

Monsoonal impact on planktonic standing stock and abundance in a tropical estuary (Cochin backwaters - India)

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Abstract

Environmental studies in the Cochin backwaters (CBW), a tropical estuary along the southwest coast of India showed that seasonal fluctuation in salinity created by the monsoonal rainfall and associated run off is the major factor controlling the distribution and abundance of micro- and mesozooplankton. During premonsoon season, the CBW was characterized by warm waters (av. 32.6 ± 0.6 °C) with relatively high salinity (>23; except in the lower estuary). On the other hand, fresh water was found to dominate the entire area during monsoon and post monsoon seasons. The enormous input of nutrients (nitrate, phosphate & silicate) into the estuary from various sources (industries, agriculture and domestic) was responsible for the high phytoplankton biomass (av. 10.4 ± 10.1 mgm⁻³) irrespective of seasons. The phytoplankton community was in general, dominated by diatoms (av. $88 \pm 12\%$), and proliferation of multiple species of diatom (*Skeletonema costatum*, *Thalassiosira subtilis* and *Nitzschia closterium* - 1600×10^3 cells L⁻¹) at different locations was observed especially during high saline condition. In case of zooplankton (micro- and meso), high standing stocks (micro. av. 81.4 ± 48.1 mgCm⁻³; meso av. 88 ± 125 mgCm⁻³, respectively) were recorded during the premonsoon season. Copepods (eg. Calanoids) formed the abundant group (av. $75 \pm 18\%$) in the meso zooplankton community irrespective of seasons. The ratio of carbon content between phytoplankton and zooplankton (P:Z) was quite high (>100) during monsoon and post monsoon seasons, but became low during premonsoon season (<5). Hence, it is suggested that during the periods of fresh water dominance, the trophic food web of Cochin estuarine system is characterized by substantial amount of unconsumed carbon at primary level owing to the reduction in phytoplankton grazers (zooplankton).

Keywords – Cochin backwaters; Salinity; Nutrients; Chlorophyll *a*; Plankton

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1. Introduction

Estuaries, the dynamic water bodies in the coastal area are the cradle grounds for phytoplankton growth because they receive constant nutrients supply from rivers and other land based discharges (Ketchum, 1967). Among nutrients, nitrogen (N) and phosphorous (P) are commonly referred as limiting nutrients (EEA, 1999; Neill, 2005), support the growth of phytoplankton to establish a suitable pelagic food web (Hilmer & Bate 1990; Adams and Bates, 1999). Besides the availability of nutrients, the physical variables such as flushing rate, salinity and turbidity also largely influence the distribution and abundance of plankton communities in estuaries (McLusky, 1971; Cleorn, 1987; Ferreira et al., 2005). The biological production (primary and secondary) becomes intense at low salinities (5-8) because of their preference to a variety of planktonic organisms (marine, brackish and fresh water) at low salinity. Hence, the estuaries are always considered as biologically active zones (Khlebovich, 1974; Kibirige and Perissinotto, 2003).

Different types of trophic relationship between the phytoplankton and zooplankton have been established in estuarine systems (Sautour et al., 1996; Perissinotto et al., 2000; Tan et al., 2004). It has been traditionally thought that the major contributions of primary production in coastal and estuarine waters are from diatoms, which subsequently get transferred through copepods to fish. However, recent studies on size-fractionated plankton communities have questioned this view, often implicating the importance of microzooplankton as the major consumers of phytoplankton in the coastal waters (Gifford, 1988; Leising et al., 2005). In many cases, when both the relative abundance and grazing rates of copepods and micro zooplankton are considered, the growth and grazing of copepods (meso zooplankton) are low compared to those of microzooplankton (Fessenden & Cowles, 1994).

CBW, a tropical micro-tidal estuary with high biological production, provides an ideal breeding ground for many economically important fin fishes and shell fishes (Qasim, 2003). As a result of massive reclamation for the rapid urbanization and industrialization, the Cochin backwaters are facing severe ecological problems including eutrophication (Gopalan et al., 1983). Sixteen major and several minor industries, situated on the banks of River Periyar discharge untreated or partially treated wastes (acids, nutrients and heavy metals) into the estuary (Balachandran et

al., 2003). Likewise, the domestic waste from the Cochin metropolitan city also creates organic pollution. All these activities eventually lead to the changes in the population and structure of trophic webs and even affected the overall functioning of this ecosystem (Unnithan et al., 1975; Menon et al., 2000).

Several studies have been conducted in the Cochin backwaters on various physico-chemical (Sankaranarayanan & Qasim, 1969; Shyanamma and Balakrishnan, 1973) and biological characteristics (Rao et al., 1975; Madhupratap et al., 1975; Qasim, 2003). Being eutrophic, primary production in the estuary is always high and is mainly constituted by nano plankton (<20 μ m) community (Qasim, 1974). Considering the planktonic grazers, a recent study has found that micro zooplankton plays an important role in the Cochin backwaters by consuming a significant fraction (~43%) of primary production (Jyothibabu et al., 2006). Among mesozooplankton, copepods formed the dominant group (Madhupratap, 1978 & 1979), with strong seasonality in accordance with the changes in salinity (Pillai et al., 1973; Madhupratap, 1987). Despite the numerous specific works that have been carried out in the estuary on plankton diversity and distribution, a comprehensive study covering the nutrients, phyto-, micro- and meso zooplankton has not been initiated. In this paper, we examine the manifestations of the monsoonal rainfall and associated run off on various plankton biomass (phyto, micro and mesozooplankton), abundance and distribution in the CBW.

2. Materials and Methods

2.1. Study area

The CBW forms a complex, network of shallow brackish water (250km²) running parallel (9° 40' & 10° 12'N and 76° 10' & 76° 30'E) to the coast, with two permanent openings to the Arabian Sea. The depth of the estuary varies from 2 to 7 m, but the ship channels at the Cochin harbor region are dredged and maintained at 10 to 13m (Qasim, 2003). Constant mixing with seawater through tidal exchanges has given it the characteristics of a tropical estuary (Balchand & Nair, 1994; Ajith and Balchand, 1996). Six major rivers discharge about 20000 x 10⁶ m³ of fresh water into the estuary annually (Srinivas, 2000) and the variation in the river discharge inducing a salinity gradient is responsible for the diverse biotopes of peculiar plankton communities in the CBW.

2.2. Sampling

The sampling was made from nine stations covering the entire estuary during premonsoon (April), monsoon (July) and post monsoon (October) seasons of 2003 as a part of the programme 'Ecosystem modeling of Cochin backwaters' (Fig. 1). Sampling was carried out in a small powerboat. The water samples collected using Niskin bottles (Hydrobios 5 L) were kept in the iceboxes and brought to the laboratory. Light transparency of the water column was measured using the Secchi disc (D_s m) and light extinction coefficient (k_e , m^{-1}) was calculated following the relationship $k_e = 1.4/D_s$, where 1.4 is an empirical constant for highly turbid waters (euphotic depth <5m; Holmes, 1970). Dissolved oxygen (DO) was estimated according to Winkler's titration method. Water samples were analysed for nutrients (ammonia, nitrate, phosphate and silicate) within 6 hr of collection following standard procedures (Grasshoff et al., 1983). For the estimation of chlorophyll *a*, 250ml of surface water was filtered through GF/F filters (pore size - 0.7 μ m), extracted with 90% acetone for 24 hours in the dark and the extinction was measured in a spectrophotometer (Model - UV 1650PC, Shimadzu) before and after acidification (Strickland & Parsons, 1972). Lugol's Iodine fixed water samples from the surface were analysed for phytoplankton species using an inverted microscope (OLYMPUS, C.K-30) according to standard protocols (UNESCO 1994; Tomas, 1997).

Microzooplankton samples were collected by filtering 5 litres of surface water initially through 200 μ m bolting net and subsequently through a 20 μ m sieve. Concentrated micro zooplankton was transferred to 100ml filtered seawater and preserved in acid Lugol's iodine. Later, the enumeration and identification of species was done using an inverted microscope (OLYMPUS, C.K-30). Conversion of biovolumes into carbon (considering a mean cell shrinkage of 40% for protozoans according to Stoecker et al., 1984) was carried out by applying a factor of 0.19 pgC μ m⁻³ for ciliates and 0.14 pgC μ m⁻³ for dinoflagellates (UNESCO, 1994). Crustacean larval forms were categorized as a single group and a factor of 16 ngC per individual was used for their conversion to carbon equivalent (UNESCO, 1994). Meso zooplankton were collected with a WP net (mesh size 200 μ m) having a diameter of 0.6m, towed horizontally just below the surface for a duration of 10 minutes (speed of the boat -1 knot). The net was fitted with a calibrated flow meter (General Oceanics, Model-2030) to quantify the volume of water filtered. Zooplankton

biomass was measured volumetrically after removing large detrital particles and the samples were preserved in 4% formaldehyde for later enumeration and identification. For conversion of meso zooplankton biomass in terms of carbon, a factor of 1ml displacement volume = 96mgC was used (Cushing et al., 1958).

2.3. Data analysis

Two-way analysis of variance (ANOVA) was used to investigate the statistical significance of environmental parameters on various plankton biomass. The data were further subjected to hierarchical cluster and multidimensional scaling (MDS) analyses to identify the similarity between stations based on salinity and the biomass of each plankton communities and this was calculated based on Bray-Curtis similarity index with $\log_{10}(x+1)$ data using PRIMER version 5.2.8 (Clark and Warwick, 1994). Also, the Pearson correlation and multivariate regression analyses were performed to find the significance among the environmental parameters, planktonic biomass and density. Species diversity (H') and species richness (D) were calculated according to

$$\text{Species diversity } (H') = \sum(P_i \text{Log}_2 (P_i)) \text{ (Shannon and Weaver, 1963)}$$

$$\text{Species richness } (D) = (S-1)/\text{Log}_e N \text{ (Margalef, 1968)}$$

Where, $P_i = n_i/n$ (proportion of the sample belonging to the i th species. 'S' is the number of species and 'N' is the total number of individuals of all the species in a sample.

3. Results

3.1. Hydrography

During premonsoon season, the central and lower reaches of CBW was characterized by warm (av. $32.6 \pm 0.6^\circ\text{C}$) and high saline waters, whereas fresh water dominance was observed towards the upper reaches of northern (stations 3 & 4) and southern (station 8) regions (Figs. 2a&b). During monsoon season, a drop in the temperature ($\sim 2 - 4^\circ\text{C}$) in surface water was observed due to the influx of fresh water (Figs. 2a&b). A slight increase in salinity (av. 4.9 ± 5.5) and temperature (av. $30.3 \pm 1.2^\circ\text{C}$) was observed during post monsoon season (Figs 2a&b). Due to the less turbidity, the light attenuation coefficient (k_d) was minimum during premonsoon (av.

$1.2 \pm 0.2 \text{ m}^{-1}$) as compared to monsoon (av. $1.7 \pm 0.2 \text{ m}^{-1}$) and post monsoon (av. $2.4 \pm 0.4 \text{ m}^{-1}$) seasons (Fig. 2c).

DO was relatively low (av. $5.8 \pm 0.9 \text{ ml L}^{-1}$) during premonsoon season, but the pH remained steady (av. 7.1 ± 0.4 ; Figs 3a&b). Spatial variation of nutrients was more pronounced than the temporal variation (Fig.3). Ammonia (NH_4) showed a sharp increase during monsoon (av. $47.8 \pm 26.5 \mu\text{M}$) and post monsoon (av. $55.2 \pm 51.8 \mu\text{M}$) seasons. The variation of nitrate (NO_3) was marginal (Figs. 3c&d), but inorganic phosphate (PO_4) showed wide fluctuation spatially and seasonally as it was high in the harbor region (Fig 3e). The silicate (SiO_4) concentration increased by two-folds during monsoon and postmonsoon (av. $>90 \mu\text{M}$) seasons as compared to premonsoon (av. $44 \mu\text{M}$, Fig.3f).

The results of two-way ANOVA test showed insignificant variance ($P > 0.05$) for environmental parameters except for phosphate ($F=5.76$, $P=0.017$) and silicate ($F=3.94$, $P=0.046$; Table. 7). The MDS graph based on salinity showed four groups of stations with $>60\%$ similarity (Fig. 5a). Group I was corresponding to the zero salinity and, group II, III and IV were in the salinity ranges (>0 to 0.5), (>0.5 to 5) and (>5 to 30) respectively. The group IV formed the largest cluster representing 7 stations (4 stations each during premonsoon and post monsoon seasons). During monsoon, the fresh water dominance was evident, as all stations were clustered in group I (Fig.5).

3.2. Phytoplankton standing stock (chlorophyll a) and abundance

Unlike the nutrient distribution, chlorophyll a showed more spatial than temporal variation (Figs. 4a). Chlorophyll a was relatively high during monsoon (av. $17.4 \pm 14.6 \text{ mgm}^{-3}$) season as compared to the premonsoon ($8.8 \pm 7.3 \text{ mgm}^{-3}$) and post monsoon ($5.9 \pm 2.7 \text{ mgm}^{-3}$) seasons. Maximum concentration of chlorophyll a (47 mgm^{-3}) was recorded in the southern estuary (station 8) during monsoon season, whereas the minimum (1.7 mgm^{-3}) was observed in the north estuary (station 4) during premonsoon season.

Out of 89 species of phytoplankton identified during premonsoon season, diatoms were the most dominant groups (58 species). Wide variations in the species richness (0.16 to 1.52; av. 0.55) and diversity (0.81 to 2.22; av. 1.62) were characteristic of this season (Table 5). Diatoms such as *Skeletonema costatum*,

Nitzschia closterium and *Thalassiosira subtilis* were abundant ($>100 \times 10^3$ cells L^{-1}) throughout the estuary during this season. Besides this, species such as *Cocconeis* sp. (320×10^3 cells L^{-1}) and *Synedra* sp. (480×10^3 cells L^{-1}) were present only in the fresh water regions (stations - 3, 4 & 8). Diatoms such as *Coscinodiscus* sp., *Navicula* sp., *Leptocylindrus danicus*, *Eucampia* sp., *Triceratium* sp., *Thalassionema nitzschioids*, *Fragilaria oceanica*, *Asterionella japonicus*, *Chaetoceros* sp., *Pleurosigma* sp. and the dinoflagellates such as *Peridinium* sp., *Gonyaulax* sp., *Ceratium furca*, *Ornithocercus* sp. etc were also observed in varying densities during premonsoon season (Table 1). The phytoplankton density varied between 76.8×10^3 cells L^{-1} and 1856×10^3 cells L^{-1} , the maximum being observed at station 2 due to the proliferation of *Nitzschia closterium* (1600×10^3 cells L^{-1} ; Fig. 4b).

The phytoplankton species diversity and richness was relatively low (av. 1.38 & av. 0.52) during monsoon, where only 65 species were identified. *Skeletonema costatum* was distributed in varying densities (12×10^3 to 230×10^4 cells L^{-1}) along with *Cocconies* sp. (2.4×10^3 to 250×10^3 cells L^{-1}) and some fresh water phytoplankton such as *Pledorina*, *Volvox*, *Pediastrum* etc (Table 1). Among dinoflagellates, *Proto-peridinium* sp. (av. 13.68×10^3 cells L^{-1}) was present at some stations. Their density ranged between 43.2×10^3 and 2419×10^3 cells L^{-1} and maximum density at station 8 was probably due to the abundant *Thalassiosira subtilis* (2400×10^3 cells L^{-1} ; Fig. 4b). Phytoplankton density progressively decreased (20.6×10^3 to 576×10^3 cells L^{-1}) during post monsoon as compared to the premonsoon and monsoon seasons (mean species diversity index 1.77 ± 0.51 and species richness index 0.47 ± 0.26). *Skeletonema costatum* was abundant (av. 50.41×10^3 cells L^{-1}) in the estuary during this season except at river mouth (Table 1). The hierarchical cluster analysis for phytoplankton density showed the presence of four groups among stations with $>80\%$ similarity irrespective of seasons. The largest group, cluster IV was constituted with 20 stations (av. $335 \pm 157.2 \times 10^3$ cells L^{-1}), while the maximum density (av. $2137.8 \pm 398.1 \times 10^3$ cells L^{-1}) was observed in group II represented by stations 3 and 9, during post monsoon (Fig. 5b).

3.3. Microzooplankton standing stock and abundance

The micro zooplankton biomass was eight times higher during premonsoon (av. 81 ± 48 mgC m^{-3}) than the monsoon (av. 10 ± 5 mgC m^{-3}) season (Fig. 4c; micro

zooplankton data during post monsoon season not available). Estuarine mouth region (station 5) showed maximum micro zooplankton biomass (154 mgC m^{-3}) and density (av. 3817 ind. L^{-1}) during premonsoon season, but a sharp decline (av. 409 ind. L^{-1}) was noticed during monsoon season (Fig. 4d).

The species richness and diversity were relatively high (1.9 ± 0.92 & 4.1 ± 0.66) during premonsoon as compared to monsoon (0.69 ± 0.35 & 2.69 ± 1.09). Ciliates formed the most abundant group (34 species in 14 genera), followed by heterotrophic dinoflagellates (2 species) and copepod nauplii. Among ciliates, 22 loricate species and 12 aloricate species were recorded during premonsoon season. *Tintinnopsis* was the most abundant genus during premonsoon and monsoon seasons, which was followed by *Euplotes* (Table 2). Six species of *Tintinnopsis* (*T. tubulosa*, *T. beroidea*, *T. uruguaensis*, *T. lohmani*, *T. glans* and *T. cylindrical*) were dominant in numbers (av. $>100 \text{ ind. L}^{-1}$) during both the seasons (Table 2) along with heterotrophic dinoflagellates (4 species of *protoperidinium*). During monsoon period, micro zooplankton was reduced to 8 species of ciliates and one species each of dinoflagellate and copepod nauplii. Maximum number of micro zooplankton species (7) was observed at stations 1 & 6 only, but species like *Tintinnidium incertum* and *Protoperidinium* sp. was present at all stations. The MDS analysis showed two major micro zooplankton groups with $> 80\%$ similarity (Fig.5c). Group I (all stations during premonsoon) possessed high density (av. $3817.5 \pm 1983 \text{ ind. m}^{-3}$), while group II (all stations during monsoon) showed low density (av. $408.8 \pm 183.7 \text{ ind. m}^{-3}$).

3.4. Mesozooplankton biomass, abundance and composition

Similar to the population and abundance of microzooplankton as described above, the mesozooplankton distribution also showed a definite spatial and temporal variation in the estuary (Fig 4e). A significant increase in mesozooplankton biomass (av. $88 \pm 125 \text{ mgC m}^{-3}$) was noticed during premonsoon as compared to monsoon (av. $1.2 \pm 1 \text{ mgC m}^{-3}$) and post monsoon seasons (av. $1.2 \pm 0.7 \text{ mgC m}^{-3}$). Premonsoon season showed the maximum mesozooplankton density (av. 8037 ind. m^{-3}), whereas it was minimum during the monsoon (av. 262 ind. m^{-3}) and the post monsoon (av. 49 ind. m^{-3}) seasons.

Irrespective of seasons, the faunal composition of meso zooplankton community was mainly represented by copepods (av. $\sim 75\%$), but other groups such

as decapods, ostracods, amphipods, hydromedusae, mysids, fish larvae etc, were also present in less number (Table. 3). The average copepod density decreased from 4457 ind.m⁻³ (70.6%) during premonsoon to 254 ind. m⁻³ (93.6%) during post monsoon and to 49 ind. m⁻³ (59.3%) during monsoon. Decapods and fish larvae formed the next dominant groups during premonsoon (23.5% & 3.3%), monsoon (7.1% & 3.8%) and post monsoon seasons (23% & 2.2%), respectively. Maximum copepod density was recorded at station 9 (30409 ind. m⁻³) during premonsoon, while a sharp decrease (<5 ind. m⁻³) was observed during monsoon and post monsoon seasons in most of the stations. Calanoids constituted the major copepod community during premonsoon, followed by Cyclopoids and Harpaticoids. Copepod species like *Labidocera pectinata*, *Paracalanus crassirostris*, *P. aculiatu*s, *Acartia centrura*, *A. bowmani*, *A. bilobata*, *Centropages alcocki*, *Pseudodiaptomus serricaudatus*, *Corycaes* sp. and *Oithona brevicornis* were dominant near the estuarine mouth (station 1), whereas species *Bestiola similis* and *Pseudodiaptomus annandalei* were common in the southern estuary (Table 4).

The monsoonal rain brings in a drastic shift in the mesozooplankton community in the CBW, lowering the copepod density (av. 254 ind.m⁻³) and number of species (3). *Acartiella gravelyi* (av. >1000 ind.m⁻³) appeared during this season, along with *Pseudodiaptomus binghami malayalus* (Table. 4). Post monsoon was mainly characterized by the dominance (av. <1000 ind.m⁻³) of *Acartia tropica* and *Acartia bilobata*, but other species (*Acartia bowmani*, *Pseudodiaptomus tollingerae*, *Paracalanus crassirostris* and *Paracalanus aculiatu*s) were also present in less numbers (Table. 4).

Despite the fact that decapods and fish larvae were widely distributed, their densities were low (av. <5 ind. m⁻³) when compared to that of the copepods. However, a substantial increase in decapod larvae (29896 ind. m⁻³) was observed at station 5 during premonsoon season (94.5% of the total density). The amphipod community was also high in fresh water regions (stations 3, 4 & 8). Other groups (sergistides, cladocerans, siphonophores and mysids) formed 5.4%, 1.9% and 10.9% of the total mesozooplankton density during premonsoon, monsoon and post monsoon periods, respectively. Three major mesozooplankton groups were identified from Bray-Curtis analysis with >80% similarity irrespective of seasons (Fig. 5d). Group II comprised of seven stations with maximum density (av. 10424

$\pm 14110.7 \text{ ind.m}^{-3}$), while group III represented 11 stations (density $166.1 \pm 135.1 \text{ ind.m}^{-3}$) and group I comprised low densities (av. $9.9 \pm 4.2 \text{ ind.m}^{-3}$) in the fresh water zone.

4. Discussion

The present observations bring out the seasonality in the environmental behavior of CBW controlled by the monsoon-induced fresh water flow. With the onset of summer monsoon, substantial increase in river discharge following rains (June - 613mm & July - 536mm) performs a clean up of the estuary, completing the seasonal cycle (Shyanamma & Balakrishnan, 1973; Menon et al., 2000). The heavy rainfall and intense cloud cover during this period reduces solar radiation and the massive input of suspended materials makes the estuary fairly turbid (Fig. 2c). During premonsoon season, dry weather prevails over the region and with a considerably reduced fresh water flow (1.69%, Srinivas et al., 2003), the estuary becomes warmer due to high solar radiation ($500 - 580 \text{ gcal cm}^{-2}\text{d}^{-1}$, Qasim, 2003). The increase in solar radiation and reduction in turbidity (due to low run off) subsequently reduces the light attenuation (k_e ; av. 1.2 ± 0.2) of the water column.

This study has also evidenced large input of nutrients into the estuary irrespective of seasons, mainly originated from domestic sewage and industrial effluents (Unnithan et al., 1975). The increased human settlement around the estuary was mainly responsible for the escalation in the domestic as well as industrial wastes into CBW (Vijayan et al., 1976; Qasim, 2003). The elevated levels of dissolved inorganic nitrogen (DIN) observed in the present study (monsoon av. $57.5 \pm 25.8 \mu\text{M}$ and postmonsoon av. $62.4 \pm 50.2 \mu\text{M}$) confirm the above finding. The high N:P ratio (monsoon av. 39.8 ± 28.2 and postmonsoon av. 57.9 ± 33.6) also indicate the excess loading of N into the estuary. When tidal activities dominate during premonsoon, the system probably reverts back to normalcy, as the primary nutrients reaches the Redfield ratio (N:P 15.9 ± 10.1). This indicates that in CBW, the nutrients are available in surplus and they do not limit the growth of phytoplankton at any time of the year (Sankaranarayanan and Qasim, 1969; Saraladevi et al., 1983; Balachandran et al., 2005).

The high concentration of chlorophyll a ($>20 \text{ mgm}^{-3}$) observed at few stations (2, 7 & 8) was primarily due to the massive growth of nano plankton ($<20 \mu$ diatom).

The productivity pattern in CBW has shown that nano plankton contributes a major portion (~60%) of the phytoplankton standing stock (Qasim et al., 1974). The abundance of nano plankton such as *Skeletonema costatum*, *Thalassiosira subtilis* and *Nitzschia closterium* throughout the year, provides a valid support to the above finding (Table 1). Diatoms (eg. *Skeletonema costatum*) are conventionally considered as a euryhaline and eurythermal phytoplankton species, which grow quickly under eutrophic conditions (Huang et al., 2004). On the other hand, dinoflagellates mostly prefer oligotrophic waters and hence, fail to survive in eutrophic waters by competing with diatoms (Menzel et al., 1963; Cushing, 1989). This was found to be true in the present study, as the dinoflagellate community was relatively less in abundance in the estuary throughout the year as compared to the diatoms.

The significant abundance in zooplankton standing stock was found to be chiefly associated with salinity, because CBW becomes an arm of the adjoining sea during premonsoon, supporting the entry of many marine zooplankton populations into the estuary (Pillai et al., 1973; Madhupratap, 1987). The high density and dominance of marine species (both micro- and meso) from the present study is evidence to their invasion into the estuary during this season. With the commencement of monsoon, the sharp drop in the salinity causes a severe desertion of zooplankton community in the estuary (Tables 3&4). Furthermore, experimental studies in CBW have revealed that microzooplankton consumes ~43% phytoplankton biomass in a day (Jyothibabu et al., 2006). Hence, the increased grazing of phytoplankton by microzooplankton would be one of the reasons for a relatively low level of chlorophyll *a* during premonsoon season, even though the environmental conditions remained conducive for maximum phytoplankton growth. The *Tintinnopsis* present during premonsoon are phytoplankton grazers which survive both in the estuarine and coastal waters (Krinsic, 1987; Gifford, 1988; Jyothibabu et al., 2006).

Besides contributing 60 - 94% of the mesozooplankton community, copepod showed strong seasonality in abundance and diversity suggesting their significant role in the trophic food web of CBW. Studies in CBW have shown that most of the copepods are either herbivorous or omnivorous species (Madhupratap, 1979). The dominance of high saline copepod species such as *Labidocera pectinata*, *Paracalanus crassirostris*, *Acartia centrura*, *Acartia spinicauda* and, *Centropages*

alcocki are indicative of their origin from the coastal waters. Moreover, most of them are opportunistic in their behavior, as they virtually disappear during rainy season (Madhupratap, 1987). The presence of *Acartiella gravelyi* and *Pseudodiaptomous binghami malayalus* indicates their salinity tolerance during monsoon. The increase in copepod density during premonsoon season could be also suggestive of their active grazing of phytoplankton independently or in combination with microzooplankton because the herbivorous copepods are capable of grazing up to 75% of the phytoplankton in a tropical estuary (Tan et al., 2004).

The regression analysis showed that salinity and inorganic nutrients does not provide any significant correlation with phytoplankton, whereas the zooplankton (both micro- and meso) showed a significant positive correlation with salinity ($P < 0.01$, Table 6). It reveals that salinity is the major factor controlling the distribution of zooplankton in CBW. The two-way ANOVA test also indicated a large seasonal variation for microzooplankton ($F = 20.68$; $P = 0.003$) and mesozooplankton ($F = 9.5$, $P = 0.002$), whereas chlorophyll *a* did not show any correlation (Table 5). The MDS analysis also indicated similarity of stations based on salinity and phytoplankton (Figs 5a-d, stress < 0.01). A stress value < 0.05 generally represents an excellent similarity (Kibirige and Perissinotto, 2003).

The present study did not make any primary productivity measurements, but it is noticed that primary production in CBW is maximum at the surface during monsoon and postmonsoon seasons, while during premonsoon season, it covers subsurface layers also (Qasim et al., 1969). Hence, it is assumed that the production of phytoplankton in the estuary exceeds zooplankton by several folds (Atkinson & Shreeve, 1995; Cushing, 1958). It can be seen from the Table 8 that the average carbon content in phytoplankton and zooplankton (P/Z) was relatively low (4.3 ± 3.6) during premonsoon, which increased to 100.9 ± 124.3 & 224.4 ± 102.6 during monsoon and postmonsoon respectively. An increase during the postmonsoon season can not be explained because of the non-availability of microzooplankton data. Since the zooplankton collections were made during day time, their vertical migration during night was not considered and this could have lead to an underestimation of the actual zooplankton biomass in CBW. In that case, the actual P/Z value might be even lesser than that obtained from the present study. The increase in the P/Z ratio during monsoon suggests that much of the phytoplankton is

left unconsumed in the system due to the lack of herbivorous zooplankton. Moreover, the inconsistent P/Z ratio reflects the variable grazing with changing seasons, primarily influenced by the monsoon-induced hydrology. Nevertheless, the surplus phytoplankton is possibly used by other members (herbivorous fishes) and when settled to the bottom, is effectively consumed by benthic fauna, supporting an alternate pathway of food chain (Qasim, 1970).

In conclusion, studies including diurnal variability of zooplankton are required to understand their actual biomass and dynamics. Similarly, a more concerted effort to understand grazing of phytoplankton by micro and mesozooplankton and estimation of phytoplankton pigments by latest technique (HPLC) can bring out more information about this eutrophic estuary.

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Table 1. Average density (No.x 10³ cells L⁻¹) of major phytoplankton species in the CBW

| Group | Seasons | | |
|---------------------------------------|------------|---------|--------------|
| | Premonsoon | Monsoon | Post monsoon |
| Bacillariophyceae (Diatoms) | | | |
| <i>Skeletonema costatum</i> | 136.00 | 113.63 | 50.41 |
| <i>Coscinodiscus</i> sp. | 33.86 | 4.99 | 10.49 |
| <i>Leptocylindrus danicus</i> | 7.56 | 5.14 | 19.29 |
| <i>Rhizosolenia</i> sp. | 0.26 | - | - |
| <i>Chaetoceros</i> sp. | 0.26 | - | - |
| <i>Eucampia</i> sp. | 0.51 | - | - |
| <i>Triceratium</i> sp. | 0.38 | 0.28 | 0.27 |
| <i>Fragilaria</i> sp. | 0.29 | - | - |
| <i>Synedra</i> sp. | 89.14 | 49.28 | 1.78 |
| <i>Thalassionema nitzschioids</i> | 0.32 | 7.63 | - |
| <i>Cocconeis</i> sp. | 48.89 | 13.86 | 2.56 |
| <i>Thalassiosira</i> sp. | 88.44 | 323.75 | - |
| <i>Pleurosigma</i> sp. | 0.18 | 1.88 | 2.11 |
| <i>Amphora</i> sp. | 0.14 | - | - |
| <i>Navicula</i> sp. | 16.78 | 12.65 | 1.33 |
| <i>Nitzschia closterium</i> | 264.62 | - | 9.49 |
| <i>Diploneis smithi</i> | - | - | 0.22 |
| Pyrrophyceae (Dinoflagellates) | | | |
| <i>Dinophysis caudate</i> | - | - | 0.22 |
| <i>Peridinium</i> sp. | 1.69 | 13.68 | 7.87 |
| <i>Gonyaulax</i> sp. | 1.60 | 2.00 | 6.56 |
| <i>Ornithocercus</i> sp. | 0.60 | - | - |
| <i>Ceratium furca</i> | 0.60 | 0.29 | 0.47 |
| Others | 9.00 | 5.47 | 10.91 |

Table 2. Average density (ind. L⁻¹) of major microzooplankton groups in the CBW

| <i>Group</i> | <i>Pre monsoon</i> | <i>Monsoon</i> |
|----------------------------------|--------------------|----------------|
| Loricates | | |
| <i>Tintinnopsis</i> sp. | 1682 | 962 |
| <i>Tintinnidium incertum</i> | 105 | 80 |
| <i>Leprotintinnus simplex</i> | 233 | 78 |
| <i>Dityocysta sehahai</i> | 100 | 45 |
| <i>Epiplocytilis undella</i> | 68 | 35 |
| Aloricates | | |
| <i>Euplotes</i> sp. | 369 | 274 |
| <i>Eutintinnus lusus undae</i> | 88 | - |
| <i>Stylonychia mytilus</i> | - | 5 |
| <i>Oxytricha marina</i> | - | 23 |
| <i>Lohmaniella</i> sp. | 118 | 60 |
| <i>Halteria chlorelligera</i> | 33 | - |
| <i>Strombidium bilobum</i> | 216 | 59 |
| <i>Rimostrombidium</i> sp. | 118 | 43 |
| <i>Strobilidium minimum</i> | 148 | 78 |
| <i>Strombidinopsis cheshirii</i> | 55 | 58 |
| Dinoflagellates | | |
| <i>Protoperidinium</i> sp. | 218 | 96 |
| Crustacean larvae | 257 | 55 |

Table 3. Average density (ind.m⁻³) of major mesozooplankton groups in the CBW

| Group | Premonsoon | Monsoon | Post monsoon |
|--------------|------------|---------|--------------|
| Hydromedusae | 5 | - | - |
| Polychaeta | 4 | - | - |
| Cladocera | 3 | 2 | 1 |
| Ostracoda | 15 | - | - |
| Amphipoda | 10 | 6 | 4 |
| Copepoda | 4457 | 254 | 40 |
| Decapoda | 3974* | 3 | 6 |
| Fish eggs | 6 | - | - |
| Fish larvae | 2 | 3 | 1 |
| Others | 42 | 2 | 2 |

* - Abundant only at station 5

Table 4. Major copepod species in the CBW during premonsoon, monsoon and post monsoon seasons

| Species | Premonsoon | Monsoon | Post monsoon |
|-------------------------------------|------------|---------|--------------|
| <i>Acartia centrura</i> | ++ | - | + |
| <i>A. bowmani</i> | + | - | + |
| <i>A. spinicauda</i> | ++ | - | - |
| <i>A. tropica</i> | + | - | ++ |
| <i>A. bilobata</i> | + | - | ++ |
| <i>A. southwelli</i> | + | - | - |
| <i>A. pecifica</i> | + | - | - |
| <i>A. plumosa</i> | + | - | - |
| <i>Acartiella keralensis</i> | + | - | - |
| <i>A. gravelyi</i> | - | +++ | - |
| <i>Pseudodiaptomus serricaudata</i> | + | - | - |
| <i>P. jonesi</i> | - | - | + |
| <i>P. aurivilli</i> | + | - | - |
| <i>P. annandalei</i> | ++ | - | - |
| <i>P. bingami malayalus</i> | - | ++ | - |
| <i>P. tollingerae</i> | - | - | + |
| <i>Paracalanus crassirostris</i> | ++ | - | + |
| <i>P. aculeatus</i> | - | - | + |
| <i>Centropages alcocki</i> | ++ | - | - |
| <i>Labidocera pectinata</i> | +++ | - | - |
| <i>Bestiola similis</i> | ++ | - | + |
| <i>Oithona brevicornis</i> | ++ | - | - |
| <i>Corycaes sp.</i> | ++ | - | - |

+++ highly abundant ($>1000\text{ m}^{-3}$), ++ moderately abundant ($100 - 1000\text{ m}^{-3}$), + presence ($1-100\text{m}^{-3}$), - absence)

Table 5. Diversity indices (H') and species richness (parenthesis) of phytoplankton and microzooplankton

| Stations | Phytoplankton | | | Microzooplankton | |
|----------|---------------|-------------|-------------|------------------|-----------|
| | Pre | Mon | Post | Pre | Mon |
| 1 | 2.22 (1.52) | 1.62 (0.82) | 2.39 (1.14) | 4.8 (3.7) | 2.8 (1.1) |
| 2 | 2.23 (0.62) | 1.94 (0.69) | 1.51 (0.41) | 3.9 (2.2) | 0.5 (0.8) |
| 3 | 2.08 (0.65) | 2.01 (0.48) | 1.87 (0.37) | 3.2 (1.3) | 1.6 (0.3) |
| 4 | 1.37 (0.23) | 0.49 (0.08) | 0.57 (0.25) | 3.3 (1.4) | 1.0 (0.2) |
| 5 | 1.55 (0.45) | 2.55 (0.66) | 1.74 (0.46) | 4.2 (3.8) | 2.2 (0.7) |
| 6 | 1.82 (0.53) | 1.52 (0.57) | 2.09 (0.50) | 4.8 (3.6) | 3.0 (1.1) |
| 7 | 1.41 (0.16) | 0.86 (0.47) | 1.90 (0.32) | 4.8 (3.6) | 2.2 (0.6) |
| 8 | 2.14 (0.54) | 0.08 (0.41) | 1.87 (0.34) | 3.8 (1.9) | 0.9 (0.2) |
| 9 | 0.81 (0.30) | - | 1.97 (0.46) | - | - |

Table 6. Regression coefficient of major environmental parameters and various plankton density and biomass

| Variables | Temperature | Salinity | NH ₄ | NO ₃ | PO ₄ | SiO ₃ |
|----------------------|-------------|----------|-----------------|-----------------|-----------------|------------------|
| Chlorophyll a | 0.262 | 0.055 | 0.077 | 0.095 | 0.032 | 0.055 |
| Phyto. total density | 0.141 | 0.055 | 0.200 | 0.224 | 0.077 | 0.054 |
| Micro. biomass | 0.678* | 0.917* | - | - | - | - |
| Micro. density | 0.700* | 0.963* | - | - | - | - |
| Meso. biomass | 0.513* | 0.818* | - | - | - | - |
| Meso. density | 0.281 | 0.522* | - | - | - | - |

* significant at 0.01 level

Table 7. Two-way ANOVA show the variation between stations and between seasons (in parenthesis) in the CBW. Degree of freedom (d.f), F statistic and probability (P). ^{**} Calculated F is significant at 5% level (P<0.05)

| Parameters | d.f | F | P- value |
|--|------------|--------------|-----------------|
| Temperature (°C) | 7 (1) | 0.89 (1.95) | 0.566 (0.205) |
| Salinity | 7 (1) | 1.12 (4.51) | 0.442 (0.071) |
| Light attenuation coefficient (m ⁻¹) | 7 (1) | 1.09 (1.33) | 0.454 (0.286) |
| DO (ml L ⁻¹) | 7 (1) | 2.02 (3.47) | 0.188 (0.105) |
| pH | 7 (1) | 0.95 (1.38) | 0.524 (0.278) |
| Ammonia (μM) | 7 (1) | 1.16 (0.44) | 0.420 (0.530) |
| Nitrate (μM) | 7 (1) | 3.43 (0.22) | 0.063 (0.655) |
| Phosphate (μM) | 7 (1) | 5.76 (1.45) | 0.017* (0.278) |
| Silicate (μM) | 7 (1) | 3.94 (1.67) | 0.046* (0.237) |
| Chlorophyll a (mg m ⁻³) | 8 (2) | 1.28 (2.53) | 0.321 (0.111) |
| Microzooplankton biomass (mg C m ⁻³) | 7 (1) | 1.34 (20.68) | 0.353 (0.003)* |
| Mesozooplankton biomass (mg C m ⁻³) | 8 (2) | 1.01 (9.50) | 0.469 (0.002)* |

Table 8. Average carbon content (mgC m⁻³) in phytoplankton, microzooplankton and mesozooplankton in the CBW during different seasons (ND - No Data)

| Group | Premonsoon | Monsoon | Post monsoon |
|------------------|------------|-----------|--------------|
| Phytoplankton | 441 ± 363 | 868 ± 729 | 293 ± 134 |
| Microzooplankton | 81 ± 48 | 10 ± 5 | ND |
| Mesozooplankton | 88 ± 125 | 1.2 ± 1 | 1.2 ± 0.7 |

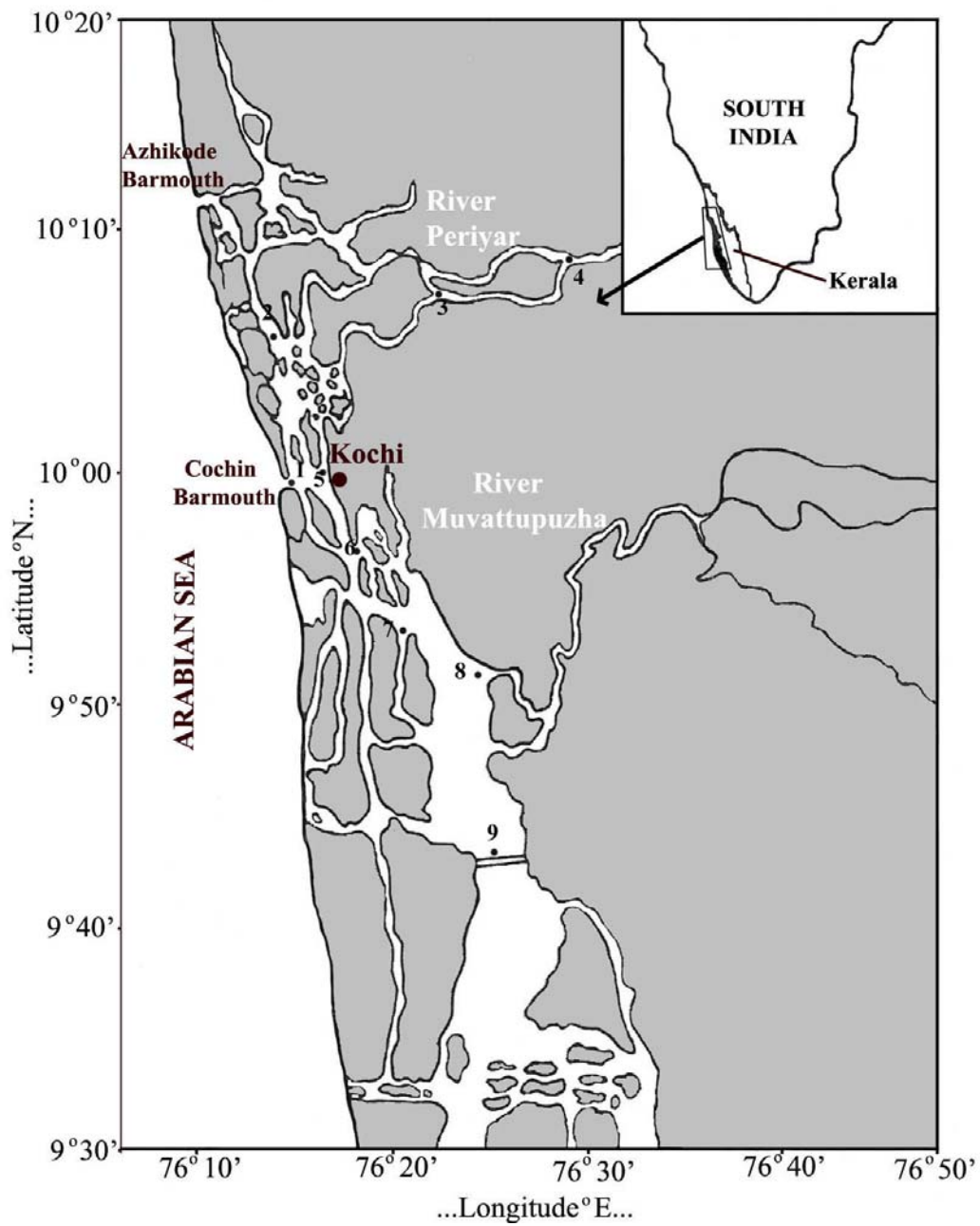


Figure 1. Station location

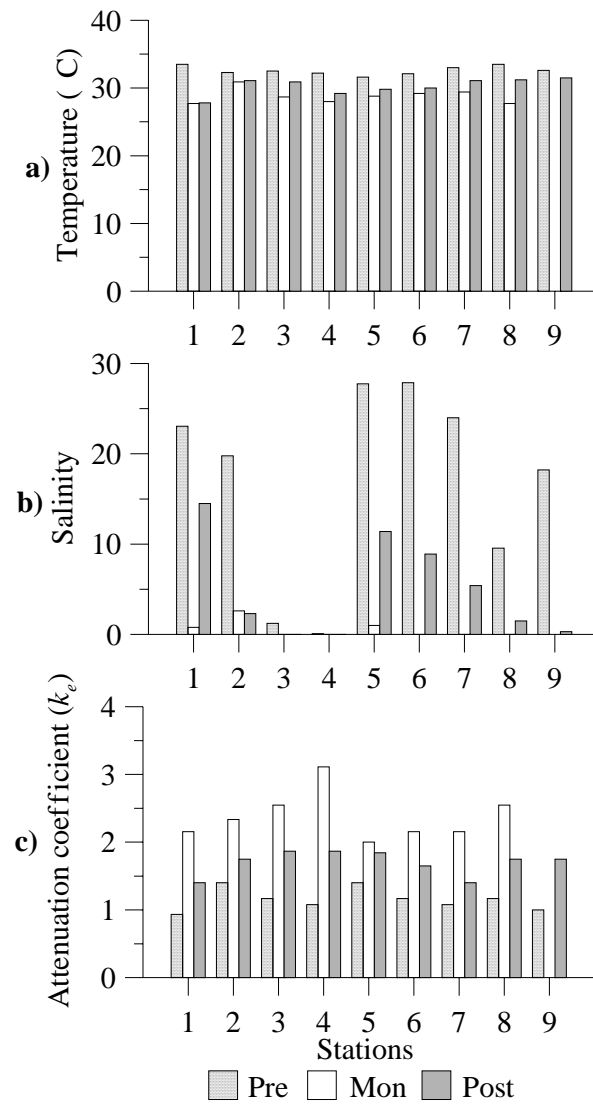


Fig. 2. Distribution of temperature (°C), salinity and light attenuation coefficient (k_e) during premonsoon, monsoon and post monsoon seasons

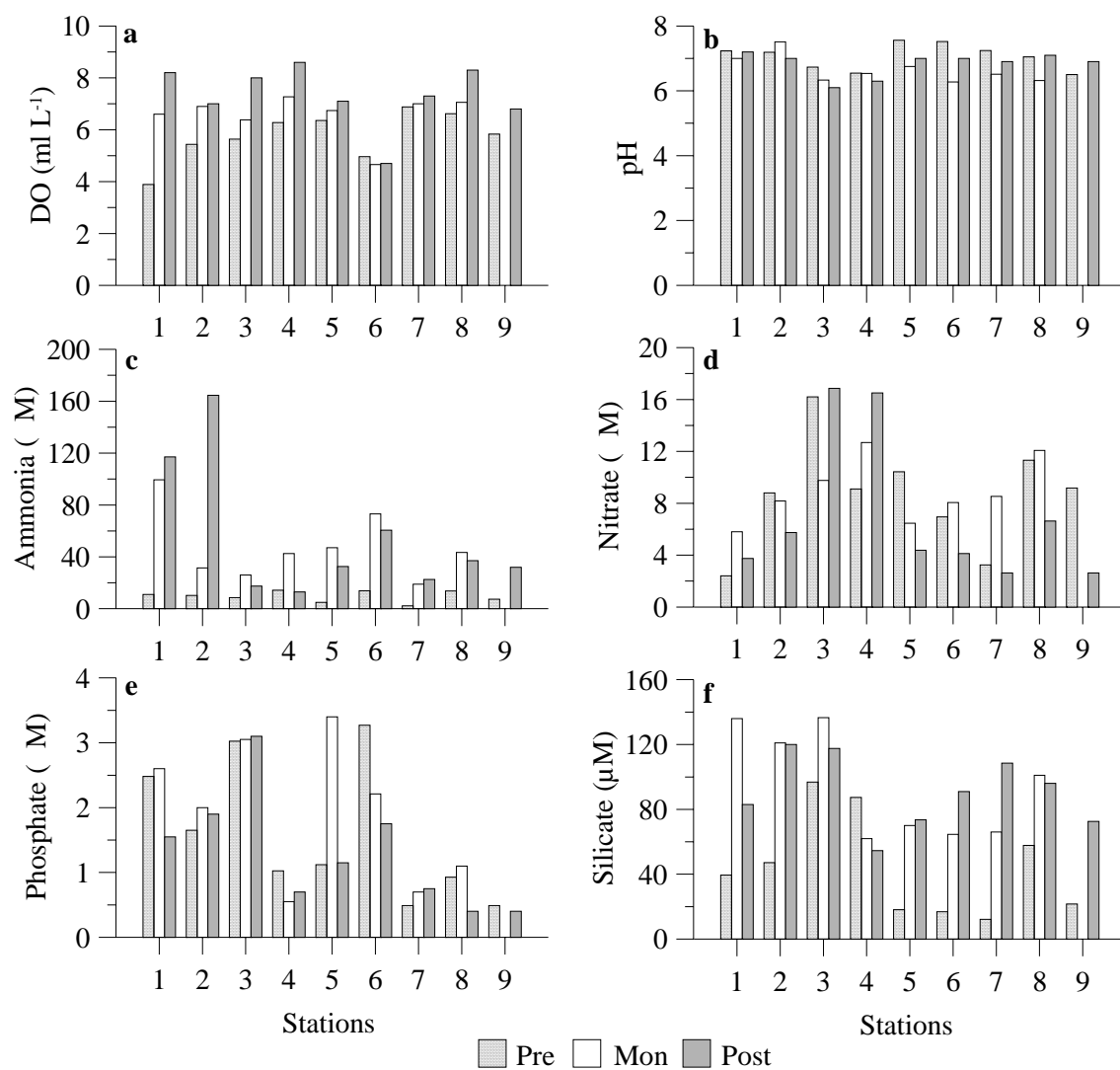


Fig. 3. Distribution of major chemical parameters during premonsoon, monsoon and post monsoon seasons

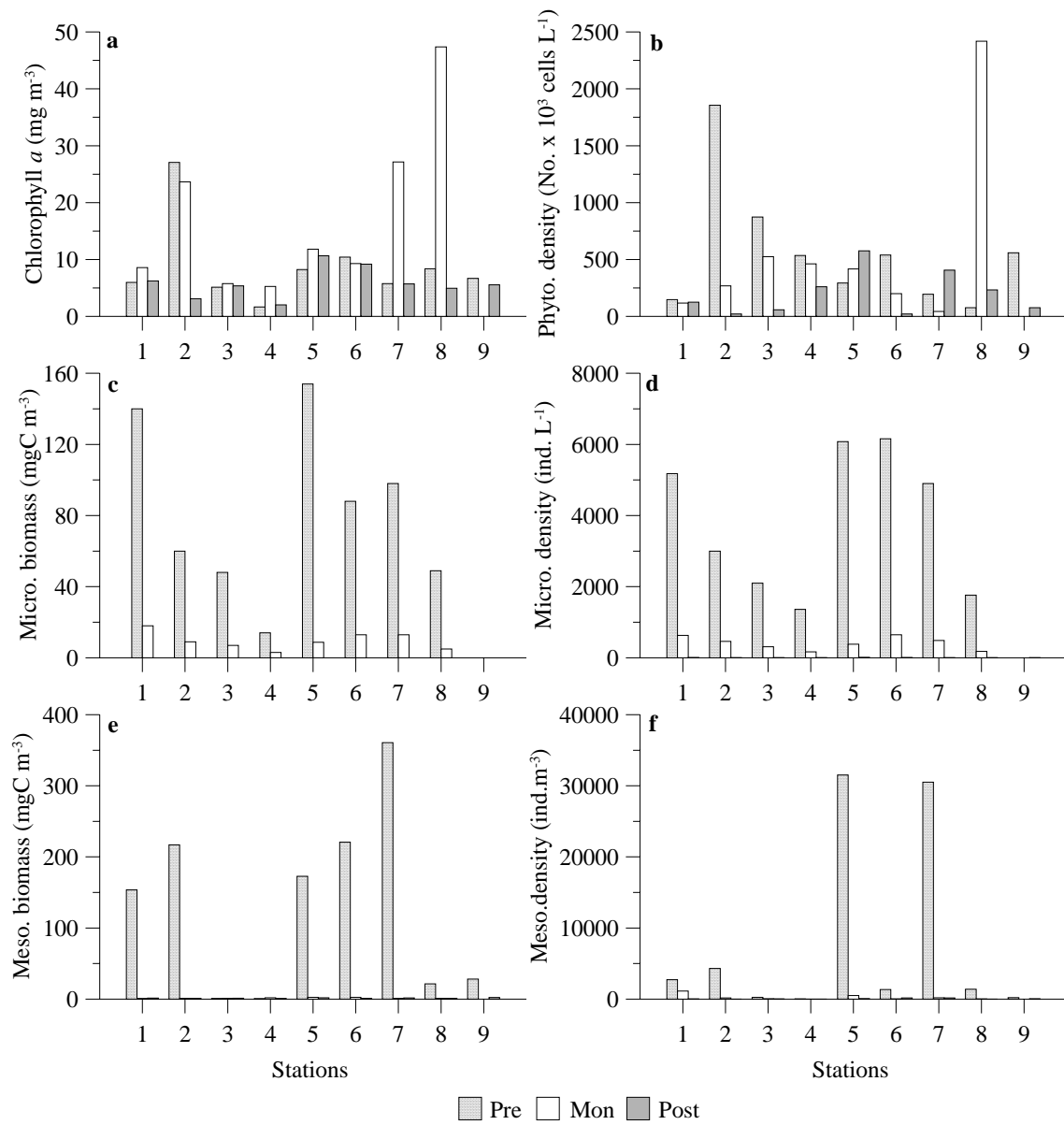


Fig. 4. Distribution of various plankton biomass and density during premonsoon, monsoon and post monsoon seasons

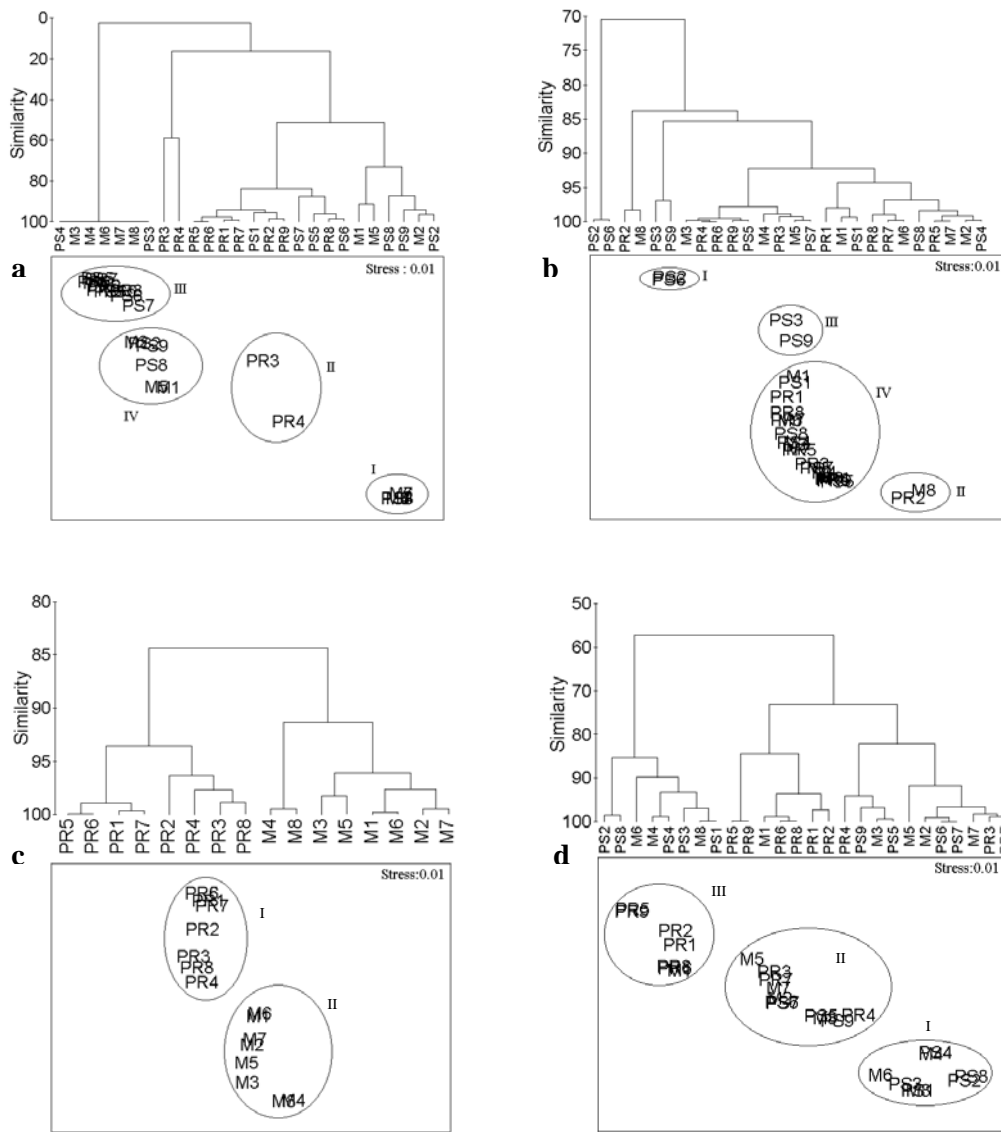


Fig. 5. Cluster and MDS analyses showing similarity of stations during the study period based on a) salinity, b) phytoplankton density, c) microzooplankton density and d) mesozooplankton density (PR-premonsoon, M- monsoon & PS-post monsoon).