IV was in the upstream of KBW (locations 10—14) with oligohaline salinity (av. 2 $\pm$ 1.9), high silicate (av. 41.5 $\pm$ 5.3) and low turbidity (av. 1.3 $\pm$ 0.17). Pairwise comparison test showed that the downstream and midstream clusters varied significantly from the upstream cluster. A comparison of the upstream and downstream regions with salinity, phosphate and turbidity showed a clear difference during the PRM. In contrast, they were not significant in the case of silicate and nitrate.

During the SWM period, the KBW was entirely freshwater dominated (oligohaline), and spatial variation in salinity was minimum, due to which, no apparent clustering of locations was evident (Figure 4). During the PSWM, three clusters of locations were formed. Cluster I with locations 1 to 3 represented the downstream, cluster II with locations 4 to 9 in the midstream and cluster III with locations 10—13 in the upstream (Figure 5). Cluster I was characterised by mesohaline salinity (av. 14.3 $\pm$ 2.1 salinity), moderate turbidity (av. 6.9 $\pm$ 1.8 NTU) and phosphate (av. 0.95 $\pm$ 0.08 μM). Cluster II was characterised by mesohaline to oligohaline levels of salinity (7.58 to 2.02) and low turbidity (av. 2.4 $\pm$ 0.39 NTU). Cluster III in the upstream (locations 10—13) was

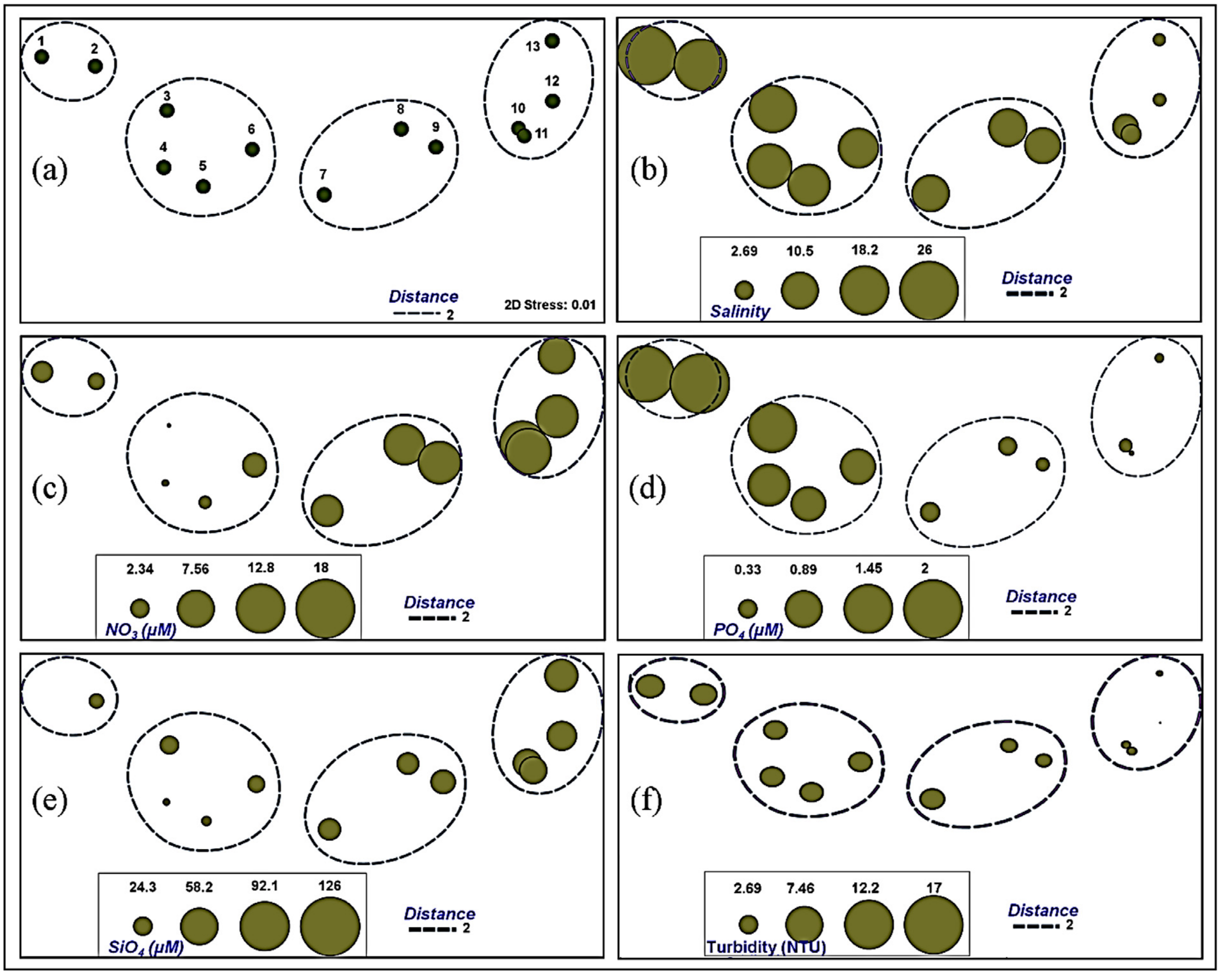

Figure 3 Grouping of (a) locations based on physicochemical variables in the KBW during the Pre-Southwest Monsoon (PRM). In subsequent panels, the proportionate concentration of (b) salinity, (c) nitrate (NO_3), (d) phosphate (PO_4), (e) silicate (SiO_4) and (f) turbidity have been presented.

limnohaline (av. 0.26 ± 0.25 salinity), less turbid (av. 2.4 ± 0.4 NTU) and low phosphate (av. 0.3 ± 0.04 μM).

3.3. Biological parameters

3.3.1. Chlorophyll *a* (Chl *a*)

Chl *a* was always in the high concentration range in the KBW. The total Chl *a* distribution in the study area is presented in Table 1. During PRM season total Chl *a* ranged from 1.95 to 9.22 mg m^{-3}, during SWM season Chl *a* ranged from 1.11 to 4.2 mg.m^{-3} and 1.48 to 6.61 mg m^{-3} in PSWM. Chl *a* was the lowest in the upstream region during SWM as compared to the other periods. The maximum Chl *a* was noticed (9.22 mg m^{-3}) during PRM at the upstream region.

3.3.2. Mesozooplankton (MSP) abundance

The total MSP abundance ranged from 13.22 to 1866 No m^{-3} (Table 1). During the PRM period, MSP abundances varied from 67.97 to 654 No. m^{-3} (Table 1). The mean MSP abundance differed between the cluster locations (Figure 6a) with a maximum in the midstream (cluster II) compared to the downstream (cluster I) or upstream regions (cluster III and IV). During the SWM, the MSP abundance decreased in the downstream and midstream compared to the PRM period (Figure 6b). During the PSWM period, MSP abundance was high in the downstream (cluster I) compared to midstream (cluster II) and upstream (cluster III) (Figure 6c). During PRM high abundance of MSP was observed in the midstream and during SWM and PSWM it was in the downstream region. Overall, the mesozooplankton abundance was found high in the mesohaline condition, specifically, in salinity levels 10—18 (Figure 6).

3.3.3. Mesozooplankton (MSP) groups

The MSP community was composed of nine groups; Copepods, Cladocera, Decapods larvae, Molluscan larvae, Ostracods, Lucifer's, Chaetognatha, fish eggs and Hydromedusae. The contribution of various groups to the total mesozooplankton abundance differed between space and seasons. During the PRM, copepods were high in the midstream (cluster II) and downstream (cluster I) compared to the upstream locations (Figure 6a). Copepods contributed 49—73% to the total MSP abundance during the PRM. Cladoceran contributed 24—40% and their presence was spatially high in the upstream locations (cluster III and IV) compared to midstream and downstream locations (cluster II and I).

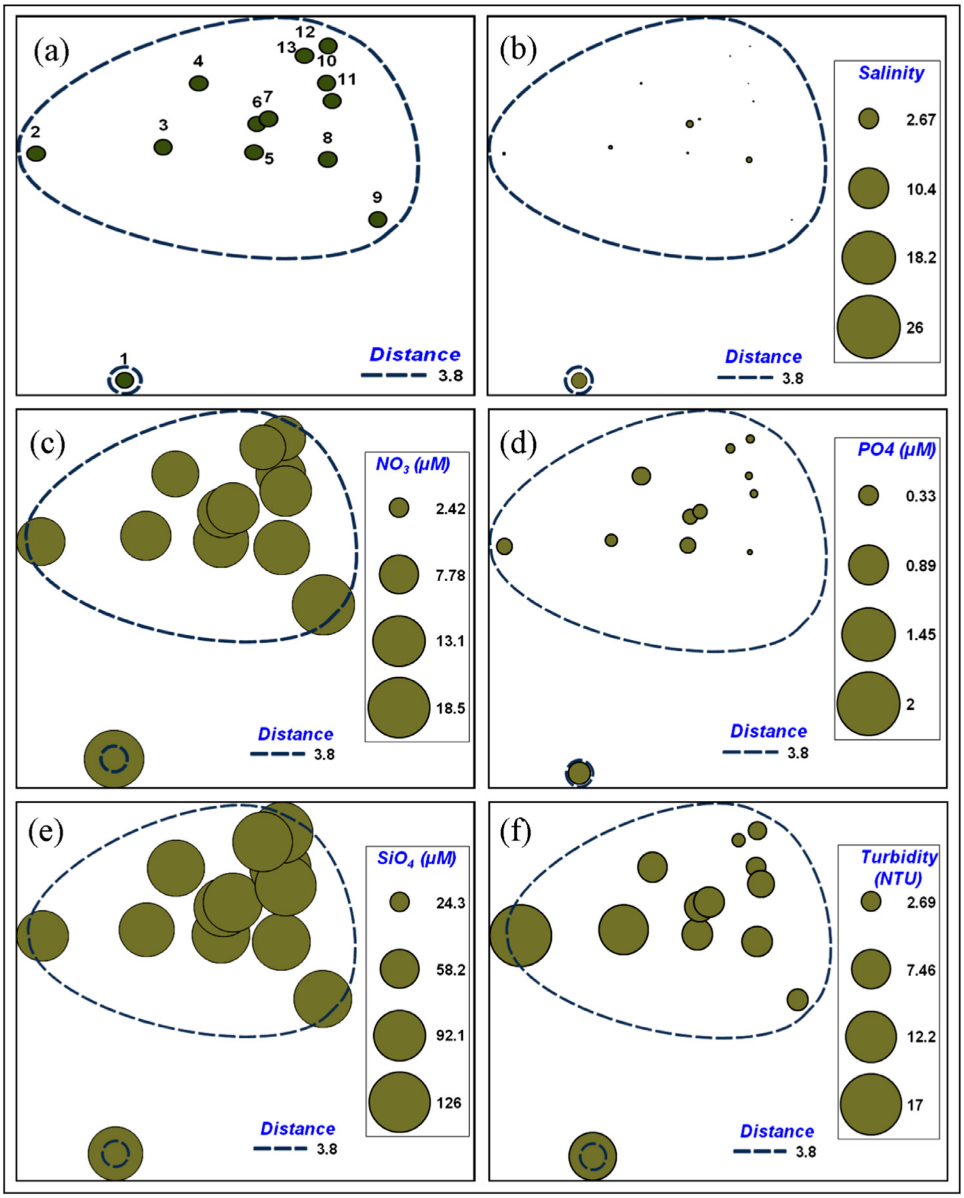

Figure 4 Grouping of (a) locations based on physicochemical variables in the KBW during the Southwest Monsoon (SWM). In subsequent panels, the proportionate concentration of (b) salinity, (c) nitrate (NO_3), (d) phosphate (PO_4), (e) silicate (SiO_4) and (f) turbidity have been presented.

During the SWM, six groups of MSP were recorded, where copepods varied from 6 to 85 No. m^{-3} and contributing 54—58% in total abundance (Figure 6b). During this time, cladocerans contributed 32—37% of the total abundance and were high in upstream locations (cluster II). During the PSWM period, nine MSP groups were recorded. In general, Chaetognatha, hydromedusae and Lucifers were found in the downstream locations during PRM, and PSWM periods, whereas their abundance was completely absent in the KBW during SWM. Chaetognatha, hydromedusae and Lucifers collectively contributed <8% of the total abundance.

3.3.4. Copepod community structure

Out of the 28 copepods species identified during the present study (Table 2), 20 belongs to the order calanoid, 6 to cyclopoid and two species to harpacticoid. Calanoids were the predominant form in the downstream and midstream regions during the PRM and PSWM; wherein cyclopoids were found dominant in the upstream locations. Some of the species like *Pseudodiaptomus annandalei* and *Acartia plumosa* were found throughout the KBW irrespective of seasons. During PSWM *A. plumosa* was dominated (>50%) and at the same time, there was an incidence of *Acartia* sp., swarm in the downstream (mesohaline) region especially in station 2 and 3.

During PRM, IndVAL analysis of copepods showed a significant difference between the cluster assemblages (Table 3). In cluster I copepods, *Acartia centrura, Acartia danae, Acartia erythraea, Acartia southwelli, Labidocera acuta, Centropages* sp., *Corycaeus* (>80 IndVal) were dominant and appeared as the indicator species of polyhaline downstream region. Similarly, in cluster II, such as *Acartia*

Table 2 Copepod species abundance during the Pre-Southwest Monsoon (PRM), Southwest Monsoon (SWM) and Post Southwest Monsoon (PSWM) periods in the Kochi back waters. Symbols: + indicates <1%, ++ indicates >1–5%, +++ indicates >5–10%, # indicates >10–20%, ## indicates >20–30%, ### indicates >30–40%, * indicates >40–50%, ** indicates >50–60% and (-) indicates absence.

		PRM				SWM		PSWM		
	Species name	Cluster I	Cluster II	Cluster III	Cluster IV	Cluster I	Cluster II	Cluster I	Cluster II	Cluster III
Copepods	*Acartia centrura*	++	+	-	-	-	-	+	-	-
	Acartia danae	+++	+	-	-	-	-	+	-	-
	Acartia erythraea	++	-	-	-	-	-	-	-	-
	Acartia plumosa	+++	###	##	+	+++	++	**	###	++
	Acartia southwelli	++	-	-	-	-	-	-	-	-
	Acartia sp.	++	#	++	+	-	-	+++	+++	+
	Acartiella gravelyi	-	-	++	#	#	#	-	++	#
	Acartiella keralensis	-	++	+	++	+++	#	+	++	++
	Acrocalanus gracilis	##	++	-	-	-	-	+++	+	-
	Allodiaptomus mirabilipes	-	-	++	#	+++	+++	-	+++	#
	Allodiaptomus sp.	-	-	+	++	+++	#	-	++	++
	Labidocera acuta	++	+	-	-	-	-	+	-	-
	Centropages sp.	++	+	-	-	-	-	+	-	-
	Heliodiaptomus cinctus	-	-	*	+++	+++	+++	-	++	+++
	Limnocalanus macrurus	-	-	-	+++	+++	#	-	+	+++
	Paracalanus sp.	+++	+	-	-	-	-	++	+	-
	Paracalanus parvus	+++	++	-	-	-	-	++	+	-
	Pseudodiaptomus annandalei	+++	###	#	++	++	++	#	##	++
	Pseudodiaptomus serricaudatus	++	+++	-	-	++	+	++	+	-
	Pseudodiaptomus bingami malayalus	-	-	++	++	++	++	-	++	++
	Corycaeus sp.	#	+	-	-	-	-	++	-	-
	Nitocra sp.	-	++	++	-	++	-	+	++	-
	Euterpina acutifrons	++	++	-	-	++	-	++	+	-
	Oithona rigida	+++	++	-	-	-	-	++	+	-
	Oithona brevicornis	++	++	-	-	-	-	++	+	-
	Thermocyclops sp.	-	-	-	++	#	#	-	+	++
	Mesocyclops sp.	-	-	++	#	#	#	-	++	#
	Microcyclops sp.	-	-	++	##	+++	#	-	++	##

Table 3 Copepods Indicator species (IndVal analysis) in each cluster assemblages during the Pre-Monsoon (PRM) and Post-Southwest Monsoon (PSWM) periods.

	Cluster 1		Cluster II		Cluster III		Cluster IV	
	Species name	IndVal	Species name	IndVal	Species name	IndVal	Species name	IndVal
PRM	*Acartia centrura*	90.5	*Acartia plumosa*	72.5	*Heliodiaptomus cinctus*	51.2	*Acartiella gravely*	83.7
	Acartia danae	83.6	*Acartia* sp.	86.9			*Allodiaptomus mirabilipes*	83.1
	Acartia erythraea	100	*Acartiella keralensis*	61.6			*Allodiaptomus* sp.	95.5
	Acartia southwelli	100	*Pseudodiaptomus annandalei*	64.9			*Limnocalanus macrurus*	100
	Acrocalanus gracilis	69.0	*Pseudodiaptomus serricaudatus*	88.0			*Thermocyclops* sp.	100
	Labidocera acuta	81.4	*Nitocra* sp.	58.1			*Mesocyclops* sp.	90.4
	Centropages sp.	95.6	*Euterpina acutifrons*	72.8			*Microcyclops* sp.	93.8
	Paracalanus sp.	70.0	*Oithona brevicornis*	65.9				
	Paracalanus parvus	53.9						
	Corycaeus	90.3						
	Oithona rigida	51.4						
PSWM	*A. centrura*	50	*Allodiaptomus mirabilipes*	63.0	*Acartiella gravely*	65.7		
	Acartia plumosa	84.4	*Heliodiaptomus cinctus*	63.2	*Allodiaptomus* sp.	52.1		
	Acartia sp.	77.9			*Limnocalanus macrurus*	78.5		
	Acrocalanus gracilis	100			*Thermocyclops* sp.	54.7		
	Labidocera acuta	50			*Mesocyclops* sp.	79.2		
	Centropages sp.	50			*Microcyclops* sp.	87.4		
	Paracalanus sp.	100						
	Paracalanus parvus	100						
	Pseudodiaptomus annandalei	59.7						
	Pseudodiaptomus serricaudatus	100						
	Corycaeus	50						
	Euterpina acutifrons	94.3						
	Oithona rigida	96.0						
	Oithona brevicornis	96.8						

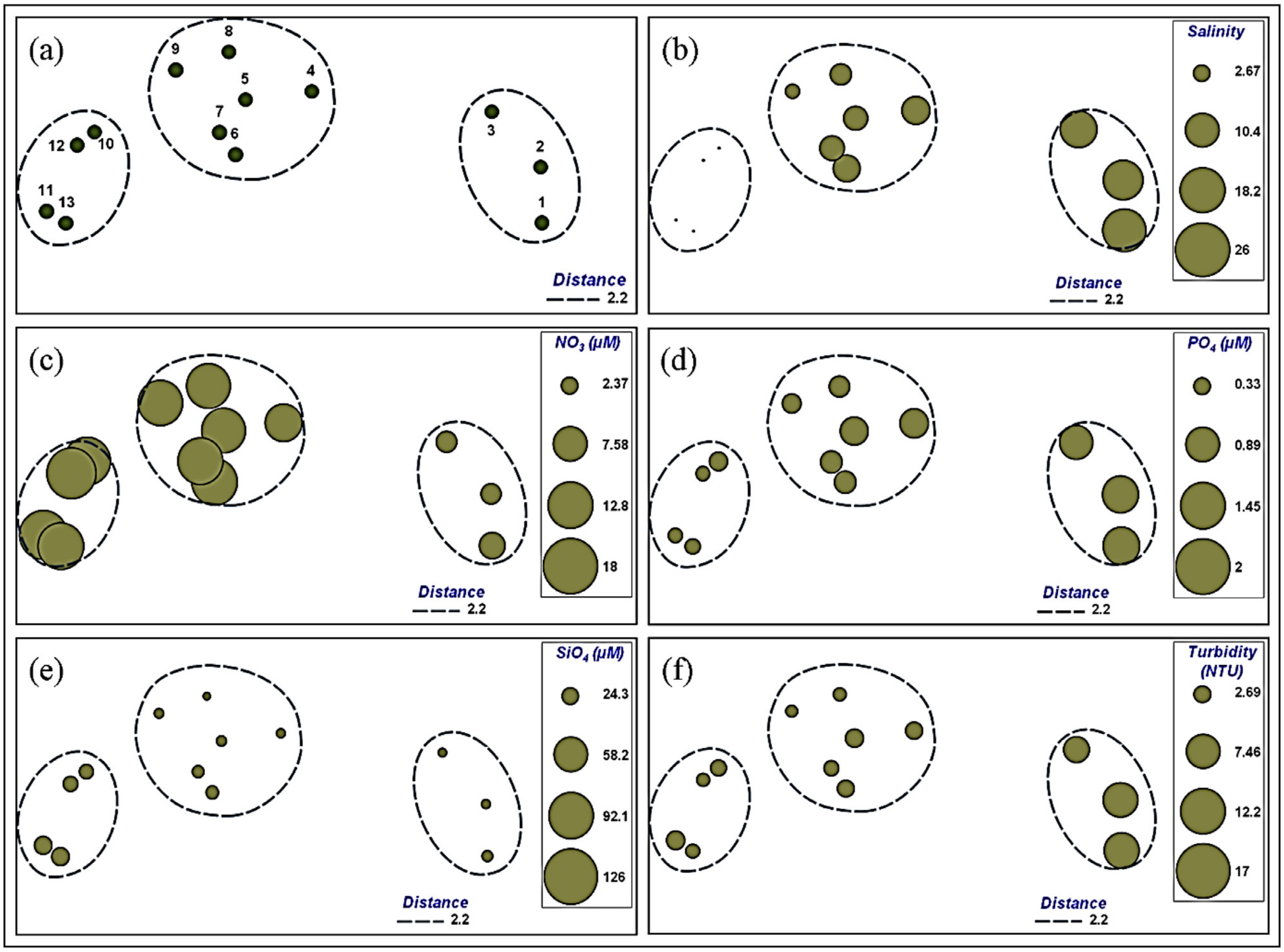

Figure 5 Grouping of (a) locations based on physicochemical variables in the KBW during the Post-Southwest Monsoon (PSWM). In subsequent panels, the proportionate concentration of (b) salinity, (c) nitrate (NO_3), (d) phosphate (PO_4), (e) silicate (SiO_4) and (f) turbidity have been presented.

sp., *Pseudodiaptomus serricaudatus* represents the indicators of mesohaline midstream region. In the other hand, *Heliodiaptomus cinctus* was predominated in the cluster III mesohaline (locations 7—9) region. And in cluster IV, *Acartiella gravelyi, Allodiaptomus mirabilipes, Allodiaptomus* sp., *Limnocalanus macrurus, Thermocyclops* sp., *Mesocyclops* sp., *Microcyclops* sp., (>80 IndVal) represented the oligohaline indicator species in the upstream region. During the SWM period, copepod species composition and abundance were almost the same over the entire stretch of the KBW, and therefore no specific indicator species was not evident in IndVAL analyses. During the PSWM, In cluster I, *A. plumosa, Acrocalanus gracilis, Paracalanus* sp., *Paracalanus parvus, Pseudodiaptomus serricaudatus, Euterpina acutifrons, Oithona rigida* and *Oithona brevicornis* were indicative copepod species and represents the mesohaline downstream region; in cluster II *A. mirabilipes* and *H. cinctus* represented as intermediate species, which characterised as mesohaline to oligohaline levels of salinity in the midstream locations; and in cluster III, species such as *Mesocyclops* sp., *Microcyclops* sp., were dominated and represented in the limnohaline upstream region (Table 3).

3.4. Regions of high MSP/copepod abundance and diversity

Multivariate RDA was performed to identify the hydrographical conditions, which was the most favouring environment to the mesozooplankton abundance and copepods community structure in the KBW. Salinity, nutrients (nitrate, silicate, phosphate) and turbidity were found to influence the copepods community structure, even though salinity as the significant factor which is explaining 38% variance during PRM and PSWM periods. And Monte Carlo significance test showed that the ordination pattern was substantial during the PRM and PSWM periods (Figure 7). During the PRM period, the downstream locations showed (cluster I) high saline and turbidity, which is declined towards the upstream locations that evident in the RDA triplot. The mesohaline region can be identified in the cluster II midstream locations, which shows in the lower right side of RDA, nitrate and silicate axes were oriented just opposed to salinity and phosphate that indicating their inverse relationship. The salinity values overlaid in the RDA plot shows the cluster I downstream locations had polyhaline salinity levels while

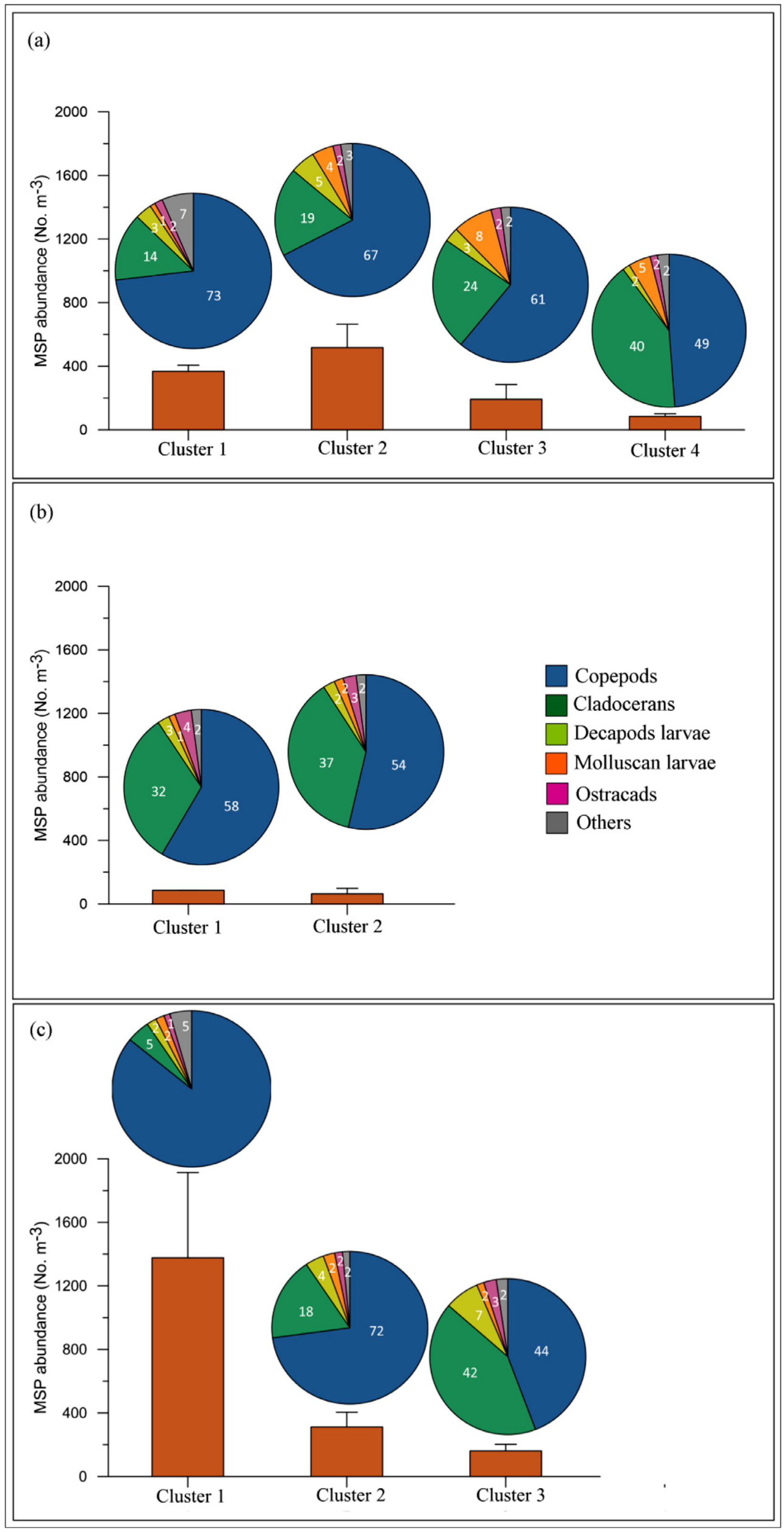

Figure 6 The total MSP abundance (bars) and their group composition (pie chart) in various clusters during (a) Pre-Southwest Monsoon (PRM), (b) Southwest Monsoon (SWM) and (c) Post-Southwest Monsoon (PSWM). Cluster locations are in accordance with Figure 2. Mean — bar chart; error bars — standard deviation.

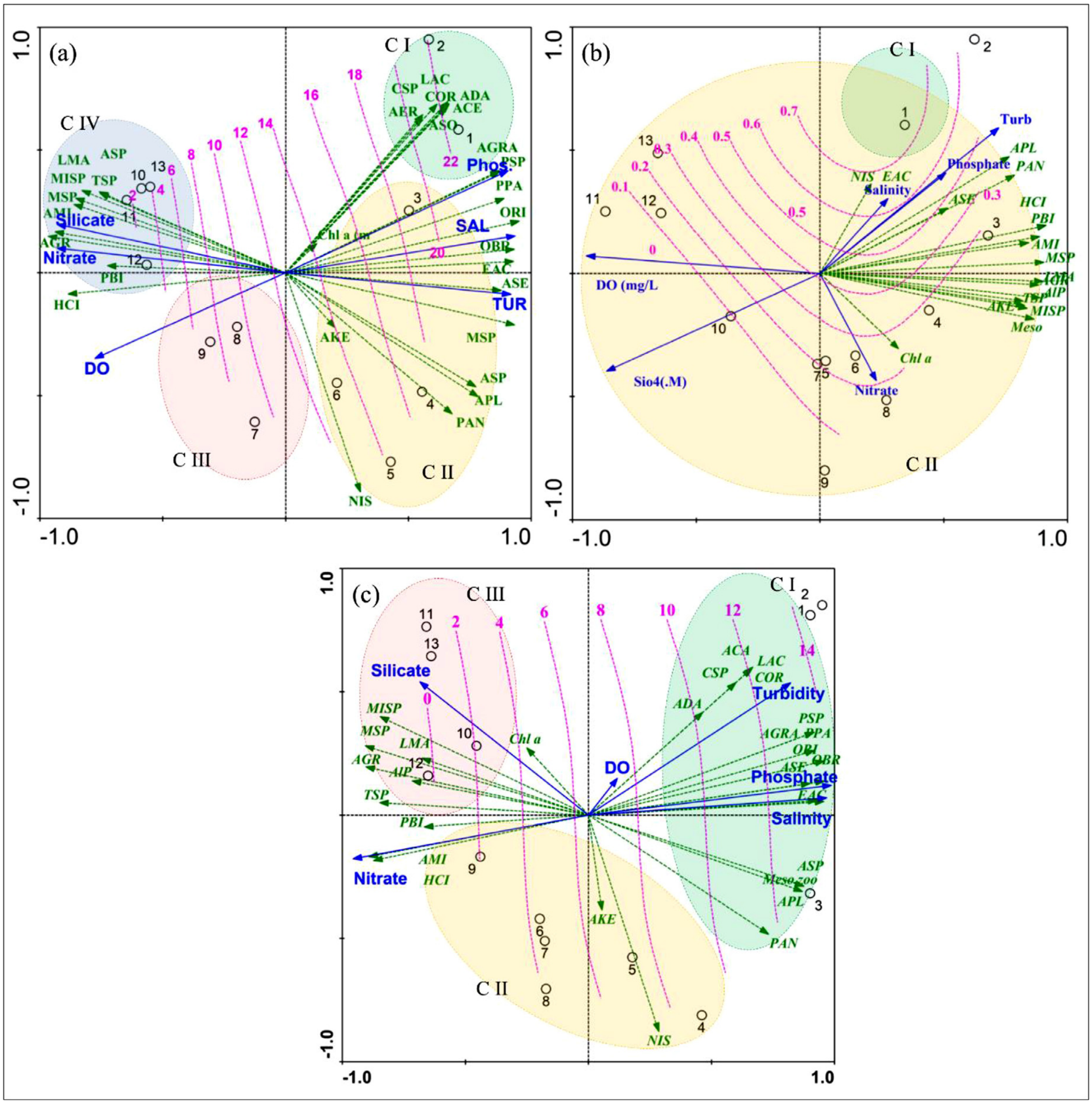

Figure 7 RDA triplot showing the distribution and interrelationships of environmental and biological parameters during (a) Pre-Southwest Monsoon (PRM), (b) Southwest Monsoon (SWM) and (c) Post- Southwest Monsoon (PSWM). The overlaid attribution contours (pink dotted line and values) represent the spatial distribution of salinity and its relationship with other environmental and biological components. Biological and environmental parameters are displayed by arrows; the blue-dotted arrows indicate the former, and the green arrows the latter. Abbreviations: SAL — Salinity; Tur — Turbidity; Chl *a* — Chlorophyll *a*; DO — Dissolved Oxygen; MSP — Mesozooplankton. *Acartia centrura* (ACA), *Acartia danae* (ADA), *Acartia erythraea* (AER), *Acartia plumosa* (APL), *Acartia southwelli* (ASO), *Acartia* sp. (ASP), *Acartiella gravelyi* (AGR), *Acartiella keralensis* (AKE), *Acrocalanus gracilis* (AGRA), *Allodiaptomus mirabilipes* (AMI), *Allodiaptomus* sp. (AlP), *Labidocera acuta* (LAC), *Centropages* sp. (CSP), *Heliodiaptomus cinctus* (HCI), *Limnocalanus macrurus* (LMA), *Paracalanus* sp. (PSP), *Paracalanus parvus* (PPA), *Pseudodiaptomus annandalei* (PAN), *Pseudodiaptomus serricaudatus* (ASE), *Pseudodiaptomus bingami malayalus* (PBI), *Corycaeus* (COR), *Nitochara* sp. (NIS), *Euterpina acutifrons* (EAC), *Oithona rigida* (ORI), *Oithona brevicornis* (OBR), *Thermocyclops* sp. (TSP), *Mesocyclops* sp. (MSP), *Microcyclops* sp. (MISP). C I indicates cluster I, C II cluster II, C III cluster III and C IV cluster IV.

the cluster II, midstream locations are mesohaline. In the upstream, salinity variations were evident nearby TB locations. Upstream locations (7—9) near to TB was mesohaline salinity levels (Av. 10.5 $\pm$ 0.5 salinity), whereas the upstream locations (10—13) was oligohaline to limnohaline levels of salinity (4.9—0.9). The high salinity and phosphate in the downstream could be due to tidal activity and water circulation. The prevalence of oligohaline salinity conditions in the locations 10—13 and mesohaline conditions in the locations (7—9) of KBW is the clear evidence of the hydraulic barrage (TB) in preventing salinity incursion towards upstream.

During PRM, MSP was oriented to the right side in RDA plot overlaid on salinity indicating their preference to the

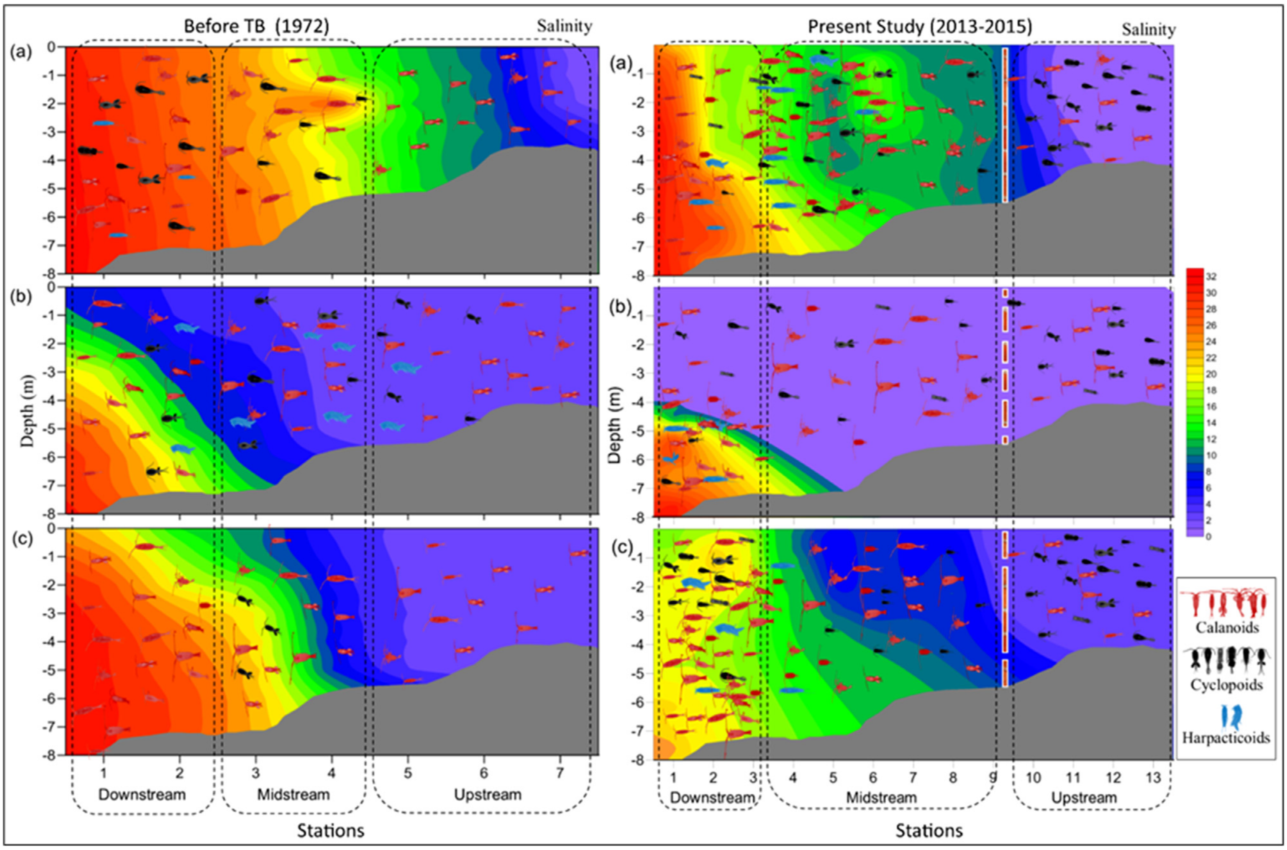

Figure 8 Comparison of salinity levels and copepods distribution in 1972 (before TB) and in the present study in the KBW. (a) Pre-Southwest Monsoon (PRM), (b) Southwest Monsoon (SWM) and (c) Post-Southwest Monsoon (PSWM) season. Salinity distribution before TB is based on Haridas et al. (1973).

mesohaline region. RDA triplot clearly shows that copepods species composition varied spatially with the variation of salinity in the KBW. In the cluster I, the copepod species such as *A. centrura, A. danae, L. acuta, Centropages* sp., *Corycaeus, A. erythraea, A. southwelli, A. gracilis, Paracalanus* sp., *P. parvus*, and *O. rigida*, species are oriented top right side of the plot represents their high abundance in polyhaline salinity, which prevails in the extreme downstream locations (1 and 2). And the other copepod species in the cluster II, *Acartiella keralensis, A. plumosa, Acartia* sp., *P. annandalei, P. serricaudatus, Nitocra* sp., *O. brevicornis* and *E. acutifrons* oriented to the right side of the plot indicates their preference to the mesohaline condition in the midstream. Similarly in cluster IV, upstream locations species such as *Thermocyclops* sp., *Microcyclops* sp., *Mesocyclops* sp., *A. gravelyi, A. mirabilipes, L. macrurus* and *Allodiaptomus* sp., oriented to the left side of the plot and opposite the salinity that indicates oligohaline is their favourable condition (Figure 7). Cluster III oriented to the lower left side of the plot and separated from cluster IV shows the marked difference in their copepods composition. However, cluster III (locations 7—9) has a close affinity with cluster II (locations 3—6) indicating both of them in mesohaline conditions.

During the SWM, the entire study area was dominated by freshwater when limnohaline condition prevailed everywhere except in the extreme downstream. Therefore, there was no clear pattern in the distribution of copepods during the SWM. Salinity was less discernible during the SWM due to the predominance of freshwater in the entire KBW. During the PSWM, the RDA plot demarcated clear spatial difference in the hydrographical parameters and copepod community structure. Salinity and turbidity were spatially high in the downstream, and their increasing gradients were oriented to the right side of the plot. Salinity overlay showed that the downstream locations had mesohaline, which decreased towards the upstream locations. Copepods total abundance was found to be in higher abundance in the downstream region, and these parameters were oriented in the right side of the plot with mesohaline. Copepods species composition varied widely during PSWM relation to salinity as evident in the triplot. The copepods species *A. centrura, Acartia* sp., *A. plumosa, A. kerlelensis*keralensis, *L. acuta, Centropages* sp., *Corycaeus, Paracalanus* sp., *A. gracilis, P. parvus, O. rigida, O. brevicornis, P. serricaudatus, E. acutifrons* and *P. annandalei* species were oriented to the right side of the plot that representing the cluster I locations in the mesohaline condition.On the other hand, in cluster II of midstream locations, copepods *Microcyclops* sp., *Mesocyclops* sp., *L. macrurus, A. gravelyi, Allodiaptomus* sp., *Thermocyclops* sp., *A. mirabilipes* and *H. cinctus* were oriented to the left side of the plot showing their affinity to oligohaline to limnohaline conditions (Figure 7). It is noteworthy that during PRM and PSWM seasons, the downstream, midstream and upstream regions of the KBW has a significant difference in copepod species composition. RDA triplot clearly showed that copepods composition was always high in the mesohaline level of salinity, especially in salinity ranges 10—15, during the PRM and PSWM period. This mesohaline condition in the KBW persisted in the midstream during the PRM and downstream during the PSWM period.

4. Discussion

The prevalence of polyhaline conditions in the downstream and oligohaline/limnohaline conditions in the upstream of KBW due to TB seems to have a substantial impact on the MSP and copepod community structure. Salinity distribution in the KBW was spatially distinct during PRM and PSWM (Figure 2a) due to the progressive increase in the tidal activity (Jyothibabu et al., 2006; Qasim, 2003). Mesohaline condition prevailed in the downstream during the PSWM, which changed to polyhaline during the PRM. During the PSWM period, the midstream, was oligohaline to mesohaline, whereas the upstream remained limnohaline, which turned to oligohaline during PRM (Figure 2). Previous studies have established that KBW is highly influenced by seawater intrusion during the PRM and PSWM and massive freshwater incursion during the SWM (Madhupratap, 1987; Menon et al., 2000; Qasim, 2003). For clear understand the current situation the present study surface salinity values were compared with the salinity values of Haridas et al., (1973) whom was reported in 1972 before the construction of TB (Figure 8). In his study during PRM salinity values varied from 8 to 31 and the maximum value was reported in downstream euhaline region and low in the upstream mesohaline region; during SWM ranged from 0.2 to 6.5 and during PSWM salinity was ranged from 0.3 to 23.5. The present salinity levels in the upstream region of the KBW show around 11 units drop during the PRM and 1 unit drop during PSWM compared to the historical times. Such a drop in salinity caused by TB altered the plankton functional groups in the KBW (Anjusha et al., 2018; Arunpandi et al., 2020; Haridevan et al., 2015).

Dissolved oxygen (DO) levels were high in the upstream with a minimum variation on either side of TB. DO was seasonally high during SWM (Table 1) and decreased lightly after that, following the pattern presented in Sooria et al., (2015). Turbidity is an indicator of estuarine conditions like flooding or re-suspension (Anon, 2001). Turbidity was always maximum in the downstream compared to midstream and upstream (Table 1). During the PRM period, turbidity was high in the downstream compared to midstream and upstream, which coincided with the estuarine turbidity maximum (Menon et al., 2000; Sooria et al., 2015). The KBW turbidity was generally high during the SWM period followed by PSWM and PRM. During the SWM season, turbidity in the KBW increased by 2—3 folds compared to the PRM, due to increased land runoff (Nasir, 2010).

Nitrate concentration did not show a definitive distribution pattern though it was relatively high in the upstream locations than the downstream. During the SWM, nitrate concentration was high in the entire stretch of KBW compared to PSWM and PRM (Figure 3c, 4c and 5c). In the downstream, silicate concentration was five-folds higher during the SWM compared to PRM period, especially towards the upstream locations compared to the downstream and middle estuary. The four rivers emptying into the upstream are sources of high nutrient levels in the KWB system irrespective of the seasons (Jyothibabu et al., 2006; Mohan et al., 2016; Qasim, 2003), There seem to be some non-point sources of nitrogen input (Arunpandi et al., 2017; Jagadeesan et al., 2016; Jyothibabu et al., 2006; Saraladevi et al., 1983; Sooria et al., 2015). The phosphate concentration was high in the downstream but decreased towards the upstream region. Compared to PRM, phosphate concentration decreased during the SWM in the entire stretch of KBW. The phosphate level in the KBW was the seasonal highest during the PRM due to high salinity and desorption of phosphate from the suspended particles (Martin et al., 2008; Sooria et al., 2015). Seasonal variations in the biological components of KBW closely followed the salinity variations (Madhupratap, 1987) with enhanced Chl *a* in regions of high nutrients (Arunpandi et al., 2020; Jyothibabu et al., 2006; Madhu et al., 2007a,b).

During the PRM, MSP abundance was high in the midstream compared to downstream and upstream. MSP abundance was minimum in the upstream compared to the downstream. However, during the SWM, MSP abundance decreased in the downstream and midstream compared to PRM period (Figure 6a), which was in accordance to earlier studies (Madhupratap, 1987; Wellershaus, 1974). It is likely that during SWM, the high freshwater flow physically pushes MSP to the downstream region (Sooria et al., 2015). During the PSWM, MSP abundance was higher in the upstream compared to the midstream and upstream (Figure 6c). It also clear that calanoid was the dominant copepod in the midstream and downstream, whereas cyclopoid dominated in the upstream.

Madhupratap and Haridas (1975) had presented the mesozooplankton composition in the KBW based on a study carried out in 1972 when there was no TB. The MSP total abundance in the KBW in the upstream during PRM, south of the presents TB, was from 246.6 to 505.2 No m^{-3} and during PSWM was from 1 to 227.7 No m^{-3}. In the present study, it is found significantly low, i.e., from 67.9 to 100.7 No m^{-3} during PRM and from 144.3 to 222 No m^{-3} during PSWM. Moreover, a significant variation in the composition of various MSP groups is evident in these studies. Overall, the seasonal copepod percentage contribution in the present study (PRM — 62%, SWM — 56% and PSWM — 67%), was remarkably higher than those presented in Madhupratap and Haridas (1975) which was 26%, 17% and 36%, respectively. Besides, cyclopoid copepods were found less in the upstream region, and calanoids are found dominant during PRM and PSWM before TB was functional (Madhupratap and Haridas, 1975). But cyclopoids were found dominant in the upstream region in the present study (Figure 8). In short, the MSP distribution shows that TB has a profound influence on the MSP composition and copepods species distribution, since the barrage imposes restrictions on natural flow pattern and significantly alters the salinity levels in the KBW.

There are some past studies available on the salinity tolerance of copepods in the KBW (Madhupratap and Haridas, 1975; Madhupratap, 1979; Martin Thompson, 1991; Tranter and Abraham, 1971; Vineetha et al., 2015). Tranter and Abraham (1971) observed *Acartia bilobata, A. centrura,* *Aeartia spinicauda, A. gravelyi* in saline conditions and *A. erythraea*, and *A. southwelli* in the high saline downstream region of KBW. Similarly, species such as *A. keralensis* and *Acartia negligens* were recorded in low saline regions during SWM, while *Acartia plumosa* was present throughout the year. Madhupratap (1979) reported that *P. annandalei* has a salinity tolerance up to 35 units, while other species such as *Accrocalanus similis, Acartia bowmani, A. centrura* and *A. bilobata* have less tolerance to salinity and they prefer the midstream of the KBW during the high saline period. During the SWM, copepods *H. cinctus, A. mirabilipes, A. gravelyi, Pseudodiaptomus binghami malayalus, O. brevicornis, O. hebes* and *O. nana* were found in the low salinity (limnohaline) upstream region. And also *Acartia* spp., *Paracalanus aculeatus, P. crassirostris, P. serricaudatus* and *P. jonesi* were found in high saline condition while *Acartia pacifica* and *A. southwelli* in extreme downstream of KBW. When compared the present study with Martin Thompson (1991), it was observed that both the studies have recorded almost similar copepods composition in different parts of the KBW.

However, the present study is the first attempt to scientifically assess the changes in the distribution and composition of MSP/ copepods community in the KBW due to the hydrographical changes imparted by TB during non-monsoon periods. The results show that copepods species showed significant zonal variations in the KBW due to the closure of TB. Statistical results also revealed salinity as the primary factor controlling the distribution and abundance of copepods in the KBW. It was also found that copepod *A. centrura, A. danae, L. acuta, Centropages* sp., *Corycaeus, A. erythraea, A. southwelli, Acrocalanus gracilis, Paracalanus* sp., *P. parvus, E. acutifrons, O. rigida* and *O. brevicornis* have preferred the polyhaline regions of KBW (downstream), whereas *A. keralensis, A. plumosa, Mesocyclops* sp., *Acartia* sp., *P. annandalei, P. seudodiaptomus serricaudatus* and *Nitocra* sp.) have preferred the mesohaline (5—18 salinity) regions. On the other hand, copepods *Acartia* sp., *L. macrurus, Thermocyclops* sp., *Microcyclops* sp., *Mesocyclops* sp., *Acartiella gravelyi* and *A. mirabilipes*) preferred the oligohaline (0.5—5 salinity) conditions. Since the TB remains open during the SWM, the entire KBW was freshwater dominated exhibiting less spatial variations in copepod composition and abundance.

Even during the PSWM period onwards, the copepod population thriving in the upstream was found to relocate towards the downstream for the mesohaline salinity. For eg.: *A. centrura, A. danae, Acartia* sp., *A. plumosa, A. keralensis, L. acuta, Centropages* sp., *Corycaeus, Paracalanus* sp., *A. gracilis, P. parvus, O. rigida, O. brevicornis, P. serricaudatus, E. acutifrons* and *P. annandalei* were found to relocate towards downstream, resulting in the retention of limnohaline and oligohaline tolerant species (*Microcyclops* sp., *Mesocyclops* sp., *L. macrurus, A. gravelyi, Allodiaptomus* sp., *Thermocyclops* sp., *Pseudodiaptomus bingami malayalus, A. mirabilipes* and *H. cinctus*) in the upstream. The shift in the niche of copepods to downstream of KBW has an impact on the biological productivity pattern and its conversion to higher trophic levels. The entire KBW was reported to be biologically productive, especially during the non- monsoon periods, due to the increase in the salinity. However, the natural seawater intrusion was prevented by the construction of TB. The closure of the barrage has created a stagnant freshwater body (of ˜80 km^2) in the upstream region, where it disconnected from the hydrodynamic processes in the KBW. The significant spatial shift in the copepods species (IndVal analysis) is clear evidence showing how artificial barrages can alter the natural biological assemblages in an ecosystem.

5. Conclusion

This study presented the seasonal hydrographical settings and the MSP/copepod assemblages in the KBW. It shows that Thannermukam barrage (TB) has a measurable impact on the distribution of mesozooplankton/copepods during the non-monsoon period. TB restricts the water flow and prevents the incursion of saline water into the upstream region, and alters the copepod community in different sections of the KBW. Copepods community in the KBW as a whole favoured mesohaline salinity levels (especially ∼10—18 salinity). This study showed that several copepods performed a spatial shift in their preferred habitat due to the flow restrictions in the KBW caused by TB. The statistical results revealed salinity as the most significant environmental variable that controls the composition, distribution and abundance of copepods in the KBW. The flow inhibition of TB in the upstream of the KBW was reflected in a remarkable change in the copepod composition. Hence, this study proposes copepods as an effective bioindicator to monitor changes in hydrographical settings in the natural aquatic ecosystem by artificial barrages.

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