

## **Short-term variability of water quality and its implications on phytoplankton production in a tropical estuary (Cochin backwaters - India)**

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### **Abstract**

Changes in the phytoplankton biomass (chlorophyll *a*), production rate and species composition were studied over two seasons using the time series measurements in the northern limb of the Cochin estuary in relation to the prevailing hydrological conditions. The present study showed the significant seasonal variation in water temperature ( $F = 69.4$ ,  $P < 0.01$ ), salinity ( $F = 341.93$ ,  $P < 0.01$ ), dissolved inorganic phosphorous ( $F = 17.71$ ,  $P < 0.01$ ) and silica ( $F = 898.1$ ,  $P < 0.01$ ) as compared to nitrogen ( $F = 1.646$ ,  $P > 0.05$ ). The uneven input of ammonia ( $3.4 - 224.8 \mu\text{M}$ ) from the upstream (from Periyar River) leads the inconsistency in the N:P ratio (range 6.8 - 262). The distinct seasonality was observed in Si:N ( $F = 382.9$ ,  $P < 0.01$ ) and Si:P ( $F = 290.3$ ,  $P < 0.01$ ) ratios as compared to the N:P ratio ( $F = 1.646$ ,  $P > 0.05$ ). The substantial increase in chlorophyll *a* (av.  $34.8 \pm 10 \text{ mgm}^{-3}$ ) and primary production (av.  $1304 \pm 694 \text{ mgC m}^{-3}\text{d}^{-1}$ ) were indicated the mesotrophic condition of the study area during the pre-monsoon and it was attributed by the large increase in the population of nanoplankton (size  $< 20\mu$ ) such as *Skeletonema costatum*, *Thalassiosira subtilis*, *Nitzschia closterium* and *Navicula directa*. In contrast during the post monsoon, prevalence of less chlorophyll *a* concentration (av.  $9.3 \pm 9.2 \text{ mgm}^{-3}$ ) and primary production (av.  $124 \pm 219 \text{ mgC m}^{-3}\text{d}^{-1}$ ) showed the predominance of heterotrophic condition. It can be stated that the preponderance of favourable environmental conditions (optimum nutrients and light intensity) prevailing during the pre-monsoon have been enhanced the abundance of nanoplankton community in the estuary, whereas during post monsoon, the light limitation due to high turbidity can reduces the nanoplankton growth and abundance, even though high nutrient level exists.

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Key words: -Nutrients; N:P ratio; Phytoplankton; Primary production; India; Cochin estuary

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## 1. Introduction

In any aquatic environment, phytoplankton growth and abundance are primarily regulated by both abiotic and biotic interactions (Sin et al., 1999). Among abiotic interactions, the fresh water influence and tidal activity can play crucial roles on phytoplankton growth and abundance in the estuary (Cloern, 1996). The constant nutrient supply always supports the rich phytoplankton production, but generally nitrogen (N) and phosphorous (P) have been considered as the potentially limiting nutrients for phytoplankton growth in the aquatic ecosystems (EEA, 1999; Neill, 2005). Phosphorous is being attributed as limiting nutrient in the fresh water dominated waters, whereas Nitrogen is being attributed in the coastal waters (Neill, 2005; Fisher et al., 1992). In polluted waters, inorganic ammonia ( $\text{NH}_4^-$ ) plays a significant role in the phytoplankton growth (EEA, 1999). In addition to nutrients, physical properties such as salinity (McLusky, 1971), turbidity and light availability (Cloern, 1987) are also found to play major roles in the regulation of phytoplankton growth and their distribution in the estuaries.

Cochin estuary (hereafter CE) is one of the largest estuarine systems ( $256 \text{ km}^2$ ) in the west coast of India, known for high biological production and plankton diversity (Menon et al, 2000; Qasim, 2003). This tropical estuary is highly influenced by the seasonally occurring monsoon driven rainfall and associated run off (Qasim, 2003), which results in dramatic changes in the overall functioning of the trophic food web (Jyothibabu et al., 2006; Madhu et al., 2007). Over the last three decades, due to various anthropogenic activities, inputs of inorganic nutrients into the estuary have been increased tremendously in the form of untreated industrial ( $0.104 \times 10^6 \text{ m}^3\text{d}^{-1}$ ) and domestic ( $0.26 \times 10^3 \text{ m}^3\text{d}^{-1}$ ) effluents (CPCB, 1996; Martin et al., 2008). This has made the system in extremely polluted condition (Miranda et al., 2008) by altering the nutrient ratios (Martin et al., 2008), which in turn, facilitates changes in the trophic functioning and entire biogeochemical processes of the estuary (Shoji et al., 2008).

Even though several works have been carried out in the CE mentioning the long term changes of physico-chemical (Sankaranarayanan and Qasim 1969; Srinivas et al., 2003) and biological characteristics (Menon et al., 2000; Qasim, 2003), no systematic studies have been reported pertaining to the short-term changes of environmental variables, that stimulate the biological processes in the estuary. Due to its extremely dynamic nature by the tidal activity, phytoplankton production in the CE is highly influenced by the short-term changes in the physico- (temperature, salinity, suspended particulate matter), chemical (dissolved oxygen, pH & nutrients) properties. Since the monsoonal rainfall controls the dynamics of the CE (Madhu et al., 2007), the seasonal variations on phytoplankton characteristics with respect to the changing salinity is very important in the overall functioning of the food web (Jyothibabu et al., 2006) and related biogeochemical

processes (Shoji et al., 2008). In this paper, we discussed (1) the short-term changes in the physico-chemical properties of the northern limb of the Cochin estuary, (influenced by the riverine as well as marine waters) based on time series measurements before and after the southwest monsoon rainfall (pre-monsoon and post monsoon), and also (2) examine its impact on phytoplankton biomass, production and abundance.

## **2. Materials and Methods**

### *2.1. Study area*

The Cochin backwaters forms a complex network of shallow brackish water running parallel to the coast (9° 40' & 10° 12'N and 76° 10' & 76° 30'E), with two permanent openings to the Arabian Sea (Fig. 1). The depth of the estuary varies from 2 to 7 m, but the ship channel at the Cochin harbour region are dredged and maintained at 10 to 13 m (Qasim, 2003). Constant mixing with seawater through tidal exchanges has given backwaters the characteristics of a tropical estuary (Balchand & Nair, 1994; Ajith and Balchand, 1996) and it is used extensively for fishing, local transport of goods and also as an outlet for industrial and domestic wastes (Menon et al., 2000). Six major rivers discharge ca. 20000 x 10<sup>6</sup> m<sup>3</sup> of fresh water annually (Srinivas, 2003). The annual rainfall in the Cochin area is about 3.2 m, with considerable variations from year to year and also ~75% of the total rainfall occurs during the monsoon period, from May or early June to September (Qasim, 2003). With the onset of monsoon, within the course of few weeks, hydrographic conditions in the estuary undergoes remarkable changes due to the fresh water discharge and after that, the system gradually changes into brackish water and marine conditions (Menon et al., 2000).

### *2.2. Sampling strategy*

Time series observations were conducted at the northern limb of the CE during October 2003 (post monsoon, with high river flow) and March 2004 (pre-monsoon, with low river flow) as a part of the project 'Ecosystem modelling of Cochin backwaters'. Totally 5 stations (Fig. 1) were selected within a stretch of ~5 km with a distance ~1 km between each station. Water samples were collected using a small power boat from 0.5 m below the surface and from 2 m depth of these stations at 3 (physico-chemical parameters) and 6 (biological parameters) hourly intervals and for 30 hour period on 4 occasions, each during post monsoon and pre-monsoon periods.

### *2.3. Methods*

The water samples were collected using 5 litre Niskin bottles. The samples for dissolved oxygen (DO) were fixed onboard and the remaining water samples were collected in 2 litre PVC bottles kept in the ice boxes and brought to the laboratory at the earliest. Suspended particulate

matter (SPM,  $\text{mgL}^{-1}$ ) was determined gravimetrically on Millipore membrane filters (pore size 0.45  $\mu\text{m}$ ) after drying at 70°C for 6-8 hours to reduce water content before weighing. Salinity was determined using a Digi Auto Salinometer (Model TSK, accuracy  $\pm 0.001$ ) and the pH using an ELICO LI 610 pH meter (accuracy  $\pm 0.01$ ). Dissolved oxygen (DO) was estimated according to Winkler's method (Grasshoff, 1983). Samples for nutrients (ammonia, nitrate, nitrite, phosphate and silicate) were analysed following the standard methods (Grasshoff, 1983).

For the estimation of chlorophyll *a*, 250 ml of water sample was filtered through GF/F filters (nominal pore size - 0.7  $\mu\text{m}$ ) and extracted with 90% acetone for 24 hours kept in the freezer. The extinction was measured using a spectrophotometer (Model - UV 1650PC, Shimadzu) before and after acidification (Parsons et al., 1984). Primary production was estimated by *in-situ* method using the  $^{14}\text{C}$ -technique (Parsons et al., 1984). Water samples at stations 1 and 4 were collected before the sunrise, immediately passed through 200 $\mu$  sieve to remove large sized zooplankton and transferred to 300 ml capacity Nalgene bottles (3 light bottles and 1 dark bottle). For estimating nanoplankton production, another portion of water samples were passed through 20 $\mu$  sieve and filled the Nalgene bottles as mentioned above. After the inoculation of 1 ml of  $\text{NaH}^{14}\text{CO}_3$  (activity 5  $\mu\text{C}$ ) solution, the light and dark bottles were deployed in a mooring system at respective depths for 12 hours for incubation. The experiments were terminated by filtering the samples on to 47mm Whatman GF/F filters and the filters were used for subsequent analysis in liquid scintillation counter after treatment with HCl fumes to remove inorganic carbon. The primary production rate was calculated according to the equation described in the protocol (Parsons et al., 1984). For qualitative and quantitative studies of phytoplankton, 1L of water sample was taken and fixed with few drops of acid Lugol's Iodine solution. After the settling and siphoning procedure, 1 ml of the aliquot of the sample were taken in a Sedgewick-Rafter counting cell in duplicate under the inverted microscope (OLYMPUS, C.K-30) for identifying and counting the phytoplankton cells (Tomas, 1997).

#### 2.4. Data analysis

Two-way analysis of variance (ANOVA) was used to calculate the seasonal variation in different physico-chemical and biological parameters. Also, the Pearson correlation and multivariate regression analyses were performed to find out the linear relationship of chlorophyll *a* to various physico- (salinity & SPM) and chemical (pH, nitrate, nitrite, phosphate & silicate) parameters.

### 3. Results

#### 3.1. General hydrography

Water column remained relatively cool in the surface (av.  $29.2 \pm 1.4^\circ\text{C}$ ) and bottom (av.  $28.9 \pm 1.3^\circ\text{C}$ ) during the post monsoon (PM hereafter) as compared to the pre-monsoon (PRM hereafter);

surface -  $32.1 \pm 1.3^{\circ}\text{C}$ ; bottom -  $31.8 \pm 1.3^{\circ}\text{C}$ ; Figs. 2a-d). Salinity showed distinct seasonality, wherein a pronounced decline was noticed both in the surface (av.  $2.2 \pm 3.7$  psu) bottom waters (av.  $3.9 \pm 6.2$  psu) during the PM. Conversely, during the PRM, the increased seawater incursion results in substantial increase in salinity (surface av.  $21.3 \pm 5.2$  psu & bottom av.  $23.5 \pm 5.3$  psu), wherein a definite south to north decrease was discernible (Figs. 2g & h). During the 1<sup>st</sup> time series observation of the PM (1<sup>st</sup> week of October 2003), salinity was rather high (11.5 - 17 psu) in the southern limb (stations 1 & 2) as compared to the north (1 - 6 psu; Figs. 2e & f). But, soon after, estuary was purely fresh water (salinity <1) dominated (due to heavy rainfall) for the next two weeks. The distribution of suspended particulate matter (SPM) was found to be more or less similar in distribution with an average  $>40$  mg L<sup>-1</sup> observed during both the sampling period (Figs. 2i-l).

Like physical parameters, distinct spatial and temporal variations were observed in the distribution of chemical parameters as well. Relatively high concentration of DO was observed during the PM (surface -  $6.6 \pm 0.9$  ml L<sup>-1</sup> & bottom -  $6 \pm 1$  ml L<sup>-1</sup>) as compared to the PRM (surface -  $5.2 \pm 1.7$  ml L<sup>-1</sup> & bottom -  $4.4 \pm 1.5$  ml L<sup>-1</sup>; Figs. 3a-d). Generally the pH was slightly higher during the PRM (av.  $>7.5$ ) as compared to the PM (av.  $\leq 7.5$ ). Marked variations in pH were obvious towards the southern region during the PM, whereas during the PRM, it was more restricted towards the north (Figs. 3e-h).

Generally, the CE showed the moderate level of inorganic nutrients in the present study during both the seasons (Figs.3i-t). The total DIN ( $\text{NO}_3 + \text{NO}_2 + \text{NH}_4$ ) showed high values during both PM (av.  $45.2 \pm 28.2$   $\mu\text{M}$ ) and PRM (av.  $53.5 \pm 36.9$   $\mu\text{M}$ ), among these, ammonia has contributed 68.3 % (av.  $35.8 \pm 34.5$   $\mu\text{M}$ ) and 70.2 % (av.  $30.8 \pm 28.3$   $\mu\text{M}$ ) during the PM and the PRM respectively. Considering the seasonal average, a slight increase in nitrate was noticeable during the PM (av.  $15.8 \pm 6.1$   $\mu\text{M}$ ) as compared to the PRM (av.  $12 \pm 5.3$   $\mu\text{M}$ ), while nitrite was rather less (<1  $\mu\text{M}$ ) in the study area during both the sampling periods. The dissolved inorganic phosphorous (DIP) showed slight increase during the PM (av.  $2.6 \pm 1.2$   $\mu\text{M}$ ) as compared to the PRM (av.  $1.7 \pm 0.8$   $\mu\text{M}$ ; Figs. 3m-p). The concentration of dissolved inorganic silicate (DISi) was very high (av.  $107.4 \pm 27.4$   $\mu\text{M}$ ) in the present study during the PM, especially during the 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> observations (Figs. 3q & 3r). In contrast, a substantial reduction in silicate (<20  $\mu\text{M}$ ) could be noticed during the PRM (Figs. 3s & 3t).

The mean N:P ratios were well above (>25) the normal Red-field ratio (16) during both the seasons and also it seemed to be inconsistent throughout the area. The N:P ratios varied between 6.8 and 262 (surface av.  $28.4 \pm 34.1$ , N=140 & bottom av.  $26.4 \pm 29.2$ , N=140) during the PM, and 4.8 and 101 (surface av.  $32.3 \pm 21.3$ , N=140 & bottom av.  $24.6 \pm 16$ , N=140) during the PRM.

Compared to the Red-field ratio, the mean Si:P ratio was consistently high (>50) during the PM (surface av.  $57.5 \pm 49.5$ , N=140 & bottom av.  $50.6 \pm 43.3$ , N=140), whereas during the PRM, the concentration was low (surface av.  $15.7 \pm 15.9$ , N=140 & bottom av.  $12.5 \pm 13$ , N=140). Similarly, the Si:N ratio were also well above the Redfield ratio (1) during the PM (surface av.  $2.6 \pm 1.2$  & bottom av.  $2.4 \pm 1.2$ ), but in contrast, these values were less than the normal Red-field ratio during the PRM (surface av.  $0.5 \pm 0.3$  & bottom av.  $0.6 \pm 0.3$ ).

### 3.2. Chlorophyll *a* and primary production

Chlorophyll *a* exhibited seasonal variation (Table 1) with high values (surface av.  $34.8 \pm 10$   $\text{mgm}^{-3}$  & bottom av.  $31.1 \pm 10.7$   $\text{mgm}^{-3}$ ) during the PRM and low values (surface av.  $9.3 \pm 9.2$   $\text{mgm}^{-3}$  & bottom av.  $8.3 \pm 5.4$   $\text{mgm}^{-3}$ ) during the PM. In the 1<sup>st</sup> time series observation during the PM, chlorophyll *a* was fairly high (>20  $\text{mgm}^{-3}$ ) at stations 1, 2 & 3, where the seawater incursion was predominant. At the same time, towards the northern limb (stations 4 & 5, where riverine influx was more) chlorophyll *a* was less (<10  $\text{mgm}^{-3}$ ) and also during the 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> observations of the PM, the chlorophyll *a* was found to be rather low (av. <10  $\text{mgm}^{-3}$ ) throughout the area (Figs. 3u & 3v). In contrast, chlorophyll *a* concentrations were relatively high (av. >30  $\text{mgm}^{-3}$ ) in all the observations made during the PRM (Figs. 3w & 3x).

Due to the technical difficulties, the primary productivity experiments were limited to only two stations (stations 1 & 4). The results showed exceptionally high primary production (av.  $1304 \pm 694$   $\text{mgC m}^{-3}\text{d}^{-1}$ ) observed during the PRM with a maximum of  $2566$   $\text{mgC m}^{-3}\text{d}^{-1}$  (station 1, during the 2<sup>nd</sup> observation), whereas during the PM, the values seemed to be less (av.  $124 \pm 219$   $\text{mgC m}^{-3}\text{d}^{-1}$ ; Figs. 4a-d). In the bottom waters also primary production was rather less (<150  $\text{mgC m}^{-3}\text{d}^{-1}$ ) during the PM (Fig 4c). Similar to chlorophyll *a*, the 1<sup>st</sup> observation of the PM showed slightly high primary production (av.  $395$   $\text{mgC m}^{-3}\text{d}^{-1}$ ) as compared to the other three observations (<100  $\text{mgC m}^{-3}\text{d}^{-1}$ ). The size fractionated production showed the dominance of nanoplankton community (<20 $\mu$ ) during the PRM as they formed a major contribution (>70%) of the total phytoplankton production. The nanoplankton production was low and inconsistent (av. 37%) during the PM (Fig. 4a & 4c).

### 3.3. Phytoplankton abundance and composition

As regards phytoplankton, more than two fold increase in the total density was observed during the PRM ( $102.32 \times 10^3$  cells  $\text{L}^{-1}$  to  $115.1 \times 10^3$  cells  $\text{L}^{-1}$ ) as compared to PM ( $34.42 \times 10^3$  cells  $\text{L}^{-1}$  to  $45.39 \times 10^3$  cells  $\text{L}^{-1}$ ). Diatoms, in general formed the most abundant group (>90%) throughout the area irrespective of the seasons (Figs. 5a & 5b). Besides diatoms, other common groups such as dinoflagellates, green algae, blue green algae were also encountered (Table. 2). Among diatoms, species such as *Skeletonema costatum*, *Nitzschia closterium*, *Thalassiosira subtilis* and *Navicula directa* were the abundant (>10000 cells  $\text{L}^{-1}$ ) species during both the seasons.

However, the density of the corresponding species were found to be much higher during the PRM as compared to the PM (Figs. 5c & 5d). Diatoms such as *Coscinodiscus granii*, *C. lineatus*, *Nitzschia seriata*, *Pleurosigma elongatum*, *Amphiprora* sp., and dinoflagellates such as *Prorocentrum micans*, *Dinophysis caudata*, *Ceratium fusus* etc were also present in less numbers ( $<1000 \text{ cells L}^{-1}$ ; Table. 2). During the post monsoon, in addition to diatoms, blue green algae such as *Microcystis* sp., *Anacystis* sp., *Lyngbya* sp., *Nostoc* sp., *Rivularia* sp., *Spirulina* sp., etc and green algae such as *Chlorella* sp., *Eudorina* sp., *Pandorina* sp., *Pediastrum duplex* and *Volvox* sp., were also encountered ( $<1000 \text{ cells L}^{-1}$ ) with increasing density towards the northern limb.

#### 4. Discussion

Previous studies have been evidenced the importance of salinity on zooplankton distribution and abundance in the CE (Madhupratap, 1987; Qasim, 2003; Jyothibabu et al., 2006; Madhu et al., 2007). However, as far as phytoplankton growth and abundance is concerned, salinity variation alone does not affect much, as the estuary is usually found to be turbid (either due to the input of terrigenous materials from the land and river or sediment re-suspension due to tidal activity) which prevents requisite light for phytoplankton growth in the water column (Qasim et al., 1972). Generally the CE exhibits high chlorophyll *a* and primary production during the time of intermediate salinity (10-25 psu) conditions prevails. It has been experimentally proved by Qasim et al, (1972) with some phytoplankton culture, dominant in the estuary. Similarly, the occurrence of phytoplankton blooms *Nitzschia sigma* (in May), *Skeletonema costatum* (in November), *Ceratium furca* (in March), *Peridinium* sp. (in April) are common in the CE, when the intermediate salinity condition exists (Devassy and Bhattathiri, 1972). The increase in chlorophyll *a* (av.  $>30 \text{ mgm}^{-3}$ ) and primary production (av.  $>1000 \text{ mgC m}^{-3}\text{d}^{-1}$ ) observed during the PRM substantiates the above statements. During the PM, the apparent decrease in chlorophyll *a* and primary production (av.  $<5 \text{ mgm}^{-3}$  & av.  $<150 \text{ mgC m}^{-3}\text{d}^{-1}$ ) was more discernible in the low salinity regions ( $<5 \text{ psu}$ ), except during the 1<sup>st</sup> time series observation (where the chlorophyll *a* was  $>30 \text{ mgm}^{-3}$ ), wherein the salinity was slightly higher (8 - 17 psu). The linear correlation between the salinity and chlorophyll *a* was found to be more significant during the PRM ( $r = 0.577$ ,  $P < 0.01$ ,  $n = 280$ ), as compared to the PM ( $r = 0.270$ ,  $P < 0.01$ ,  $n = 280$ ; Figs. 6a & 6c). This indicates that to some extent the increase in salinity seems to accelerates the phytoplankton growth in the estuary even though the prevalence of significant seasonal variation in the salinity ( $F = 341.93$ ,  $P < 0.01$ ) persists (Table 1).

Since the CE carries large quantity of suspended materials in the form of detritus (large fall out of plant and animal material) and sediments (terrestrial and riverine origin) throughout the year, the resultant water column turbidity limits the light penetration in the euphotic zone (Qasim & Sankaranarayanan., 1972). This is primarily attributed by both autochthonous materials during the

PRM and allochthonous materials during the monsoon. High SPM observed during both the seasons (PRM - av.  $49.6 \pm 12.7 \text{ mg L}^{-1}$  & PM - av.  $43 \pm 19.7 \text{ mg L}^{-1}$ ), normally indicates the turbid condition of the estuary, which shows the lack of seasonality ( $F=11.25$ ,  $P>0.05$ ). Comparable values of light attenuation coefficients in the CE during the PRM (av.  $1.7 \pm 0.2 \text{ m}^{-1}$ ) and the monsoon (av.  $1.2 \pm 0.2 \text{ m}^{-1}$ ) seasons substantiates the above statement (Madhu et al, 2007). The increased chlorophyll *a* showed that the autochthonous (phytoplankton) materials formed the dominant fraction of SPM during the PRM, whereas the decrease in chlorophyll *a* during monsoon reveals the dominance of allochthonous (suspended sediments) materials in the SPM. Since the primary production is light limited in the estuaries (Cole et al., 1992; Heip et al., 1995), the SPM concentration between 10 and  $100 \text{ mg L}^{-1}$  is expected to suppress phytoplankton growth to certain extent (Peterson and Festa, 1984). Hence, the high concentration of SPM (av.  $>40 \text{ mg L}^{-1}$ ) in the CE irrespective of the seasons found to reduce the light availability to the bottom waters most of the time (especially during monsoon and post monsoon months). The linear correlation of chlorophyll *a* and SPM did not show significant relationship during both PRM ( $r=0.144$ ,  $P>0.05$ ; Figs. 6b & 6d) and PM ( $r=0.015$ ,  $P>0.05$ ; Figs. 6f & 6h) and it suggests that SPM alone could not be a limiting factor for phytoplankton growth in the CE.

As far as the nutrient status is concerned, the CE possess moderate level of inorganic nutrients (ammonia, nitrate, phosphate and silicate), with relatively high concentration during the period of fresh water discharge (monsoon) and low concentration during the PRM, when the system remains predominantly marine (Sankaranarayanan and Qasim, 1969). Miranda et al., (2008) has been evidenced high level of ammonia ( $>100 \text{ } \mu\text{M}$ ) in the upstream regions of the estuary, where the industrial and domestic waste disposal was more. Bio-optical measurements have proved that the degradation of CDOM (coloured dissolved inorganic matter) by light (photolysis) can release ammonia and phosphate (Franko & Heath, 1982; Bushaw et al., 1996), predominantly in the areas where more river discharges occurred (high CDOM concentrations occur in freshwater zone). Recently, Madhu et al, (2008 unpublished data) observed high CDOM in the CE indicating that CDOM concentrations in the fresh water dominated zone of the CE can be a source of inorganic ammonia. Even though ammonia formed the dominant fraction of DIN ( $\sim 69\%$ ), its wide fluctuations (PM av.  $35.8 \pm 34.5 \text{ } \mu\text{M}$  & PRM av.  $30.8 \pm 28.3 \text{ } \mu\text{M}$ ) have caused inconsistency in the DIN:DIP ratios (6.8 - 262).

The nitrate level observed during both the seasons (PM av.  $15.8 \pm 6.1 \text{ } \mu\text{M}$  & PRM av.  $12 \pm 5.3 \text{ } \mu\text{M}$ ) showed its anthropogenic origin (Miranda et al., 2008) from the catchments area. The lack of seasonal variation in the DIN ( $F=1.646$ ,  $P>0.05$ ) and N:P ratio ( $F=1.25$ ,  $P=0.326$ ) revealed that the



system sustains excess of inorganic nitrogen irrespective of seasons (Table. 1). The high concentration of DIP (av.  $2.62 \pm 1.19 \mu\text{M}$ ) and DISi (av.  $104.4 \pm 28.2 \mu\text{M}$ , N=280) observed during the PM shown that it might have been originated from the terrestrial run off due to the heavy rain fall. Definite seasonal fluctuations in the DIP (F=1.646, P>0.05) and DISi (F=1.646, P>0.05) also reflected in the higher averages of Si:P (>50) and Si:N (>2.5) ratios as well, as compared to the Red-field ratios (16 & 1, respectively). The linear correlation of chlorophyll *a* between DIN, DIP and DISi does not show significant relationship during both PM (Figs. 6f, i & j) and PRM (Figs.6h, k & l). This revealed that the nutrient concentration does not found to limit the phytoplankton growth in the CE as it always found to exceed required concentrations for optimum growth of phytoplankton.

During the PRM, the CE is behaved as productive system due to the high chlorophyll *a* (av.  $33 \text{ mgm}^{-3}$ ) and primary production (av.  $1304 \pm 694 \text{ mgC m}^{-3}\text{d}^{-1}$ ). The predominant nanoplankton production (>70% of the total primary production) during this period was primarily facilitated by the proliferation of diatoms such as *Skeletonema costatum* (av.  $27.03 \times 10^{-3}$ ), *Thalassiosira subtilis* (av.  $24.31 \times 10^{-3}$ ), *Nitzschia closterium* (av.  $23.24 \times 10^{-3}$ ), *Navicula directa* (av.  $5.13 \times 10^{-3}$ ). Dry weather prevailed during the PRM with a considerably reduced fresh water flow (1.69%, Srinivas et al., 2003), high solar radiation ( $500\text{-}580 \text{ g cal cm}^{-2} \text{ d}^{-1}$ ) and the optimum nutrient concentrations facilitated the highest growth of nanoplankton community in the CE (Qasim et al., 1968). The blooms of *Skeletonema costatum*, *Nitzschia sigma* frequently appeared during the PRM season between salinity 19 and 30 psu (Devassy and Bhattathiri, 1974), but bloom of *S. costatum* was observed in low salinity (4 psu) region also (Joesph and Kunjukrishna 1975) indicating the euryhaline behaviour of *S. costatum* (Gopinathan 1972). This study showed that dinoflagellates were not very abundant phytoplankton community in the CE; they mostly prefer oligotrophic waters and hence, fail to survive in the eutrophic waters (Menzel et al, 1963).

During the PM, oxidation of allochthonous organic matter usually enhances bacterial respiration rate in the CE, when the rate of primary production decreases (Shoji et al., 2008). Normally, primary production  $<120 \text{ mgC m}^{-3}\text{d}^{-1}$  shows the characteristics of an heterotrophic estuary (del Giorgio et al., 1997) and hence the low primary production (av.  $124 \pm 219 \text{ mgC m}^{-3}\text{d}^{-1}$ ) prevalent during the PM revealed the heterotrophic condition of the study area. This low primary production is mainly attributed by the reduced light availability ( $250\text{-}300 \text{ g cal cm}^{-2} \text{ d}^{-1}$ ) due to the input of allochthonous materials and increase in cloud cover (Qasim et al 1968). Even though diatoms formed the dominant component of the phytoplankton community (>80%), its density was less during the PM (av.  $37.34 \times 10^{-3} \text{ cells L}^{-1}$ ) as compared to the PRM (av.  $104.63 \times 10^{-3} \text{ cells L}^{-1}$ ). Similarly, the densities of major nano- diatoms were also less during the PM (Fig. 5c). Besides diatoms and dinoflagellates, fresh water green algae and blue green algae were commonly found in

study area during the PM as compared to the PRM (Table 2), which showed the community shift of phytoplankton due to the changes in salinity commonly occurred in the CE (Devassy and Bhattathiri 1974).

## **5. Conclusions**

From this study, it is obvious that short-term variations in the water quality play a significant role on phytoplankton characteristics in the CE. The predominant nanoplankton community during the PRM perform as active converters of inorganic nutrients into phytoplankton biomass, whereas during the PM, due to the limited growth of nanoplankton populations, the inorganic nutrients could not be efficiently fixed into organic form and sustains heterotrophy due to the high bacterial respiration. The significant seasonality in the nutrient recycling suggests that this system will be very sensitive to further increase in nutrient loading. Future research needs to be focussed on better understanding and predicting how fresh water discharges affect phytoplankton growth and nutrient recycling processes in the Cochin estuary.

## **Acknowledgements**

We wish to thank Dr. S. R. Shetye, Director, National Institute of Oceanography, Goa for the encouragement and support. The study was supported by Integrated Coastal and Marine Area Management-Project Directorate (ICMAM-PD), Ministry of Earth Sciences, Govt. of India, Chennai under the programme 'Ecosystem Modeling of Cochin backwaters'. This is NIO contribution no ----

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**Table 1.** Two-way ANOVA shows the variation between stations and between seasons (in parenthesis) in the Cochin estuary. Degree of freedom (d.f), F statistic and probability (P).

| Parameters                                  | Surface |                 |                                |
|---|---------|-----------------|--------------------------------|
|   | d.f     | F               | P-value                        |
| Temperature (°C)                            | 4 (1)   | 0.819 (69.38)   | 0.574 (0.001)                  |
| Salinity (psu)                              | 9 (1)   | 8.068 (341.93)  | 0.034 (5.03x10 <sup>-5</sup> ) |
| SPM (mg L <sup>-1</sup> )                   | 9 (1)   | 6.834 (11.25)   | 0.045 (0.028)                  |
| pH  | 9 (1)   | 11.884 (318.43) | 0.017 (5.8x10 <sup>-5</sup> )  |
| DO (ml L <sup>-1</sup> )                    | 9 (1)   | 2.078 (69.83)   | 0.248 (0.001)                  |
| DIN (µM)                                    | 9 (1)   | 0.991 (1.646)   | 0.503 (0.269)                  |
| DIP (µM)                                    | 9 (1)   | 1.301 (17.71)   | 0.402 (0.014)                  |
| DIS (µM)                                    | 9 (1)   | 2.255 (898.13)  | 0.225 (7.38x10 <sup>-6</sup> ) |
| N:P   | 9 (1)   | 44.75 (1.25)    | 0.001 (0.326)                  |
| S:N   | 9 (1)   | 1.180 (382.9)   | 0.438 (4.02x10 <sup>-5</sup> ) |
| S:P   | 9 (1)   | 9.523 (290.3)   | 0.025 (6.96x10 <sup>-5</sup> ) |
| Chlorophyll <i>a</i> (mg m <sup>-3</sup> )  | 9 (1)   | 0.152 (177.3)   | 0.952 (1.4x10 <sup>-4</sup> )  |
| Total phyto. density (No. L <sup>-1</sup> ) | 4 (1)   | 0.421 (359.4)   | 0.789 (4.56x10 <sup>-5</sup> ) |
| Diatoms (No. L <sup>-1</sup> )              | 4 (1)   | 0.270 (330.87)  | 0.884 (5.37x10 <sup>-5</sup> ) |
| Dinoflagellates (No. L <sup>-1</sup> )      | 4 (1)   | 0.312 (69.62)   | 0.857 (0.001)                  |

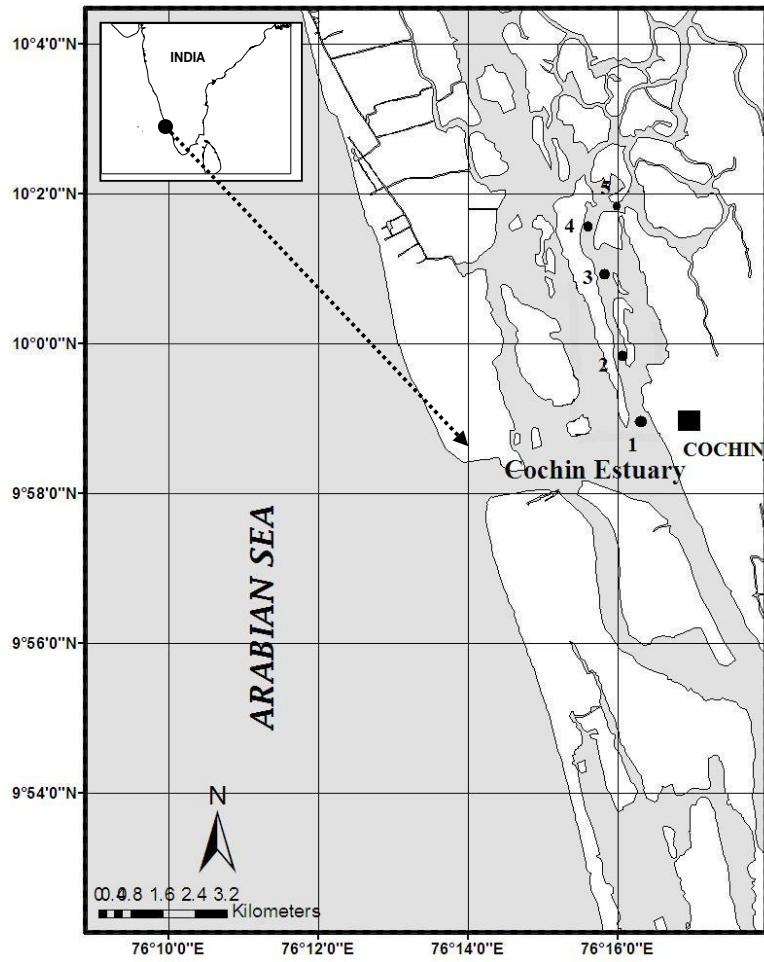
**Table 2.** Species composition of phytoplankton at different sampling stations of the Cochin estuary during the post monsoon and pre-monsoon season (in parenthesis).

| <b>Diatoms</b>                    | <b>Stations</b> |           |           |           |           |
|-----------------------------------|-----------------|-----------|-----------|-----------|-----------|
|                                   | <b>1</b>        | <b>2</b>  | <b>3</b>  | <b>4</b>  | <b>5</b>  |
| <b>Centrales</b>                  |                 |           |           |           |           |
| <i>Lauderia sp</i>                | - (+)           | - (+)     | - (+)     | - (+)     | - (+)     |
| <i>Planktoniella sol</i>          | - (+)           | - (+)     | - (+)     | - (-)     | - (-)     |
| <i>Skeletonema costatum</i>       | ++ (+++)        | ++ (+++)  | ++ (+++)  | ++ (+++)  | ++ (+++)  |
| <i>Thalassiosira subtilis</i>     | +++ (+++)       | +++ (+++) | +++ (+++) | +++ (+++) | +++ (+++) |
| <i>Leptocylindrus danicus</i>     | + (+)           | + (+)     | - (+)     | - (+)     | - (-)     |
| <i>Coscinodiscus lineatus</i>     | + (+)           | + (+)     | + (+)     | - (+)     | - (-)     |
| <i>C. marginatus</i>              | - (+)           | - (+)     | - (-)     | - (-)     | - (-)     |
| <i>C. granii</i>                  | ++ (+)          | + + (+)   | - (+)     | + (-)     | - (+)     |
| <i>C. gigas</i>                   | + (+)           | +         | + (+)     | - (-)     | - (-)     |
| <i>Asteromphalus sp.</i>          | (+)             | - (-)     | - (-)     | - (+)     | - (-)     |
| <i>Actinoptychus sp.</i>          | - (+)           | - (+)     | - (-)     | - (-)     | - (-)     |
| <i>Rhizosolenia alata</i>         | + (+)           | + (+)     | - (+)     | - (+)     | - (-)     |
| <i>R. imbricata</i>               | - (+)           | - (+)     | (+)       | - (+)     | - (-)     |
| <i>R. styliformis</i>             | - (+)           | - (-)     | - (-)     | - (+)     | - (-)     |
| <i>Bacteriastrum hyalinum</i>     | - (-)           | - (+)     | - (+)     | - (-)     | - (+)     |
| <i>C. lorenzianus</i>             | + (+)           | + (+)     | - (+)     | - (+)     | - (-)     |
| <i>C. curvisetus</i>              | + (+)           | + (+)     | - (+)     | - (+)     | - (+)     |
| <i>Eucampia zodiacus</i>          | + (+)           | + (+)     | + (+)     | - (-)     | - (-)     |
| <i>Ditylum brightwelli</i>        | - (+)           | - (+)     | - (-)     | - (-)     | - (-)     |
| <i>Biddulphia sp.</i>             | + (+)           | + (+)     | - (+)     | + (+)     | - (-)     |
| <b>Pennales</b>                   |                 |           |           |           |           |
| <i>Fragilaria sp.</i>             | - (+)           | - (+)     | - (+)     | - (+)     | - (+)     |
| <i>Thalassionema nitzschioids</i> | + (+)           | + (+)     | + (+)     | + (+)     | - (+)     |
| <i>T. frauenfeldii</i>            | - (-)           | - (-)     | - (-)     | - (-)     | - (-)     |
| <i>Navicula directa</i>           | + (+++)         | ++ (+++)  | + (++)    | ++ (++)   | + (++)    |
| <i>N. distans</i>                 | - (-)           | - (-)     | - (-)     | - (-)     | - (-)     |
| <i>Pleurosigma elongatum</i>      | + (+)           | - (+)     | + (+)     | - (+)     | - (+)     |
| <i>P. normanii</i>                | - (+)           | - (+)     | - (+)     | - (+)     | - (+)     |
| <i>Nitzschia closterium</i>       | +++ (+++)       | +++ (+++) | +++ (+++) | +++ (+++) | +++ (+++) |
| <i>N. longissima</i>              | - (+)           | + (+)     | - (+)     | - (+)     | - (+)     |
| <i>N. sigma</i>                   | + (+)           | - (+)     | + (+)     | - (+)     | - (+)     |
| <i>N. seriata</i>                 | ++ (++)         | + (++)    | + (++)    | + (++)    | + (++)    |
| <i>Surirella sp.</i>              | + (+)           | - (+)     | - (+)     | + (+)     | - (+)     |
| <i>Amphiprora sp.</i>             | + (++)          | + (++)    | + (+)     | + (+)     | + (+)     |
| <b>Dinoflagellates</b>            |                 |           |           |           |           |
| <i>Prorocentrum micans</i>        | + (++)          | + (++)    | + (++)    | + (+)     | + (+)     |
| <i>Dinophysis caudata</i>         | - (+)           | - (+)     | - (+)     | - (-)     | - (+)     |
| <i>Amphisolenia bidentata</i>     | - (+)           | - (+)     | - (+)     | (+)       | - (-)     |
| <i>Ornithocercus sp.</i>          | - (+)           | + (+)     | - (+)     | - (+)     | - (+)     |
| <i>Gymnodinium sp.</i>            | - (+)           | - (+)     | - (+)     | - (+)     | - (+)     |
| <i>Ceratium fusus</i>             | + (+)           | + (+)     | + (-)     | - (+)     | - (+)     |
| <i>C. tripos</i>                  | - (+)           | - (+)     | - (+)     | - (+)     | - (+)     |
| <i>C. macroceros</i>              | + (+)           | + (-)     | + (-)     | + (-)     | - (-)     |
| <i>Gonyaulax spinifera</i>        | - (+)           | - (+)     | - (+)     | - (-)     | - (-)     |
| <i>Protoperidinium sp.</i>        | - (+)           | - (+)     | - (+)     | - (+)     | - (+)     |

|                                 |       |       |        |        |        |
|---------------------------------|-------|-------|--------|--------|--------|
| <i>Podolampus bipes</i>         | - (+) | - (+) | - (+)  | - (-)  | - (-)  |
| <i>Phalacroma rotundatus</i>    | - (+) | - (+) | - (+)  | - (+)  | - (+)  |
| <b>Blue green algae</b>         |       |       |        |        |        |
| <i>Anabaena sp.</i>             | + (-) | + (-) | + (-)  | ++ (-) | ++ (-) |
| <i>Anacystis sp.</i>            | + (-) | + (-) | + (-)  | + (-)  | ++ (-) |
| <i>Lyngbya sp.</i>              | + (-) | + (-) | + (-)  | + (-)  | + (+)  |
| <i>Microcystis sp.</i>          | + (-) | + (-) | ++ (-) | ++ (-) | ++ (-) |
| <i>Nostoc sp.</i>               | - (-) | + (-) | + (-)  | + (+)  | ++ (+) |
| <i>Rivularia sp.</i>            | + (-) | + (-) | + (-)  | + (-)  | + (-)  |
| <i>Spirulina sp.</i>            | + (-) | + (-) | + (-)  | ++ (-) | ++ (-) |
| <i>Trichodesmium erythraeum</i> | - (+) | - (+) | - (-)  | - (-)  | - (-)  |
| <b>Green algae</b>              |       |       |        |        |        |
| <i>Chlorella sp.</i>            | + (-) | + (-) | ++ (-) | ++ (-) | ++ (-) |
| <i>Eudorina sp.</i>             | + (-) | + (-) | + (-)  | + (+)  | + (+)  |
| <i>Pandorina sp.</i>            | (-)   | + (-) | + (-)  | + (+)  | + (+)  |
| <i>Pediastrum duplex</i>        | + (-) | + (-) | + (-)  | + (-)  | + (-)  |
| <i>Volvox sp.</i>               | + (-) | + (-) | + (-)  | + (-)  | + (+)  |
| <b>Flagellates</b>              |       |       |        |        |        |
| <i>Dictyocha sp</i>             | - (+) | - (-) | - (+)  | - (+)  | + (-)  |

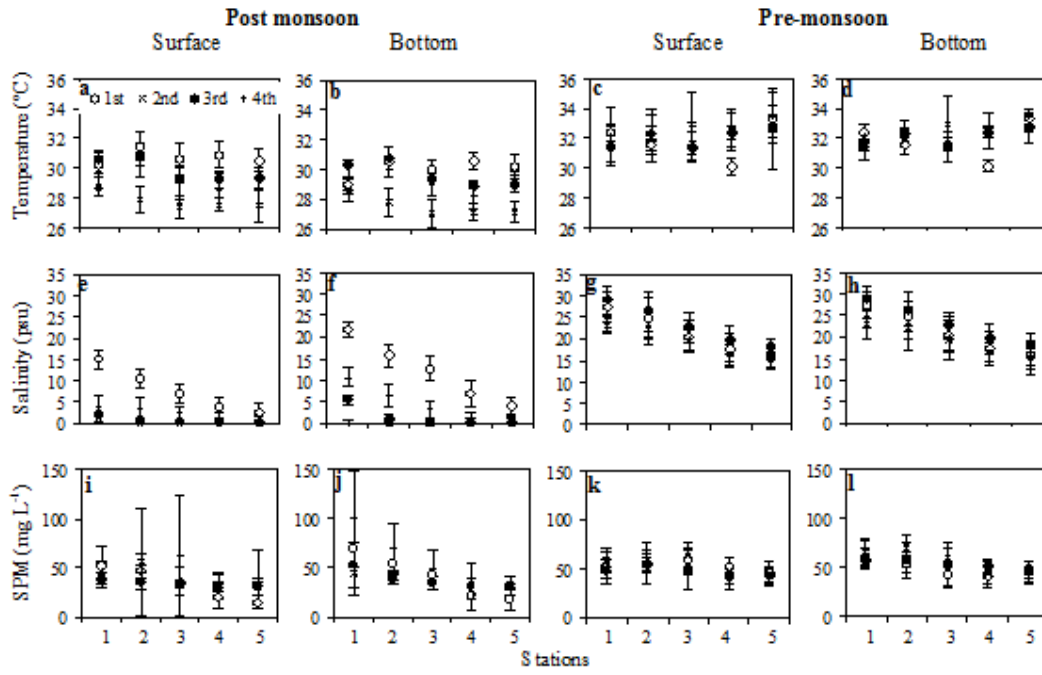
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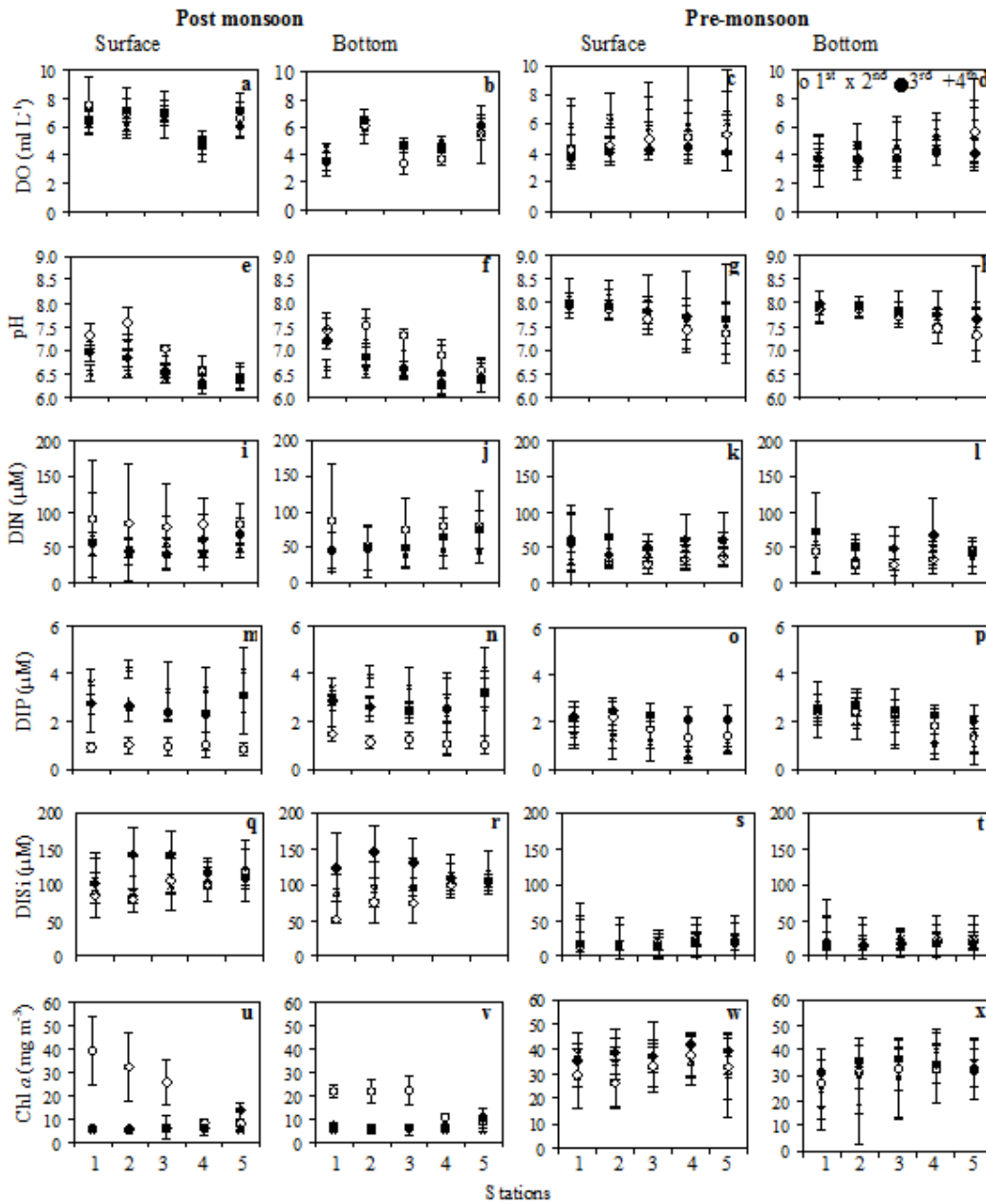


**Figure 1.** Study area in the Cochin backwaters showing the station locations for the time-series observation

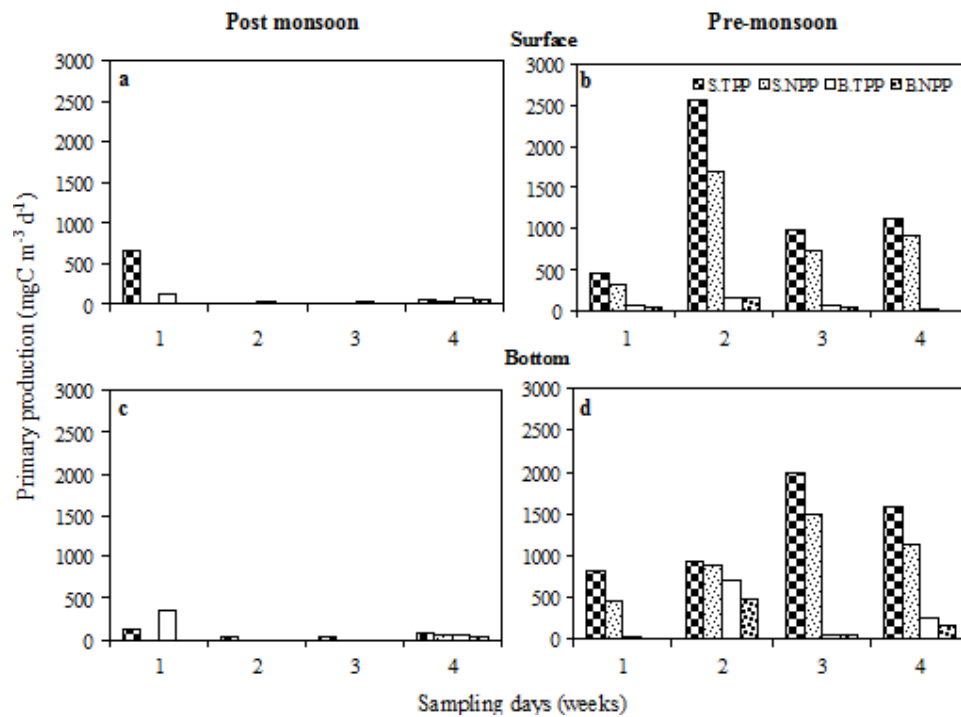




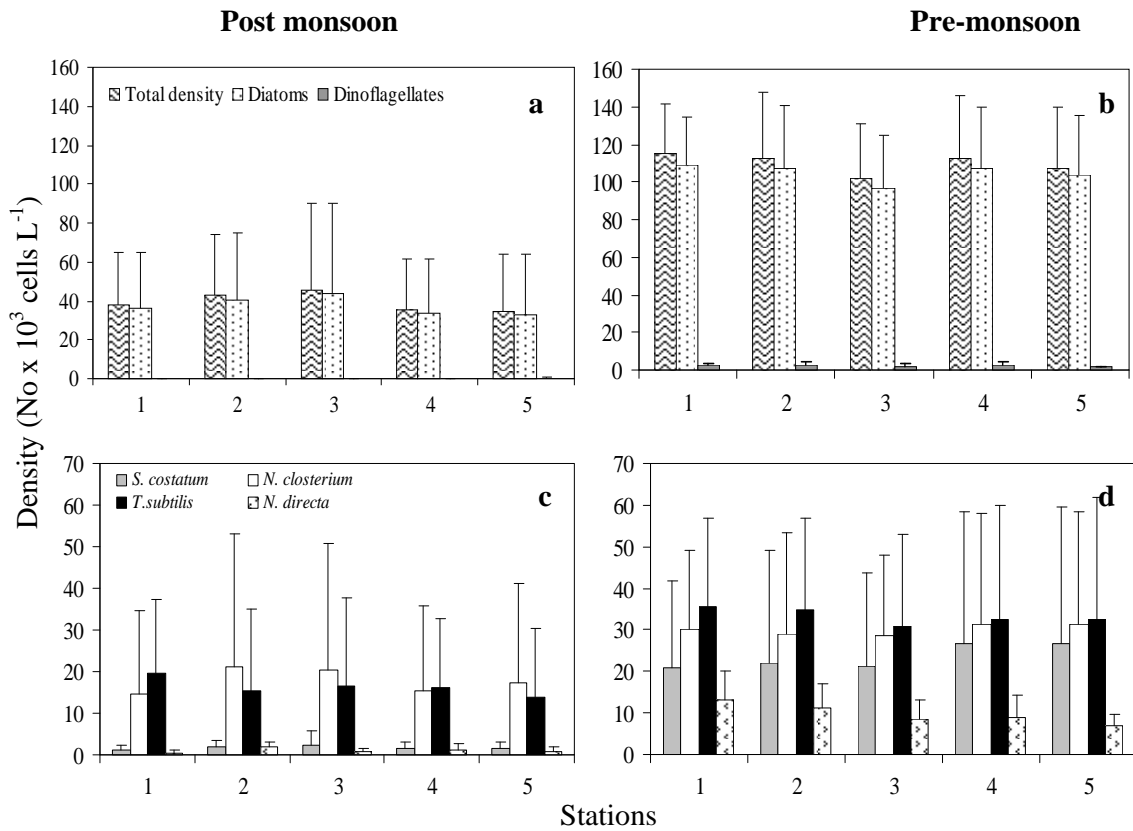
**Figure 2** - Distribution of temperature (°C), salinity (*psu*) and SPM (mg L<sup>-1</sup>) in the Cochin estuary during the post monsoon 2003 and pre-monsoon 2004



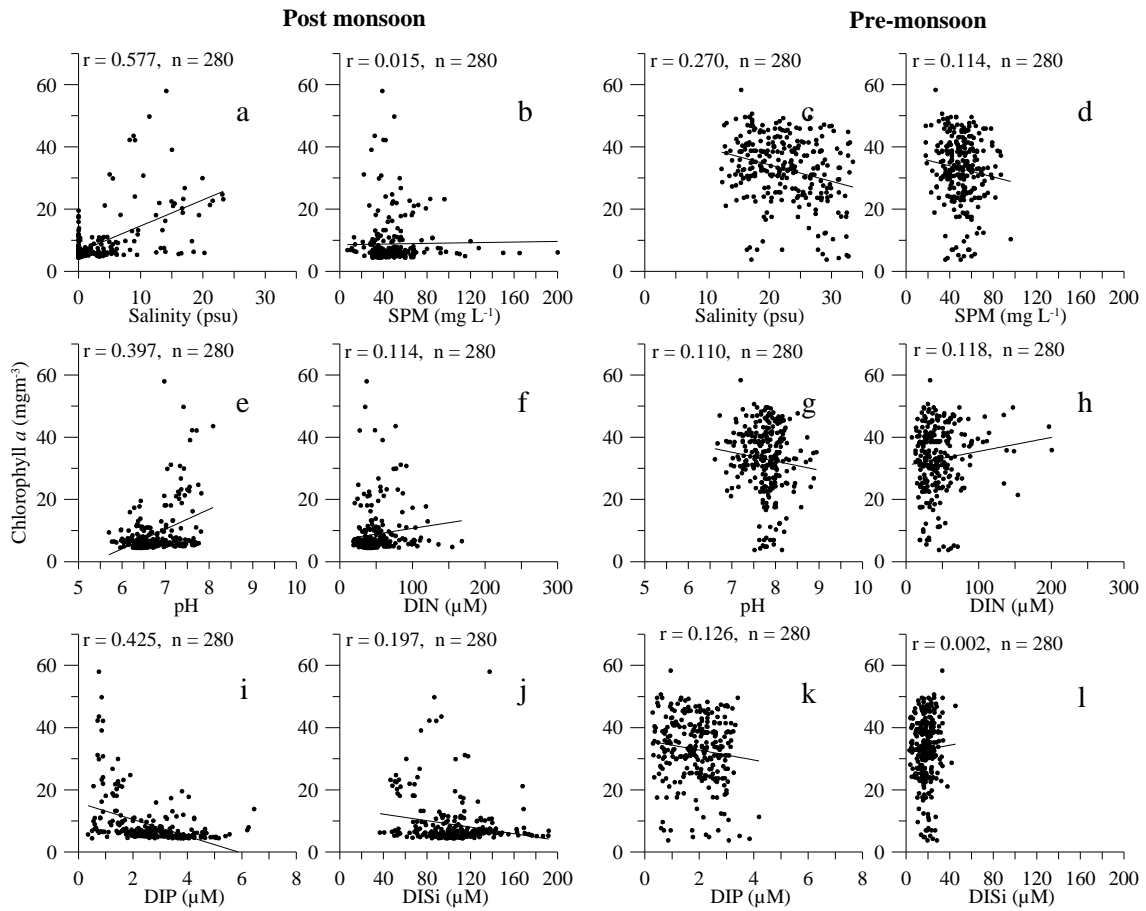
**Figure 3** - Distribution of major chemical parameters and chlorophyll *a* in the Cochin estuary during the post monsoon 2003 and pre-monsoon 2004



**Figure 4** - Distribution of primary production in 2 selected stations (1 & 4) in the Cochin estuary during Post monsoon 2003 and pre-monsoon 2004 (S.TPP- Total primary production in the surface, S.NPP- Nanophytoplankton production in the surface, B.TPP - Total primary production in the bottom, B.NPP - Nanophytoplankton production in the bottom).



**Figure 5** - Phytoplankton density in the surface (a & c) and bottom (b & c) waters of the Cochin estuary during post monsoon 2003 and pre-monsoon 2004.



**Figure 6** - Linear correlation of chlorophyll *a* with major environmental parameters during the post monsoon and pre-monsoon season