Indian Journal of Marine Sciences
Vol. 37(2), June 2008, pp. 132-140

Seasonal and tidal dynamics of nutrients and chlorophyll *a* in a tropical mangrove estuary, southeast coast of India

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Received 27 January 2008; revised 20 May 2008

Seasonal and tidal dynamics of dissolved nutrients (NH_4-N, NO_3+NO_2-N, PO_4-P and DOC), chlorophyll *a*, and primary production was studied in Pichavaram mangroves, Southeast coast of India. Seasonal changes showed an increase in salinity after tsunami (Pre-Tsunami; 24 ± 4.61, Post-Tsunami; 31 ± 2.35) due to the opening of sand bar at Coleroon River mouth causing an influx of seawater into the mangrove region at flood flow. However, dissolved nutrients showed no marked changes after tsunami and followed the seasonal pattern as observed prior to the event. There is an *in situ* regeneration of nutrients as a primary nutrient source rather than riverine input during a major part of the year. The nutrient balance of the Pichavaram mangroves was influenced by the tidal cycle. This is indicated by the changes in tidal height, salinity, inorganic nutrients, DOC and chlorophyll *a* over a 24 hours diurnal survey in both wet and dry seasons. The main features of the low tidewater were high concentrations of the nutrients showed the effects of tidal pumping mechanism. The tidal range were high after the December 2004 tsunami (Tidal range: Pre tsunami; 69±4.7, Post tsunami 126 ±11.8). It did not causes significant changes in the chemistry of the mangrove surrounding water column.

Key words: Pichavaram mangroves, tsunami, inorganic nutrients, DOC, Chlorophyll *a*, primary productivity, tidal pumping

Introduction

Mangrove ecosystems are important contributors of organic carbon and other nutrients to the adjacent coastal ecosystems. The mangrove ecosystem may significantly influence adjacent coastal areas through various mechanisms such as nutrient and carbon export[1,2], sediment stabilization and storm protection and nursery habitat for economically important species[2]. The mangroves provide nutrients for phytoplankton growth, thus enhancing secondary production and promotion of commercial fisheries[3]. The net primary production of mangroves derived from indirect measurements is an average 58±7 mol C m^{-2} yr^{-1}[4]. Almost one third of the net primary production of this ecosystem can be lost as plant litter, such as leaves and twigs. About half of above litter is exported from mangrove creeks to the adjacent coastal waters[5]. The export of such a large amount of organic matter has a recognizable effect on the nutrients or biomass of consumer communities in coastal waters[6]. The presence or absence of freshwater inputs into mangrove creeks seems to be an important factor affecting the direction and magnitude of material fluxes[7]. The distribution and behavior of nutrients are usually affected by tidal, seasonal and weather conditions. Mangroves are also important as effective barriers against the giant waves such as the tsunami since it reduces the velocity of the waves.

The changes in seasonal and tidal behavior of nutrients, Chlorophyll *a* and phytoplankton primary productivity before and after the December 26, 2004 Indian Ocean tsunami in the Pichavaram mangrove forests have been examined in the present study. It consists of the influence of tides on nutrient outwelling and also the effect of the recent tsunami on the mangrove surrounding water column.

Materials and Methods

Study area

The Pichavaram mangrove forest (Fig. 1) is located along the southeast coast of India (Lat 11° 21′ N and 79° 59′E). This mangrove covers an area of 13 km^2, with a heterogeneous mixture of mangrove trees and shrubs. This mangrove ecosystem is located between two predominant estuaries, the Vellar in the north and Coleroon in the south. There are numerous creeks, gullies and canals traversing the mangroves discharging freshwater into the system. The average water depth of the main channel and creeks ranged from 0.5 to 1 m. A major irrigation channel (Uppanar)

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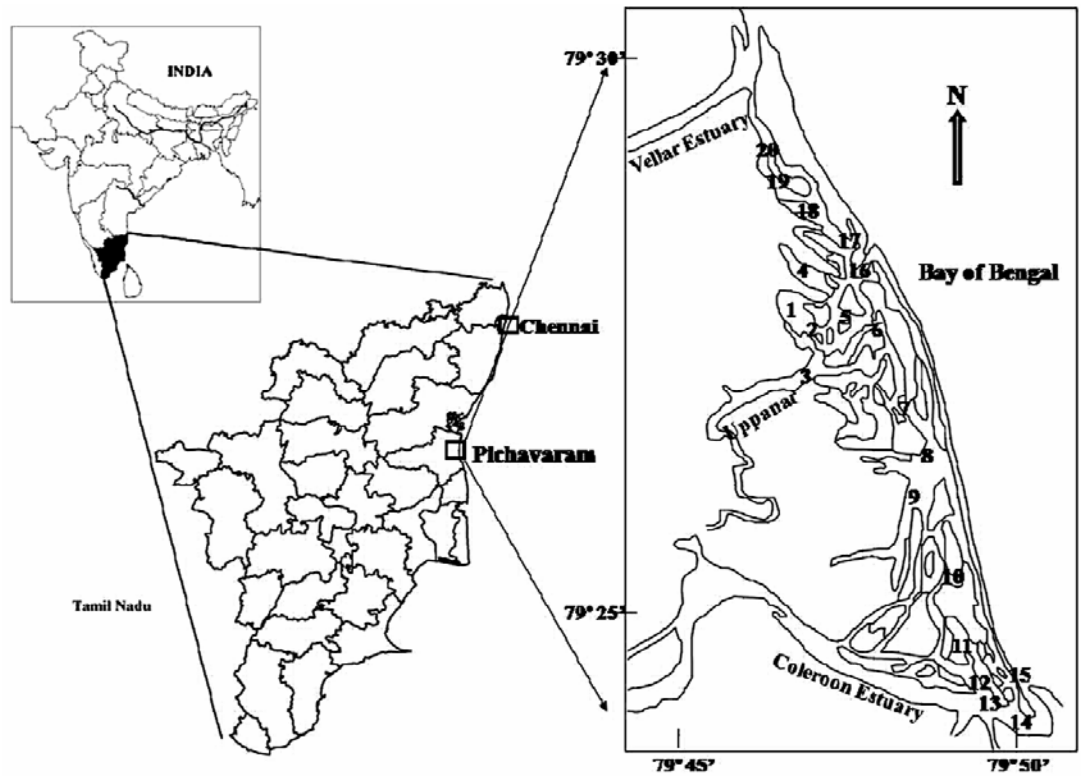

Fig. 1—Map of Pichavaram mangroves with sampling locations

discharges agricultural effluent from the delta to this ecosystem. The tides are semidiurnal with average tidal amplitude of 0.5 to 1m. Quaternary sediments dominate the geology of this area. The average annual rainfall (70 years) is 1310 mm yr^{-1} and annual average for number of rainy days is 56. About 75-90% of total rainfall is generally recorded during the northeast monsoon (October-December). During south west monsoon period rainfall is low.

The Pichavaram mangroves received greater attention after the December 2004 Indian Ocean tsunami. In this region the mangroves closer to the coast (Bay of Bengal) were uprooted and ~6 fishermen hamlets were washed away by tsunami waves. Waves of about 10 to 15' had been reported entering the mangrove forest at the time of the tsunami. It caused minimal damage due to the presence of the dense mangrove forest. The present study and sampling was undertaken immediately after tsunami to examine the degree of impact on the physico-chemical and nutrient chemistry in the mangrove surrounding water column.

Sampling and analytical procedures

The surface water samples were collected from 20 fixed stations during January, April and August 2004 and during January, June 2005 (Fig.1). Tidal variations over a period of 24 hours was monitored once in the wet (August 2004, Pre Tsunami) and dry (June 2005, Post Tsunami) seasons in the middle of the mangrove creek. pH, Salinity, temperature, and dissolved oxygen were measured with multi probe (Horiba, W-22.2). The samples were filtered with pre combusted (4h, 450°C) Whatman GF/C filters. After filtration, the samples were kept frozen (-20°C) until analysis (within 48hrs). The samples were analyzed in triplicate for dissolved organic carbon (DOC). It was determined by using Shimadzu TOC-5000 as the difference between total carbon and dissolved inorganic carbon. Standard curves were prepared with analytical grade salts potassium hydrogen phthalate and sodium bicarbonate. NH_4-N was measured by the modified indophenols blue method[8]. Nitrate, nitrite, phosphate and chlorophyll *a* were analyzed by standard methods using a spectrophotometer (Hitachi U-2000).

Results

Seasonal changes in environmental variables

The mean surface water temperature varied from 27° to 28° C in the wet season (August and January) and 29° to 32° C in the dry season (April and June)

(Table 1). Spatial variation of salinity showed significant variations during the study period (Fig. 2). The salinity had varied between 16 and 30 during the wet season and 28 to 34 during the dry season. The highest and the lowest salinities and temperature were found high during dry season and low at wet seasons respectively (Table 1). The high salinity during dry season is due to evaporation, poor input of freshwater from the Coleroon river into the mangrove region and seawater intrusion after Tsunami. The average dissolved oxygen in the mangrove surrounding waters during dry season varied between 4.85 and 6.31 mg l^{-1} and in wet season it is fluctuated from 5.83 and 7.03 mg l^{-1} (Table 1).

Table 1—Mean values (±SD) and Range (in parenthesis), (n=20) of nutrients and other measured parameters

Parameters	Dry season	Wet season
Water Temperature (°C)	31.78 ± 0.89 (29 - 32)	27.70 ± 1.61 (26 - 28)
Salinity (psu)	31 ± 2.35 (28 - 34)	24 ± 4.61 (16 - 30)
DO (mg l^{-1})	5.57 ± 1.17 (4.84-6.31)	6.31 ± 1.39 (5.83-7.03)
NH_4-N (µm)	68.6 ± 12.9 (64.2 - 72.91)	58.6 ± 14.4 (45.98 - 65.63)
NO_3+NO_2-N (µm)	3.6 ± 1.4 (3.29 - 3.86)	4.2 ± 2.0 (1.26 - 6.18)
PO_4-P (µm)	3.7 ± 0.7 (2.8 - 4.7)	2.8 ± 0.9 (0.88 - 4.89)
DOC (µm)	324.8 ± 70.2 (229 - 421)	258.9 ± 56.3 (192 - 324)
Chlrophyll<u>a</u> (µg l^{-1})	8.62 ± 3.43 (6.5 - 10.7)	11.42 ± 3.27 (8.61 - 12.74)
Primary Productivity (mg C m^{-2} d^{-1})	0.31 (0.2 -0.39)	0.4 (0.23-0.41)

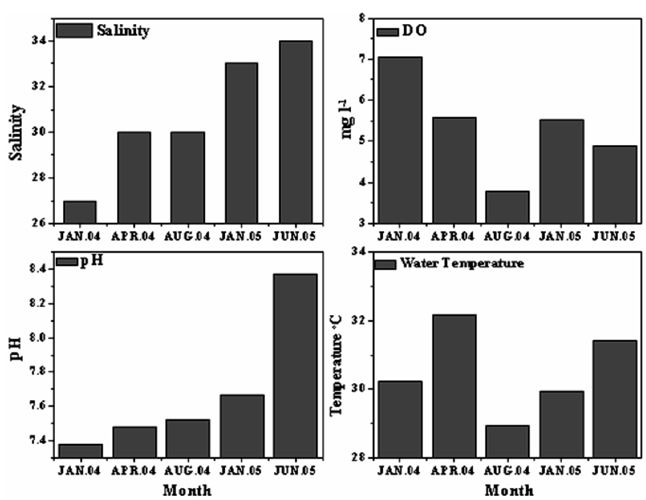

Fig. 2—Seasonal variation environmental variables in mangrove surrounding waters

Seasonal changes in dissolved inorganic nitrogen

The present study reveals that in Pichavaram mangroves, ammonium - N is predominant in the dissolved inorganic nitrogen (DIN) throughout the study period. The mean NH_4^+-N variations in Pichavaram mangroves ranged between 45.98µm and 72.91µm. The lowest values being realized mainly during the wet season and highest values during the dry season (Fig. 3). There is significant ammonium import through freshwater inflow in this regime. Accordingly, plots of ammonium nitrogen against salinity showed no significant correlations (wet season, r^2=0.15; dry season, r^2=0.18). The higher values in the upper reaches are mainly derived from terrestrial runoff and drainage from agricultural areas being discharged by Uppanar Canal (Khan Sahib Canal) into the mangrove region. The mean NO_3-N+NO_2-N had varied between 1.26 µm and 6.18 µm with lowest concentration during dry season and highest concentration during wet season (Fig. 3). The higher values during wet season are associated with land-derived sources like agricultural runoff and aquafarm outlet from the surrounding areas of the mangrove region (Table 1).

Seasonal changes in dissolved inorganic phosphate

Seasonal changes in the concentration of phosphate (PO_4-P) varied between 1.88µmol and 4.89µmol with lowest values during dry season and highest values during the wet season (Fig. 3). The sources of phosphate in Pichavaram mangroves are from agricultural runoff during the wet season and due to remineralization from the bottom sediments during the dry period. This mangrove ecosystem receives only a negligible quantity of freshwater from the Cauvery River other than October–December and therefore becomes highly stratified. Thus the nutrients are settled in the bottom sediments after monsoonal rain and the mangrove sediments thus act as a "*nutrient-trap*" [1]. The sediments then release the "settled" nutrients in the absence of external sources (freshwater) and when sediment temperatures are high, rapid remineralization of the nutrients occur in the mangrove sediments.

Seasonal variations of dissolved organic carbon (DOC)

DOC concentrations varied from 192 µmol (wet season) to 421 µmol (dry season) (Fig. 3). The DOC

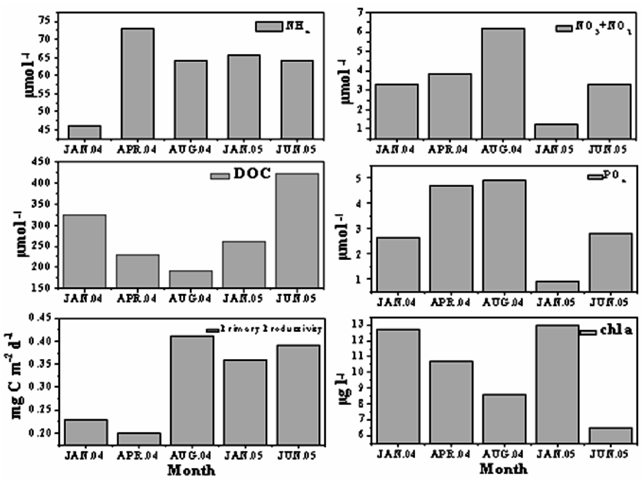

Fig. 3—Seasonal variations of measured parameters in mangrove surrounding waters

concentrations were highest during the dry season (Table 1), due to the greater degradation of litter at higher temperatures and low freshwater inflow into the mangrove forest. Leaf litter represents a much greater source of leachable DOC in mangrove forests[9]. According to Anderson and Christensen (1978)[10], increased porewater salinity due to persistent poor freshwater input and evaporation lead to increased leaf senescence. The leaf litter fall may contribute elevated DOC especially during dry season. It is estimated that the litter produced in the canopy of Pichavaram mangrove forests is 6310 t yr^{-1}. Of this total production, ~3786 t yr^{-1} is exported; representing a major source of dissolved organic matter and nutrients to the Bay of Bengal[1]. The present study suggests that the DOC production in Pichavaram mangroves is mainly derived from leaf litter decomposition and degradation product of microalgae.

Seasonal variations of chlorophyll *a* and Primary Productivity

Chlorophyll is considered as the most reliable index of phytoplankton biomass. Chlorophyll *a* showed significant seasonal variations and varied from 6.5 μgl^{-1} to 12.92 μgl^{-1} (Fig. 3). The concentration of chlorophyll *a* was highest during wet season and lowest during June dry season (Table 1). The high concentration chlorophyll *a* during wet season is due to monsoonal runoff. However, on spatial survey, the high concentration of chlorophyll *a* in the upper reaches of the mangrove estuary suggests the impact of sewage and effluent from aquafarms on phytoplankton biomass. This is further substantiated by the positive correlation between DO and chlorophyll *a* (r^2=0.5). This will reflect rich and productive population of phytoplankton growth and bacteria supporting the notion that active mineralization of aqua pond effluent in the upper reaches of the mangrove estuary.

In the case of Pichavaram mangroves, the present study indicate that primary productivity was high during wet season and water quality characteristics were altered by effluent discharge into the upper reaches of the mangrove creek. The upper reaches of the Pichavaram mangrove waters appears to have some capacity to assimilate or transform nutrients derived from periodic inputs from the adjacent shrimp ponds and agricultural areas. The assimilative and/or dissimilative mechanisms were not examined in the present study. It is likely that a combination of processes, most likely mineralization and subsequent dissipation (e.g., respiration, denitrification) by planktonic food webs, and dilution and physical processing by tides, were the major mechanisms of assimilation.

Because of this recycling phenomenon, nutrients were converted into assimilable forms. This result an initial increase in chlorophyll *a* concentration and the sampling was carried out predominantly during the early morning hours and daytime increases in DO levels, most likely reflected the increase in phytoplankton biomass, as supported by the positive correlations of these factors with chlorophyll *a* concentration. The same has been observed by Trott & Alongi, (1999 and 2000)[11, 12] for the Australian mangroves of a similar nature–receiving effluents from shrimp culture ponds and other minor inputs, as mentioned earlier.

According to Kathiresan (2000)[13], the gross primary production in Pichavaram mangroves is 8 g C m^{-3} d^{-1} and about 21% of which was contributed by phytoplankton biomass. Phytoplankton primary production may play an important role in sustaining secondary production because of the poor nutritional quality of mangrove detrital material[5]. Purvaja & Ramesh (2000)[1] reported a gross phytoplankton primary productivity of 0.31g C m^{-2} d^{-1} for the Pichavaram mangroves. In the present study, the aquatic primary productivity during the entire study period varied appreciably with seasons and it ranged from 0.2 to 0.41 g C m^{-2} d^{-1} (Fig. 3). The gross primary production was highest during wet season (August) (0.41 g C m^{-2} d^{-1}) due to high concentration of nutrients brought by river into the mangrove region and lower during dry season (0.20 g C m^{-2} d^{-1}) (Table 1). During monsoonal period, the organic matter rich terrestrial runoff and aquafarm effluent from the mangrove surrounding areas stimulating the rich phytoplankton growth and thereby increasing the rates of primary production in the water column.

Tidal variations

The variations of the parameters with tidal cycle had been conducted during 7th and 8th August 2004 (wet season, Pre-tsunami) and 23rd and 24th June 2005 (dry season, Post-Tsunami). The surface water samples were taken hourly in the middle of the mangrove creek over a period of 24 hours. During the sampling period in both wet and dry seasons two lower and two higher tides were predicted (Fig. 4). The results of the present study showed that the mean tidal range over 24 hours in both wet and dry season was 69±4.7cm and 126±11.85cm respectively (Table 2). Furthermore, the high tidal range during the dry season (23rd and 24th June 2005) was due to influx of large volume of seawater at flood tide into the mangrove region after Asian tsunami on 26th December 2004. The sediments at the river mouth were removed by the tsunami waves and were deposited into the mangrove region. The river mouth of both Coleroon and Vellar which had a sand bar prior to tsunami was opened after the impact and caused the copious influx of seawater into the creeks and canals of the mangrove forest in Pichavaram, at least temporarily. During this study period (August 2004 to June 2005) we observed an increase in the mean tidal amplitude at Pichavaram mangroves from annual mean tidal range of 0.5 to 2m. This is due to the opening of sand bar at the river mouth after tsunami.

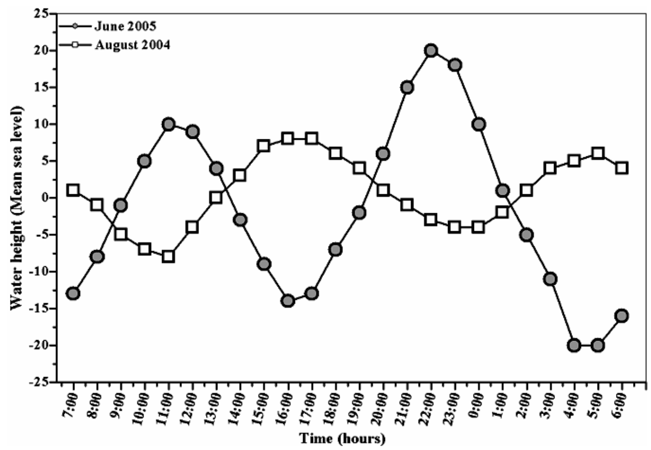

Fig. 4—Changes in the water height before and after Tsunami

Table 2—The range and mean values (±SD), (n=24) of nutrients and other measured parameters over 24 hours survey

Parameters	Dry season (June, 2005)	Wet season (August, 2004)
Water height (cm)	126 ±11.8 (108-148)	69±4.7 (60-76)
Salinity (psu)	31.49± 2.5 (23.42-34.15)	29.68±1.99 (27.3-33.1)
pH	8.03±0.4 (7.42-8.65)	7.67±0.13 (7.42-7.87)
DO (mg l^{-1})	6.44±0.88 (5.24-7.92)	7.58±1.4 (10.66-5.84)
NH_4-N (µm)	64±12.6 (43-88)	67.9±18.7 939-96)
NO_3+NO_2-N (µm)	3.76±1.4 (1.5-6.4)	5.66±1.3 (4-7.4)
PO_4-P (µm)	4.52±1.4 (1.41-6.57)	3.41±1.2 (1.5-5)
DOC (µm)	427±85.3 (288-603)	327±32.4 (268-389)
Chlrophyll a (µg l^{-1})	5.35±1.5 (3.1-9.21)	16.9±3.9 (8.5-26.9)

Diurnal and tidal variations of environmental variables

The mean salinity during wet and dry season recorded over 24 hours was 29.68±2.0 and 31.49±2.58 respectively (Table 2). The salinity had varied between 27.21 and 33.18 in wet season (Fig. 5) and 29.27 to 34.15 during the dry season (Fig. 6). In both wet and dry seasons the water level had correlated positively with salinity [(wet season r^2= 0.58, n=24, p<0.01), (dry season r^2=0.45, n=24, p<0.05)] and salinity gradient had been recorded during flood flow in dry season. In the wet season, during ebb flow, salinity decreased due to the dilution by the less saline estuarine waters. In the first 5 hours of measurements in both seasons, it is observed that, before low tide, there was high salinity gradient with water level, with a mean of 32.4±1.07 during dry season (Fig. 6) and 27.32±1.95 during the wet season (Fig. 5). The seawater intrusion into the estuary might have enhanced the salinity. In both seasons, water level had been poorly correlated (wet season, r^2=0.29; dry season, r^2=0.005) with pH. During the ebb tide and at night, pH reached minimum values in coincidence with the oxygen minimum. Dissolved oxygen concentration during dry season had varied between 5.24 and 7.92 mg l^{-1} and the mean concentration over 24 hours was 6.44±0.88 mg l^{-1}. During wet season it had varied between 5.84 and

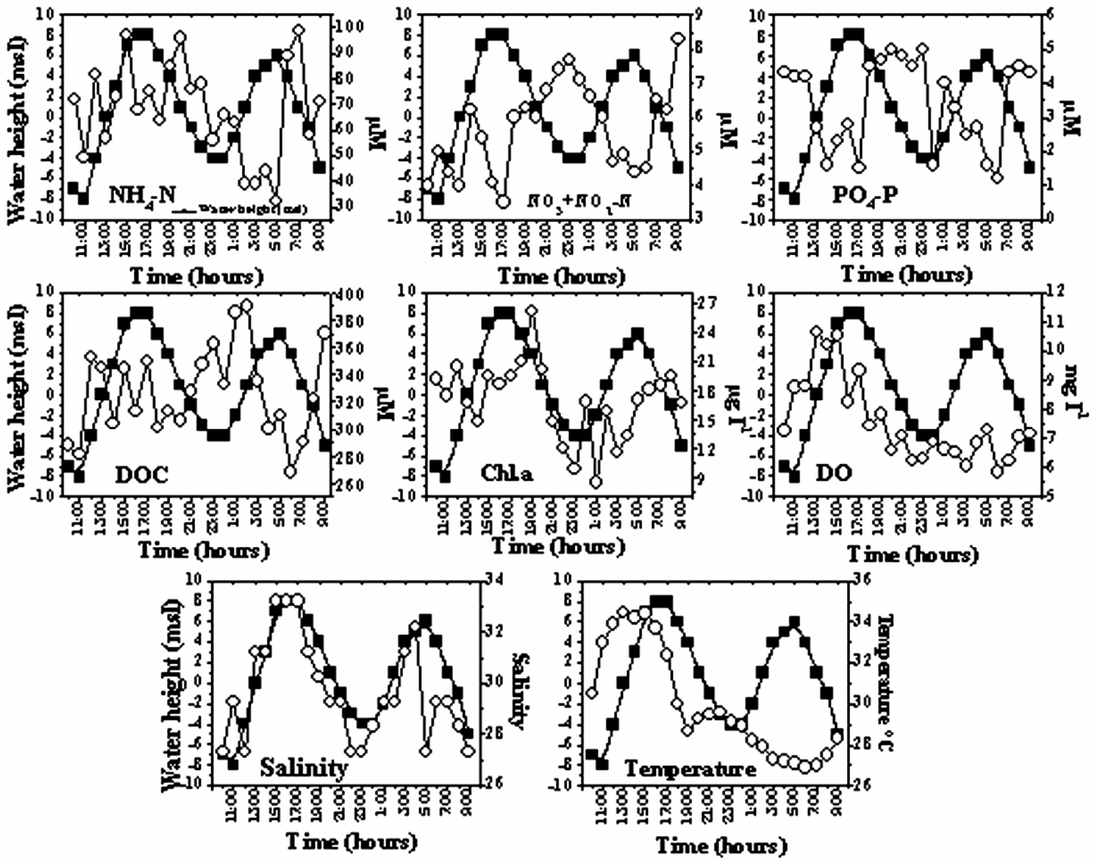

Fig. 5—Tidal variation of nutrients, chlorophyll *a* and environmental variables in mangrove surrounding waters during wet season

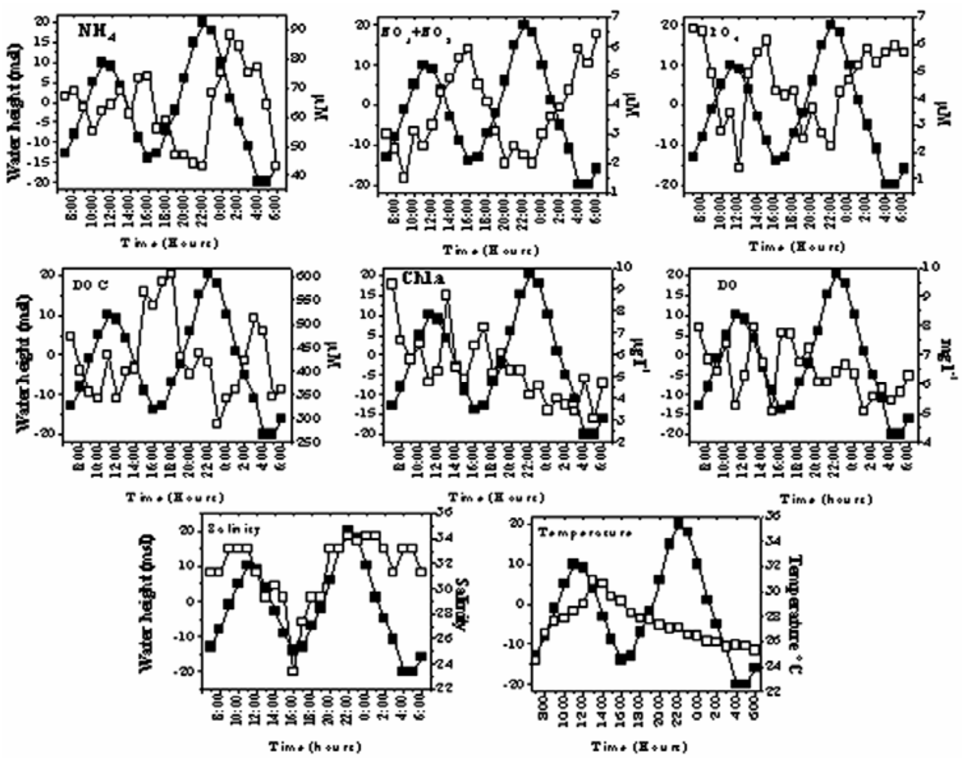

Fig. 6—Tidal variation of nutrients, chlorophyll *a* and environmental variables in mangrove surrounding waters during dry season

10.66 mg l^{-1} with a mean concentration of 7.58±1.4. The dissolved oxygen concentration in both seasons showed a day time high and a night time low since aquatic primary production occurs only during the day.

Diurnal and tidal variations of ammonium nitrogen (NH_4-N)

Ammonium nitrogen (NH_4^+-N), nitrate+nitrite [(NO_3^-+NO_2^-)-N)], Phosphate (PO_4^{3-}-P) and DOC covaried drastically in this ecosystem (Fig. 5 and 6). These components present minimum values at high tide and maxima at low tide. The concentration of ammonium nitrogen (NH_4^+-N) in both dry and wet seasons was higher during the night, which seems to be preferentially taken up by autotrophic organisms. Previous studies[1], have shown that ammonium nitrogen is regenerated within the mangrove estuary rather than imported. The present study infers that the intertidal origin of ammonium is caused, to some extent, by benthic biological processes of nitrogen excretion by the micro- and macro-benthos, dissimilatory reduction of nitrate under anaerobic conditions and microbial ammonification of organic materials in sediments. Accordingly, plots of ammonium nitrogen against salinity and water height showed no significant correlations. The increased nutrient concentrations at the low tide might be a consequence of influx of nutrient depleted sea water into the mangrove creek.

Diurnal and tidal variations of nitrate+nitrite nitrogen (NO_3+NO_2-N)

The mean concentration of nitrate+nitrite during dry season was [(NO_3^-+NO_2^-)-N)] was 3.76±1.43µm (Fig. 6). It is fluctuated between 1.5µm and 6.4µm over 24 hours. During wet season the mean concentration was 5.66±1.3 (Fig. 5) and it is varied among 4µm and 7.4µm. During the first 5 hours of measurements, at the flood tide, high salinity water caused a significant drop of nitrate+nitrite. Conversely, as the ebb tide approached, there was a marked increase in concentration during both dry and the wet seasons. Nitrate+nitrite had the best correlation with water level (r^2= -0.73, n=24, p<0.01) and salinity (r^2= -0.51, n=24, p<0.01) in dry season but during wet season it showed no significant correlation with either water height (r^2=-0.4, n=24) or salinity (r^2=-0.45, n=24, p<0.05). Balls (1994)[14] reported conservative mixing particularly for nitrate+nitrite concentration, as evidenced of its riverine origin. Also, Page *et al*., (1995)[15] found that nitrate nitrogen (NO_3^-N) concentration decreased with increasing salinity. This will cause the dilution of nitrate enriched mangrove surrounding water by tidal sea water. It is presumed that the oxidation of ammonium nitrogen, produced within the intertidal mangrove zone (recycling), may enter the pool of nitrate+nitrite nitrogen.

Diurnal and tidal variations of phosphate phosphorous (PO_4-P)

The mean concentration of phosphate (PO_4-P) during dry season was 4.52±1.43µm (Fig. 6) and it varied between 1.41µm and 6.57µm. During the wet season the mean concentration was 3.0±1.28µm varying between 1.5µm and 5µm (Fig. 5; Table 2). The plots of phosphate with water height showed a negative correlation in both dry and wet season [dry season (r= -0.67, n=24 p<0.01), wet season (r=-0.51, n=24, p<0.05)] and the correlation between salinity and phosphate was insignificant in dry season. During wet season, with salinity, phosphate showed a weak negative correlation (r^2=-0.43, n=24, p<0.05). This clearly suggests input of PO_4-P via fresh water export of land-derived and runoff from agricultural areas into the mangrove system. During the ebb tide, the concentration was high. This revealed that the dilution of seawaters during the flood tide decrease the concentration of phosphate. Balls (1994)[14] showed that conservative mixing of nutrients, particularly phosphate, was function of estuarine flushing time, as related to the particle-water interaction and chemical speciation. The present study infers that there is no significant correlations between phosphorous and salinity during the dry period. This biophilic element should also be partly regenerated biological processes of nutrient regeneration on the intertidal sediments, and not slowly exported by the river runoff.

Diurnal and tidal variations of dissolved organic carbon (DOC)

The mean concentration of dissolved organic carbon during dry season (DOC) was 427±85.3µm (Fig. 6) and it varied from 288µm to 603µm (Table 2). The plots of DOC with water height (r^2= -0.46, n=24, p<0.05) and salinity (r^2= -0.65, n=24, p<0.01) showed negative correlation. During wet season, the mean concentration of DOC was 327±32.48 ranging between 268µm and 389µm (Fig. 5). The plots of DOC with water level and salinity were inconsistent. During dry season, the concentration of DOC is slightly lower during night time. This will reveal that the photosynthetic activity produced a measurable increase in DOC during the day. This will elucidate the existence of a labile pool of dissolved organic matter from photosynthetic origin, and respiration of DOC at night. Balasubramanian and Venugopalan (1984)[16] suggested that part of the DOC pool in Pichavaram mangroves may consist of exudates or degradation products of microalgae and riverine input.

Diurnal and tidal variations of Chlorophyll *a*

The mean chlorophyll *a* values during dry season were 5.35±1.54µg l^{-1} and were observed to fluctuate between 3.1µg l^{-1} and 9.21µg l^{-1} (Fig. 6). In the wet season, mean values were 16.9±3.9µg l^{-1} and over a period of 24 hours it varied from 8.5µg l^{-1} to 26.5µg l^{-1} (Fig. 5). During both wet and dry seasons chlorophyll *a* showed wide variation over time. During the day time the values are high and declining at night. The relationship between the chlorophyll *a* and DO in dry season was positive (r^2= 0.79, n=24, p<0.01), and negative with salinity (r^2= -0.48, n=24, p<0.05). This will reveal that the chlorophyll *a* was derived from land-derived sources (Uppanar River) and sediments resuspended from the bottom at the ebb tide during the dry season. Similarly, during wet season, DO and chlorophyll *a* showed positive correlation (r^2= 0.31 and n=24), suggesting the DO production by phytoplankton and vice versa.

Discussion

The nutrient balance of the Pichavaram mangrove estuary was influenced by the tidal cycle and seasonality. This is indicated by the changes in inorganic nutrients, DOC and chlorophyll *a* in different seasons. This has been further established during the 24 hour diurnal survey in both the wet and dry seasons. Fresh water runoff had been strongly influenced the surficial temperature and salinity of the mangrove estuary. The enhanced salinity range during January and June 2005 was due to influx of large volume of seawater into the mangrove region during flood flow after the tsunami on 26th December 2004. The sediments at the river mouth were taken away by tsunami waves and deposited into the mangrove region. The sand bar at the river mouth was opened after the impact and caused the seawater intrusion into the creeks and canals of the mangrove forest.

There is no significant and/or negligible ammonium import through freshwater inflow observed during this study, but was predominantly from the effluent releases of the aqua ponds. High concentration of NO_3^-+NO_2^-N during rainy season are associated intensively with land derived sources like agricultural runoff from surrounding areas of the mangrove region contributing to the elevated nutrient loading in the surface waters. The present study infers leaf litter-derived DOC production in the mangrove waters due to efficient degradation by the microalgae. The high concentration of chlorophyll *a* during wet season was due to monsoonal runoff where high concentrations of nutrients brought into this mangrove system stimulated rich phytoplankton growth. The gross primary production was highest during monsoon due to high concentration of nutrients brought by the River Cauvery into the mangrove region and was low during dry period.

The effect of tidal amplitude has a prime role in the extent of variation in dissolved nutrient concentrations. The main feature of the low tidewater was high concentration of the inorganic nitrogen, phosphate and DOC indicating the "*tidal pumping*" mechanism[17]. Due to above mechanism porewaters with elevated concentrations of dissolved nutrients invade the creek waters from surrounding mangrove sediments following the gradual release of hydrostatic pressure towards low water. The high/low tide ratio of nutrients concentrations indicate that most of the diurnal nutrient oscillations in Pichavaram mangroves are due to dilution of nutrient-depleted seawater intrusion into the mangrove region during flood tide. The high tidal ranges during the dry season (June 2005), was due to the heavy influx of seawater into the mangrove region after tsunami. The present study had elucidated wide variations in water quality from pre-tsunami conditions and within the diurnal cycle.

Conclusion

The nutrient balance of the Pichavaram mangrove estuary was influenced by the tidal cycle and seasonal variations as revealed by the changes in inorganic nutrients, DOC and chlorophyll *a* in different seasons and a 24 hours diurnal survey during wet and dry seasons. The effect of tidal amplitude was important in determining in the extent of variations in nutrient concentrations. The main features of the low tidewater were high concentrations of the inorganic nitrogen, phosphate and DOC. The present study had established tidal pumpimg phenomena in this ecosystem. Furthermore, in the present study infers that there was an enhanced salinity and tidal range after tsunami. The tsunami resulted in no significant changes in nutrient outwelling and phytoplankton primary production of the mangrove surrounding waters in Pichavaram mangroves.

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