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Post-Tsunami Changes in Water Quality of Kalpakkam Coastal Waters, East Coast of India with Special Reference to Nutrients

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Abstract: Studies were carried out to evaluate the changes in water quality of Kalpakkam coast during post-Tsunami with special emphasis on nutrient contents. Samples were collected fortnightly from five locations, both surface and bottom at each location, during the period January-May 2006. Results revealed marginal decrease in DO (from 5.76 to 5.21 mg l^{-1}), increase in nitrate (from 1.14 to 3.43 µmol l^{-1}), silicate (from 5.55 to 7.20 µmol l^{-1}), phosphate (from 0.19 to 0.25 µmol l^{-1}) and decrease in chlorophyll-*a* content (from 6.15 to 4.34 mg m^{-3}) during the post-Tsunami period. Increase in nutrient contents did not commensurate with increase in chlorophyll possibly due to increase in turbidity in the coastal waters during the post-Tsunami period. A baseline data on TP and TN has been established for this coastal waters for future impact studies.

Key words: Tsunami, Kalpakkam, coastal water, nutrient change.

Introduction

The nutrient contents in any coastal waters determine its fertility potential (Harvey, 1960) and, therefore, it is important to gather information about their distribution and behaviour in different coastal ecosystems. Although, the life supporting processes in marine coastal ecosystems require many inorganic substances, nitrogen, phosphorous and silicon are considered to be more important, as they play a key role in phytoplankton abundance, growth and metabolism (Raymont, 1980; Grant and Gross, 1996) than the others. Therefore, studies pertaining to the source of origin, distribution pattern and rate of utilization of these inorganic components have become an imperative scientific research in coastal areas in last few decades.

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Considering the important role physico-chemical parameters play on the productivity potential of coastal waters, numerous studies pertaining to this have been made in coastal waters of India to evaluate their seasonal and spatial behaviour (Jayaraman, 1951, 1954; Ramamirtham and Patil, 1964; Sankaranarayanan and Reddy, 1968; Naqvi et al., 1978; Rajendran et al., 1980; Panigrahy et al., 1984; Sasmal et al., 1986; Choudhury and Panigrahy, 1991) and their impacts on the occurrence and abundance of phytoplankton populations (Ramamurthy, 1953; George, 1953; Subrahamanyan, 1959a, b; Rao, 1969; Varshney et al., 1983; Prasannakumar et al., 2000; Madhupratap et al., 2001; Sasmal et al., 2005). Though information on general hydrography and biology from Kalpakkam coastal waters are available (Nair and Ganapathy, 1983; Nair, 1985; Satpathy et al., 1987; Satpathy and Nair, 1990; Satpathy and Nair, 1996), the data on nutrients are scarce (Satpathy, 1996a). Moreover, continuous and systematic study on

nutrients has not been reported so far. In view of this, a study was organized during post-monsoon period (January-May, 2006) to estimate nutrient (nitrite, nitrate, ammonia, total nitrogen, phosphate, total phosphorous and silicate) contents in the coastal waters of Kalpakkam to elucidate any change in nutrient concentration between pre- and post-Tsunami, to find out any major change over the years due to anthropogenic impacts and to create baseline data for future so that the impact of the Prototype Fast Breeder Reactor (PFBR) (which is under construction and is going to use about 30 m^3sec^{-1} sea water for its cooling purpose) on the coastal waters can be studied. Moreover, total nitrogen (TN) and total phosphorous (TP) in this coastal waters are reported for the first time and form the baseline data for future. Additionally, general hydrographical parameters such as salinity, pH, dissolved oxygen (DO), turbidity and chlorophyll-*a* were also estimated, to correlate them with nutrient levels.

Methodology

Study Area

Kalpakkam coast (12° 33' N Lat. and 80° 11' E Long.) is situated about 80 km away from the mega city Chennai (Figure 1). At present a nuclear power plant (Madras Atomic Power Station) and a desalination plant are located near the coast. MAPS uses the seawater at the rate of 35 m^3sec^{-1} for the purpose of cooling the condenser. After extracting the heat, the heated seawater is released into the sea. Two backwaters namely the Edaiyur and the Sadras backwater system are two important features of this coast. During the period of North East monsoon and seldom during South West monsoon, these two backwaters get opened to the coast discharging considerable amount of freshwater to the coastal milieu for a period of 2 to 3 months. This part (Tamil Nadu) of the peninsular India receives bulk of its rainfall (~ 80%) from NE monsoon. The average rainfall at Kalpakkam is about 1000 mm. With the stoppage of monsoon, a sand bar is formed between the backwaters and sea, due to the littoral drift, which is a prominent phenomenon in the east coast of India. The Sadras backwater receives the domestic sewage of the Kalpakkam township, whereas anthropogenic influences in the Edaiyur backwater is negligible. During the present study the Sadras backwater remained disconnected from sea from the month of March, whereas the Edaiyur backwaters mouth remained open due to the dredging activities. During January-May 2006, samples were collected corresponding to the post-NE monsoon period from five prefixed locations of different environmental stresses. The stations were fixed with help of Global Positioning System (GPS) and are in a transect parallel to the shoreline, ~500 m inside the sea (Figure 1). The average depth of the water column at the sampling locations was about 7-8 m. The 1st and 5th stations are situated opposite the opening of the Sadras Backwater and Edaiyur Backwater respectively. The 3rd and 4th locations are near the intake point and the discharge point of MAPS respectively.

Methods

Samples were collected fortnightly in pre-cleaned polythene bottles and bottom samples were drawn by using a Niskin water sampler. Winkler's titrimetric method (Grasshoff et al., 1983) was followed for the estimation of DO. Salinity measurements were carried out by Knudsen's method (Grasshoff et al., 1983). Turbidity of the water samples was measured by turbidity meter (CyberScan IR TB 100) having 0.01 NTU resolution. pH measurement was carried out by a pH meter (CyberScan PCD 5500) with a resolution of 0.01. The dissolved micronutrients such as, nitrite, nitrate, ammonia, silicate, phosphate along with TN and TP were estimated by following standard methods (Parsons et al., 1984; Grasshoff et al., 1983), after filtering the water samples through 0.45 µ millipore filter paper. Chlorophyll-*a* was analyzed by spectrophotometry following the method of Parsons et al. (1984). For all the spectrophotometric analyses, a double beam UV–Visible Spectrophotometer (Chemito Spectrascan UV 2600) was used. Statistical analyses such as correlation matrix, cluster analysis and Principal Component Analysis (PCA) were carried out by using XLStat 2006 and StatistiXL 1.6 software.

Results and Discussion

Hydrographic Parameters

pH

pH values did not show significant variation during the present study. It ranged from 7.9-8.4 in surface waters and 7.9-8.3 in bottom waters. The monthly average values varied between 8.01±0.08 and 8.28±0.05 for surface but 8.04±0.06 and 8.26±0.03 for bottom. Highest and lowest values for both surface and bottom waters were observed during February and May respectively (Table 1). There was no conspicuous variation in the station-wise average values of pH (Table 2). The insignificant variation in pH observed could be attributed to the negligible terrestrial runoff and precipitation in the post-monsoon period.

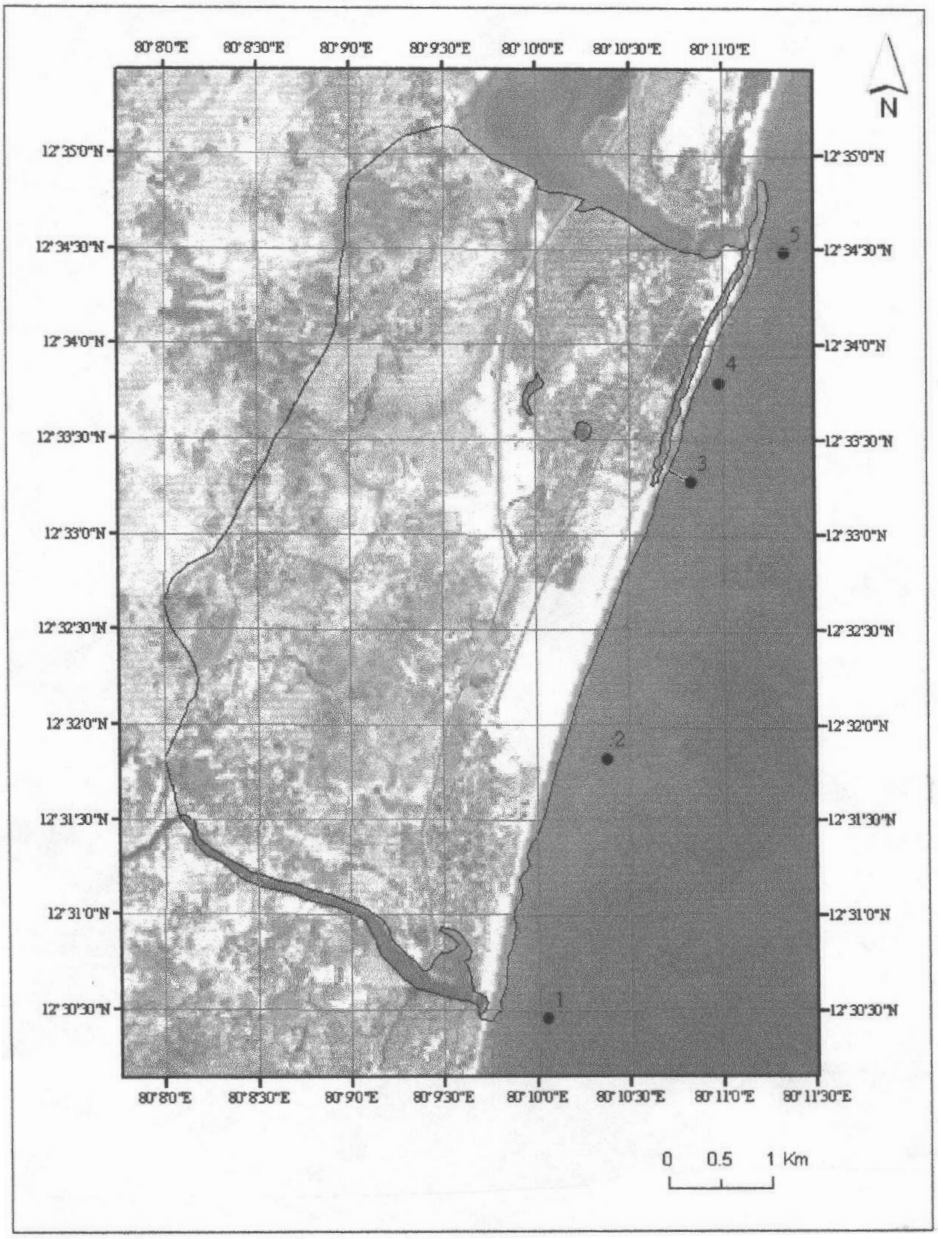

Figure 1: Study area showing the sampling locations.

Moreover, the extensive buffering capacity of the seawater that causes the change of pH within a very narrow limit (Riley and Chester, 1971) could be another factor for this marginal change.

Salinity

There was no significant difference in salinity between surface and bottom suggesting the absence of stratification. The observed surface and bottom salinity values ranged from 25.63-35.97 psu and 27.50-35.97 psu respectively. As expected, during the present study the salinity increased from January to May (Table 1), which can be attributed to the dilution of water mass due to addition of fresh water from the two backwaters to the coastal waters during January, which decreased in the subsequent months resulting in the increase in salinity. Since the depth of the water column is less (~6-7 m), there was no distinct variation in the surface and bottom salinity of any individual location (Table 2).

To establish the variation of the water quality parameters, a two-way analysis of variance (ANOVA) was performed using station, season and depth as factor, and it has been revealed that the variation of salinity over

season (F = 549.4; p< 0.000001) and station (F = 10.9; p< 0.011) are highly significant. The 1st location showed relatively low salinity (Table 2) as compared to other locations due to the relatively high freshwater discharge from the Sadras Backwater into the coastal waters. Salinity in coastal environments varies seasonally depending upon the mixing of highly saline seawater with the riverine fresh water in different quantities. During monsoon high quantity of freshwater discharge from the rivers causes the decline in the salinity of the surface waters (La Fond, 1954) and in the subsequent months the restoration occurs as the salinity continuously increases upto May/June as recorded in the present investigation. Similar behaviour of salinity in the coastal waters has also been reported by Varma & Reddy (1959) and Subramanyan & Sen Gupta (1965). On comparison of present salinity values with those available from the same locality (Satpathy, 1996a) during the same period did not reveal any change, indicating little impact of Tsunami on salinity.

Dissolved Oxygen (DO)

The DO contents varied between 3.3-7.6 mg l^{-1} and 4.4-5.9 mg l^{-1} for surface and bottom samples respectively. The surface values were marginally higher than the bottom values throughout the study period. A decrease in concentration of DO from January to May was noticed as evident from the monthly average values, which ranged from 4.64±0.19 mg l^{-1} in May to 7.40±0.24 mg l^{-1} in January for surface and 4.66±0.13 mg l^{-1} in May to 5.38±0.10 mg l^{-1} in February for bottom samples (Table 1). No clear trend in DO content was observed in respect of stations. The highest station-wise concentration for both the surface and bottom samples were encountered at 2nd location and there was no significant variation between the locations (Table 2). The range of DO observed during different months and at different stations showed that the coastal waters is not well saturated.

Dissolved oxygen is an important parameter in assessing water quality. In aquatic systems, oxygenation is the result of an imbalance between the process of

Table 1: Monthly variation of hydrographical parameters in the coastal waters of Kalpakkam from January-May, 2006

		pH		*Salinity*		*Turbidity*		*DO*	
Month		*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
January	Surface	8.20	±0.06	27.19	±1.35	5.47	±4.61	7.40	±0.24
	Bottom	8.19	±0.04	27.85	±0.31	8.19	±4.56		
February	Surface	8.28	±0.05	32.89	±2.10	6.49	±4.02	5.43	±0.14
	Bottom	8.26	±0.03	32.94	±2.50	15.22	±8.59	5.38	±0.10
March	Surface	8.22	±0.02	35.11	±0.33	8.58	±5.30	5.11	±0.50
	Bottom	8.22	±0.03	35.23	±0.48	21.27	±26.68	5.05	±0.36
April	Surface	8.25	±0.33	35.77	±0.10	10.74	±3.17	5.03	±0.73
	Bottom	8.11	±0.07	35.80	±0.05	15.68	±9.53	4.92	±0.36
May	Surface	8.01	±0.08	35.91	±0.06	13.99	±2.02	4.64	±0.19
	Bottom	8.04	±0.06	35.89	±0.05	17.80	±3.32	4.66	±0.13

Table 2: Station-wise variation of hydrographical parameters in the coastal waters of Kalpakkam from January-May, 2006

		pH		*Salinity*		*Turbidity*		*DO*	
Stations		*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
1	Surface	8.14	±0.12	33.92	±3.44	9.73	±4.92	5.02	±1.09
	Bottom	8.14	±0.12	34.08	±2.91	18.57	±11.75	4.99	±0.34
2	Surface	8.15	±0.11	34.23	±2.77	7.69	±5.05	5.50	±0.88
	Bottom	8.16	±0.11	34.05	±3.13	13.70	±6.23	5.16	±0.42
3	Surface	8.18	±0.10	34.11	±2.90	14.11	±8.12	5.41	±0.93
	Bottom	8.16	±0.10	34.08	±3.01	8.70	±5.09	5.05	±0.37
4	Surface	8.16	±0.11	34.82	±1.89	10.20	±4.69	5.11	±0.43
	Bottom	8.15	±0.07	35.45	±0.57	26.38	±32.73	4.83	±0.36
5	Surface	8.32	±0.37	34.94	±1.44	12.21	±3.29	4.98	±0.42
	Bottom	8.17	±0.10	35.35	±0.51	14.48	±4.37	4.83	±0.31

photosynthesis, degradation of organic matter and reaeration (Granier et al., 2000). During the present study the DO content of surface samples was relatively high as compared to the bottom samples (the average depth of stations was about 6-7 m). This observation agrees with the well known concept that the surface layers are characterized by high DO content due to photosynthetic activity and atmospheric dissolution/reoxygenation, whereas, oxidation of organic matter coupled with respiration causes reduction in DO content of the bottom waters. The variation in DO in coastal waters is also a function of physicochemical properties of water, which alter its solubility (Aston, 1980). A decrease in DO content from January to May was observed during the present investigation, which was associated with increasing salinity. This could be due to the fact that DO reached maximum level during the NE Monsoon period (October-January) concomitant with relatively low salinity resulted from precipitation, land run off and mixing of low saline waters rich in DO from the backwaters (Sadras and Edaiyur) with the coastal waters.

With the stoppage of the monsoon the salinity steadily increased from January onwards reaching a maximum in May. This process affects the solubility of oxygen thereby bringing down its concentration. Concentration of DO in the present study (average 5.21 mg l^{-1}) is marginally lower as compared to the earlier reported values (5.76 mg l^{-1}) from this coast (Satpathy, 1996a) during the same period for reasons not known to us. The bottom sediment had mixed with the shallow coastal waters by the strong turbulent Tsunami wave. As a result, oxygen was consumed for the decomposition of organic matter present in the water column. This hypothesis is strengthened further by the evidence that nutrients content in the coastal waters during post-Tsunami period have also increased (even a year after Tsunami) as compared to earlier period. Thus, Madras coastal waters, which was well saturated with oxygen (Subramanian and Sen Gupta, 1965), has been found to be not so, clearly indicating the role of Tsunami on the DO level. Moreover, fluctuation and no clear trend could also be attributed to the demand of oxygen by various complex processes occurring simultaneously in the surface layers.

Turbidity

The turbidity values ranged 1.44-17.76 NTU for surface waters and 1.85-92.77 NTU for bottom waters during the present study. Monthly average values of turbidity ranged from 5.47±4.61 NTU in January to 13.99±2.02 NTU in May in the surface waters and 8.19±4.56 NTU in January to 21.27±26.68 NTU in March in the bottom waters. Turbidity or water transparency is an important water quality parameter, which decides the depth of euphotic zone and thus indirectly acts as one of the key factors for productivity potential of coastal waters. The influx of silt born surface runoff, resuspension of surficial sediments by stirring action and high density of phytoplankters are the key factors which governs turbidity in estuarine and coastal waters and, thereby regulates the light penetration (Qasim et al., 1968; Dehadrai, 1970; Kalimurthy, 1973).

The surface waters turbidity during the present study increased from January to May (Table 1), whereas the bottom waters turbidity increased from January to March with a marginal decrease in April which again increased in May. This pattern of turbidity variation showed that the surface runoff is not the dominant factor regulating turbidity of the seawater in this area during January to May; rather the resuspension of surficial sediments by stirring action and currents might be the factor controlling it. However, the station-wise values were marginally high at 1st and 4th location, which could be due to the effect of the two backwaters. It has been reported that the wave action increases during the summer due to the northerly wind and the northward current prior to the onset of the SW monsoon (Varkey et al., 1996; McCreary et al., 1996 and Hugen et al., 2003) resulting in turbulent condition in the coastal waters. Thus, such restless condition in shallow coastal waters seems to have greatly favoured the resuspension of the bottom sediment due to stirring action resulting in low water transparency during summer (Qasim et al., 1968, Nixion, 1988). Moreover, the role of phytoplankters for the increased turbidity values in April and May can't be overlooked, as phytoplankton production in summer is generally high as compared to the remaining periods of the year (Ganapati and Rao, 1958, Prasannakumar et al., 2002) at this location.

Nutrients

Nitrogenous Nutrients

Nitrite concentration varied from 0.04-0.78 µmol l^{-1} in surface samples and 0.09-0.89 µmol l^{-1} in bottom samples. Highest concentrations for surface and bottom samples were observed during May, whereas lowest surface and bottom concentrations were observed in April and May respectively. Monthly average values showed that nitrite concentration gradually decreased from January (0.35±0.31 µmol l^{-1}) to April (0.14±0.07 µmol l^{-1}) and there was a visible increase (0.38±0.28 µ mol l^{-1}) in May in the surface waters, whereas for bottom samples the lowest concentration (0.18±0.04 µmol l^{-1}) was

observed in February which gradually increased and attained the peak value (0.45±0.33 µmol l^{-1}) in May (Figure 2a). The concentrations in the bottom samples as expected were always higher than that of the surface waters except for January. The station-wise values showed wide variations and ranged 0.18±0.14 to 0.25±0.20 µmol l^{-1} and 0.26±0.20 to 0.34±0.27 µmol l^{-1} for surface and bottom respectively (Figure 2b). Concentration of nitrate ranged from below detection limit (BDL) to 31.93 µ mol l^{-1} for the surface waters and 0.05- 25.27 µmol l^{-1} for the bottom waters. The highest values for surface and bottom were observed in May and lowest for the same in February (Figure 3a). Average values of various stations ranged 1.90±4.51 to 5.92±10.52 µmol l^{-1} in the surface samples and 3.41±7.16 to 5.09±9.94 µmol l^{-1} for the bottom samples (Figure 3b).

Contrary to the nitrite trend nitrate values did not show discernable difference between surface and bottom. Throughout the study period the ammonia values did not show any typical trend and most of the times it was below the detection limit. Its concentration varied BDL to 11.74 µmol l^{-1} and BDL to 3.14 µmol l^{-1} for surface and bottom respectively. Variations were wide for January and April (Figure 4a) and 1st & 3rd locations (Figure 4b). Values of TN ranged 6.23 to 69.31 µmol l^{-1} and 9.75-45.44 µmol l^{-1} for surface and bottom samples respectively. The highest and lowest values were obtained during January and May respectively for both surface and bottom samples (Figure 5a). The organic nitrogen contributed a major fraction of the TN concentration, which ranged 54.74-97.99% in surface and 50.28-96.23% in bottom waters. During January-March the organic nitrogen contribution remained almost constant, whereas in April it decreased and further declined in May (Table 5). Station-wise, the average value ranged 14.88±6.17 to 21.87±17.27 µmol l^{-1} and 15.14±5.18 to 21.49±13.01 µmol l^{-1} for surface and bottom respectively (Figure 5b). The variation trend in TN level was similar to that of nitrate. The variations in organic nitrogen among stations were not wide (70.72-82.33% for surface and 72.63-75.37% in bottom waters).

Nitrite is the intermediate oxidation state between ammonia and nitrate, and as such it can appear as a transient species by the oxidation of ammonia or by the reduction of nitrate. According to Santschi et al. (1990) and Chandran & Ramamurthy (1984) nitrite is often released into the water as an extracellular product of the planktonic organisms. Thus, being the most unstable form of inorganic nitrogen in seawater and due to its extracellular production, nitrite distribution depicts irregular picture and wide variations in coastal milieu. Relatively high concentration of nitrite in surface samples observed during January could be due to surface runoff and discharge from backwaters rich in nutrient contents into the coastal waters during NE monsoon period (October- January). Moreover, its poor utilization by the phytoplankton community during this period due to non-conducive conditions prevailed in the coastal waters could be another factor. Relatively high surface nitrite concentrations observed at 1st and 5th locations as compared to other locations could be due to the influence of the two backwater systems, which discharges nutrient rich water into the coastal waters (Ramadhas, 1977).

A comparison of the nitrite values reported from this coast prior to Tsunami (Satpathy, 1996a) showed that the mean value obtained during the present study (0.22 µmol l^{-1}) is lower than that of the earlier reported value (0.40 µmol l^{-1}). Considering the unstable nature of nitrite, possibly the observation is contrary to the post-Tsunami increase of other nutrients. With onset of the marine conditions from the post-monsoon to summer the nitrite concentrations decreased progressively. The monthly average values of nitrite showed a strong negative correlation ($p \geq 0.001$) with pH and a weak positive correlation ($p \geq 0.005$) with nitrate (Table 3). This shows the freshwater influx could be the chief contributor of nitrite in this coastal waters during this period. Station-wise average values of nitrite showed a strongly negative correlation ($p \geq 0.001$) with DO (Table 4), which could be attributed to the release of nitrogenous nutrient in the process of degradation of the organic matter at the expense of oxygen resulting in increase of nitrite content with decrease in DO levels. Similar negative correlations of nitrogenous nutrients with DO have been reported by Shirodkar and Jayakumar (1990), Singh et al. (1990) and Gopinath et al. (2002).

Out of the nine oxidation states (-3 to +5) of nitrogen, nitrate is thermodynamically the most stable form of combined inorganic nitrogen in well-oxygenated waters. Variations in nitrate and its reduced inorganic compounds are predominantly the results of biologically activated reactions. Quick assimilation by phytoplankton and enhancement by surface runoff results in large-scale spatio-temporal variation of nitrate in the coastal milieu (Qasim, 1977; De Souza, 1983; Zepp, 1997). Like nitrite, monthly average surface value of nitrate was higher in January than the other months which could be due to the similar reasons as described for nitrite. The BDL values were encountered in the month of March and April only in the surface samples. This could be attributed to the relatively high phytoplankton production during March and April as reflected from the coinciding relatively high concentration of chlorophyll-*a* observed during the same

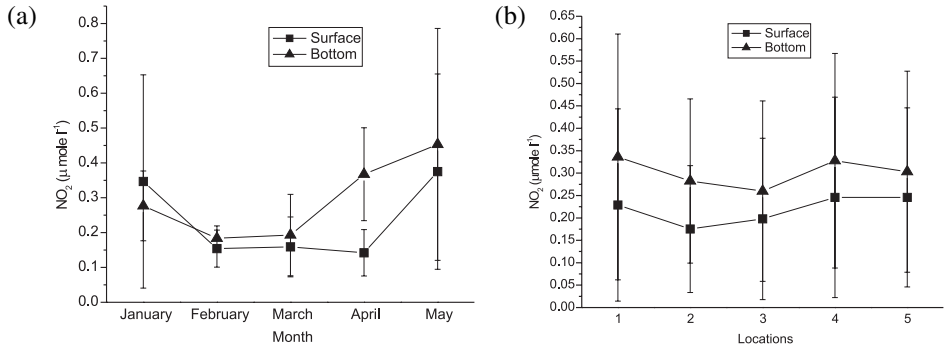

Figure 2: Monthly (a) and station-wise (b) variation of nitrite in the surface and bottom waters.

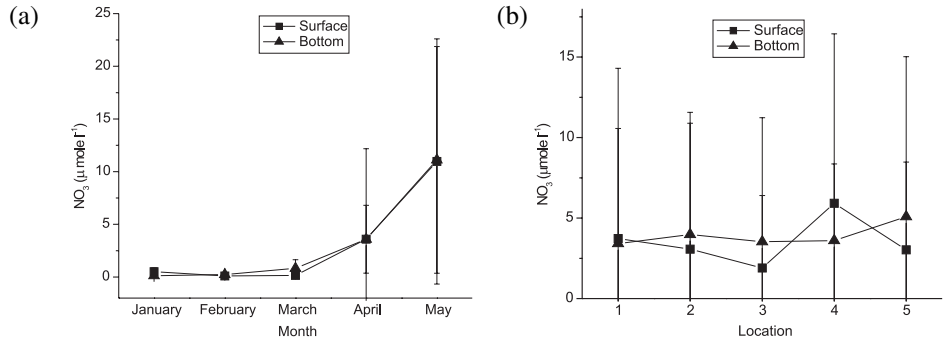

Figure 3: Monthly (a) and station-wise (b) variation of nitrate in the surface and bottom waters.

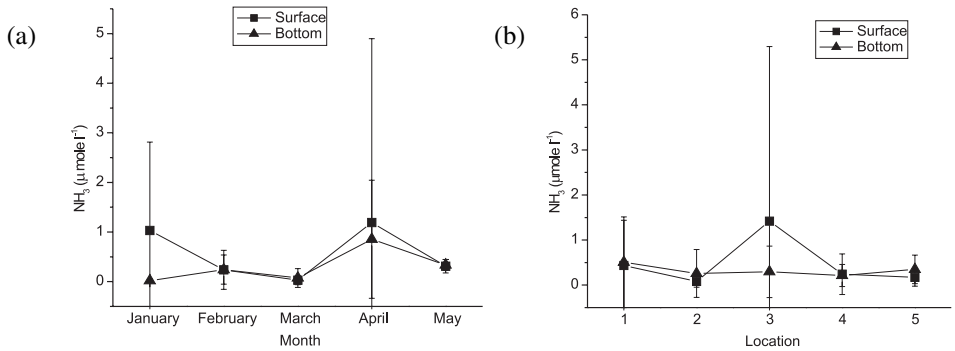

Figure 4: Monthly (a) and station-wise (b) variation of ammonia in the surface and bottom waters.

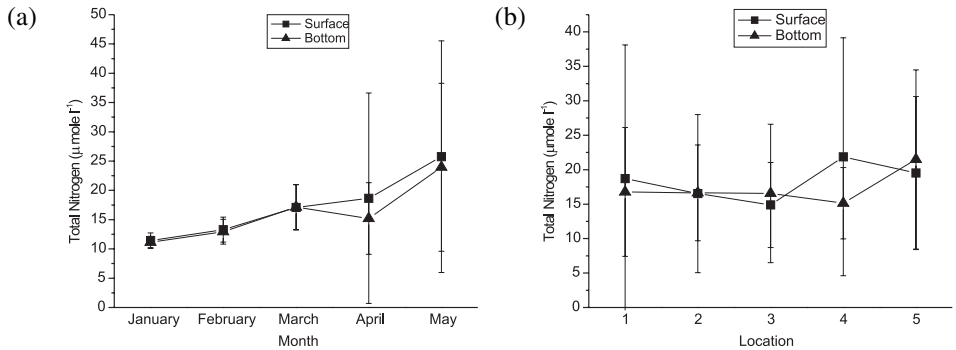

Figure 5: Monthly (a) and station-wise (b) variation of TN in the surface and bottom waters.

period, which corroborates observations of Ganapati and Rao (1958) and Prasannakumar et al. (2002) from the same region. Unlike the monthly average values, the station-wise average values showed a more or less uniform distribution without much variation.

In the present study, the average value (January-May) of nitrate for surface waters was found to be 3.43 µmol l^{-1}, much higher than the earlier reported values of 1.14 µmol l^{-1} for the same time period from this coast (Satpathy, 1996a). Tsunami impact as described under DO could be one of the factors responsible for this increase. Similar increase in nutrient concentrations in the post-Tsunami period has been reported by Reddy et al. (2005) from Dakshina Kannada coast, Southwest coast of India. Furthermore, human activities have markedly altered the earth's nitrogen cycle by doubling the natural rate of nitrogen fixation and causing atmospheric nitrogen decomposition to increase from three-fold to more than ten-fold compared to pre-industrial time (Kronvang et al., 1993; Bonsdorff et al., 1997). Increase in nutrient levels in many coastal marine systems in recent past has been observed (Ryther and Dunstan, 1971; Kronvang et al., 1993; Bonsdorff et al., 1997). In the present study, nitrate showed a strong positive correlation ($p \geq 0.001$) with total nitrogen in both month-wise and station-wise values and strong negative correlation ($p \geq 0.001$) with pH in month-wise values. However, it didn't show any significant correlation with salinity, whereas report by others (Choudhury and Panigrahy, 1991; Satpathy, 1996a) showed negative correlation between nitrate and salinity. This insignificant correlation between nitrate and salinity observed in this study could be due to low freshwater influx into the coastal waters.

Ammonia, the chief excretory product of the marine invertebrates, is also well known as a nutrient, which is preferred over nitrate by the phytoplankton community in certain environmental conditions. The above two factors i.e. excretory release and utilization by phytoplankton significantly affects the concentration of ammonia (Olson, 1980; Gilbert et al., 1982) in the marine environment. Peak value of ammonia was observed during the month of April, which coincided with the high chlorophyll-*a* concentration. Positive correlation ($p \geq 0.01$) between ammonia and chlorophyll-*a* was noticed in monthly average values. This suggested that the phytoplankton community, or the zooplankton community that might have proliferated during this period, released ammonia as the excretory product. Similarly a strong positive correlation ($p \geq 0.001$) with TP and weak positive correlation ($p \geq 0.01$) with silicate was observed. This could be due to the grazing effect of zooplankton on phytoplankton that released phosphorous and silicate (Cooper, 1952). The wide variation and irregular trend of ammonia observed during the present study could also be due to its oxidation to other forms or reduction of nitrate to lower forms in coastal waters (Sankaranrayanan and Qasim, 1969).

Total nitrogen values gradually increased from January to May. This could be due to the process of upwelling, which is a common phenomenon in the east coast of India during the pre- monsoon and summer resulting in high primary productivity (Murty, 1968; La Fond, 1957). The lowest values of TN were obtained in April, which coincided with the high chlorophyll-*a* values indicating its higher rate of utilization by the phytoplankton community. The 4th and 5th locations were found to have relatively high TN concentration as compared to other locations, which could be possibly due to the continuous discharge of the Edaiyur backwaters containing nitrogenous fertilizers from the nearby agricultural fields. No distinct trend was observed among the stations as well as between surface and bottom values. The decrease in organic nitrogen from January-May (Table 5) coincided with the increase in the inorganic nitrogen (nitrite + nitrate + ammonia) during the same period. This could be attributed to the microbial activity that degraded the organic nitrogen into its inorganic forms.

Phosphate and TP

Inorganic phosphorous concentration ranged 0.05-1.05 µmol l^{-1} and 0.05-0.46 µmol l^{-1} for surface and bottom waters respectively. Surface concentration remained high during January and February, whereas the bottom concentrations were higher during the other periods (Figure 6a). The monthly average values showed that the concentration for surface waters decreased from January to March and remained almost constant for the rest of the study period, whereas the bottom concentration gradually increased from January to April with a marginal decrease in May. The highest concentration in surface and bottom samples was observed at the 1st location (Figure 6b). As expected its level was higher in bottom samples than the surface for different stations; however, for months such distinct trend was not observed. The variation in concentration of TP also showed similar trend to that of the inorganic phosphate and it ranged 0.14-1.19 µmol l^{-1} in the surface waters and 0.27-1.28 µmol l^{-1} in bottom samples. Monthly average TP concentration of surface samples showed gradual decrease from January to March and then increased to its maximum and thereby decreasing in May (Figure 7a). However, for bottom samples a gradual increase from January to March and

Table 3: Correlation matrix (Pearson) of Station-wise average values

Variables	*pH*	*Salinity*	*Turbidity*	*DO*	*Nitrite*	*Nitrate*	*Ammonia*	*TN*	*Silicate*	*Phosphate*	*TP*	*Chlo-a*
pH	**1**											
Salinity	0.279	**1**										
Turbidity	-0.124	0.511	**1**									
DO	-0.100	**-0.585**	-0.514	**1**								
Nitrite	-0.175	0.410	**0.737**	**-0.815**	**1**							
Nitrate	-0.248	0.416	-0.080	-0.458	0.341	**1**						
Ammonia	-0.078	-0.321	0.091	0.349	-0.231	-0.509	**1**					
TN	0.235	0.391	-0.354	-0.376	0.045	**0.788**	-0.363	**1**				
Silicate	-0.355	-0.165	0.490	**-0.557**	**0.736**	0.038	-0.097	-0.165	**1**			
Phosphate	-0.081	0.240	**0.721**	**-0.793**	**0.887**	0.071	0.112	-0.076	**0.790**	**1**		
TP	0.326	0.483	0.431	**-0.577**	**0.570**	0.263	-0.038	0.153	0.085	**0.570**	**1**	
Chlo-a	0.152	**0.778**	**0.807**	**-0.710**	**0.625**	0.113	-0.012	-0.031	0.181	**0.630**	**0.596**	**1**

a: $p \geq 0.001$, b: $p \geq 0.005$, c: $p \geq 0.01$

Table 4: Correlation matrix (Pearson) of Monthly average values

Variables	*pH*	*Salinity*	*Turbidity*	*DO*	*Nitrite*	*Nitrate*	*Ammonia*	*TN*	*Silicate*	*Phosphate*	*TP*	*Chl-a*
pH	1											
Salinity	-0.336	1										
Turbidity	-0.407	0.631	1									
DO	0.398	-0.790	-0.587	1								
Nitrite	-0.877	-0.028	0.246	-0.012	1							
Nitrate	-0.891	0.519	0.424	-0.499	0.706	1						
Ammonia	0.026	-0.024	-0.197	0.380	0.156	0.099	1					
TN	-0.740	0.735	0.497	-0.634	0.408	0.904	-0.037	1				
Silicate	-0.229	-0.208	0.000	0.419	0.488	-0.035	0.604	-0.225	1			
Phosphate	-0.055	-0.470	-0.036	0.630	0.497	-0.107	0.402	-0.398	0.676	1		
TP	0.266	-0.049	-0.068	0.252	-0.022	-0.263	0.769	-0.400	0.652	0.525	1	
Chlo-a	-0.404	0.277	0.400	-0.206	0.360	0.387	0.576	0.336	0.566	0.126	0.500	1

a: $p \geq 0.001$, b: $p \geq 0.005$, c: $p \geq 0.01$

Table 5: Percentage contribution of organic phosphorous and organic nitrogen to the TP and TN concentrations

	Organic phosphorous (%)		*Organic nitrogen (%)*	
	Surface	*Bottom*	*Surface*	*Bottom*
Months				
January	26.74	40.41	83.50	96.23
February	43.25	42.78	96.30	94.92
March	50.38	38.54	97.99	93.60
April	67.33	52.27	73.58	68.37
May	36.94	23.64	54.74	50.28
Stations				
1	33.47	29.81	76.54	74.62
2	60.73	44.93	79.92	72.86
3	48.04	48.25	76.37	75.37
4	57.28	38.96	70.72	72.63
5	50.81	39.13	82.33	73.29

an abrupt elevation in April to reach maximum followed by decline in May was observed. The wide variation observed might be caused by various processes like adsorption and desorption of phosphate and buffering action of sediments under varying environmental conditions (Pomeroy, 1965). The organic phosphorous contribution to the TP concentration ranged from 26.74% in February to 67.33% in April for surface and 23.64% in May to 52.27% in April for bottom (Table 5). Station-wise average values of TP did not show much variation with respect to surface and bottom (Figure 7b). The contribution of organic phosphorous in station-wise values ranged 33.47-60.73% and 29.81-48.25% for surface and bottom waters respectively (Table 5).

Phosphate constitutes the most important inorganic nutrient that can limit the phytoplankton production in tropical coastal marine ecosystems (Cole and Salford, 1989) and thereby the overall ecological processes. Phosphate concentration in coastal waters depends upon

its concentration in the fresh water that mixes with the seawater within the land-sea interaction zone, phytoplankton uptake, addition through localized upwelling and replenishment as a result of microbial decomposition of organic matter. Usually seawater serves as the main source of phosphate in estuarine and coastal waters except those receiving fresh water contaminated with domestic wastes containing detergent and wastes from agro fields rich with phosphate-phosphorous fertilizer.

In the present study phosphate concentration in the surface waters in the month of January was higher at 1st location, which receives the Sadras Backwater discharge containing domestic sewage. This is also reflected in the average values observed for station 1 (Figure 7b). The average (January-May) value (0.25 µmol l^{-1}) of inorganic phosphorous contents during the present study was found to be marginally higher than that of the earlier reported value (0.19 µmol l^{-1}) by Satpathy (1996a) from this coast during the same period. This post-Tsunami increase in phosphate concentration could be due to the incursion of the nutrient rich deeper water into the coastal waters (Reddy et al., 2005) and the resuspension of the coastal sediment that releases phosphate to the water column (Chandran and Ramamurthy, 1984). Moreover, release of phosphate from sediments due to stirring action by strong tidal waves could also be another causative factor. The station-wise values showed strong negative correlation ($p \geq 0.001$) with DO and strong positive correlation ($p \geq 0.001$) with nitrite and silicate. The above positive correlation of phosphate with nitrite and silicate showed its continental origin since land runoff acted as the important source of nitrite and silicate at this location during January to May. Unlike phosphate, the peak value of TP was observed in April. This could be attributed to the increase in the organic fraction of phosphorous almost three times to that of the inorganic phosphate during this period (Table 5). The increase in the organic phosphorous from January to April could be due its release into the coastal waters by the gradually developing planktonic community. Relatively higher values of TP were observed at 4th and 5th locations, which could be due to the Edaiyur Backwater discharge that might have served as the source of phosphorous. Higher concentration of organic phosphorous in surface waters compared to the bottom waters could be due to the relatively intense production and consumption activities in the surface layers.

Silicate

Concentration of silicate during the present study ranged 2.33-26.55 µmol l^{-1} in surface and 1.13-20.70 µmol l^{-1} in bottom waters samples. Its concentration in the bottom samples remained high except in January when the surface concentration was higher than the bottom as observed from Figure 8a. Unlike other nutrients (nitrate and ammonia) silicate values were never found to be BDL. The lowest values for surface and bottom were observed during February. Higher silicate concentration was observed during January, which decreased in February and gradually increased up to April with a slight decrease in May. Silicate content at first location was found to be higher for both; surface (9.13±6.96 µmol l^{-1}) and bottom (10.52±4.45 µmol l^{-1}) samples, while the lowest values for surface and bottom were noticed at 2nd (6.62±1.54 µmol l^{-1}) and 5th (7.85±1.64 µmol l^{-1}) location (Figure 8b) respectively. The average silicate value for the surface waters in the present study was 7.2 µmol l^{-1} which is higher than that of the earlier reported values (5.55 µmol l^{-1}) from this coast (Satpathy, 1996a) during the same period.

The spatio-temporal variation of silicate in coastal waters is influenced by several factors, more importantly the proportional physical mixing of sea water with fresh water (Purusothaman and Venugopalan, 1972), adsorption of reactive silicate into suspended sedimentary particles (Lal, 1978), chemical interaction with clay minerals (Aston, 1980; Gouda and Panigrahy, 1992), co-precipitation with humic compounds and iron (Stephns and Oppenheime, 1972), and biological removal by phytoplankton, especially by diatoms and silicoflagellates (Rao, 1969; Aston, 1980, Liss and Spencer, 1970). In the present study, fresh water discharge from the backwaters rich in silicate (29.23 µmol l^{-1} for Edaiyur, 111.69 µmol l^{-1} for Sadras; unpublished data) into the coastal waters could be the reason for the observed higher values during January. The higher values at 1st location could also be ascribed to the Sadras backwater discharge. Apart from the strong positive correlation ($p \geq 0.001$) with phosphate, silicate showed a weak positive correlation ($p \geq 0.005$) with nitrite in the station-wise average values. In month-wise average values it showed a weak positive correlation ($p \geq 0.005$) with phosphate and total phosphorous. Entry of silicate into a coastal milieu mainly takes place through land drainage rich with weathered silicate material (Lal, 1978). Since fresh water is the main source of silicate, the above positive correlation of silicate with phosphate and nitrite showed their terrigineous origin as described earlier.

Chlorophyll-*a*

The values of chlorophyll-*a* ranged 0.57-8.29 mg m^{-3} and 1.33-15.95 mg m^{-3} for surface and bottom samples

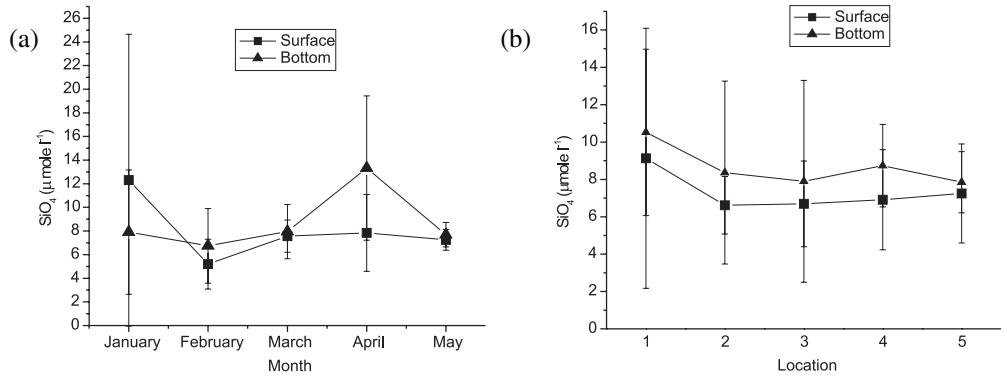

Figure 6: Monthly (a) and station-wise (b) variation of silicate in the surface and bottom waters.

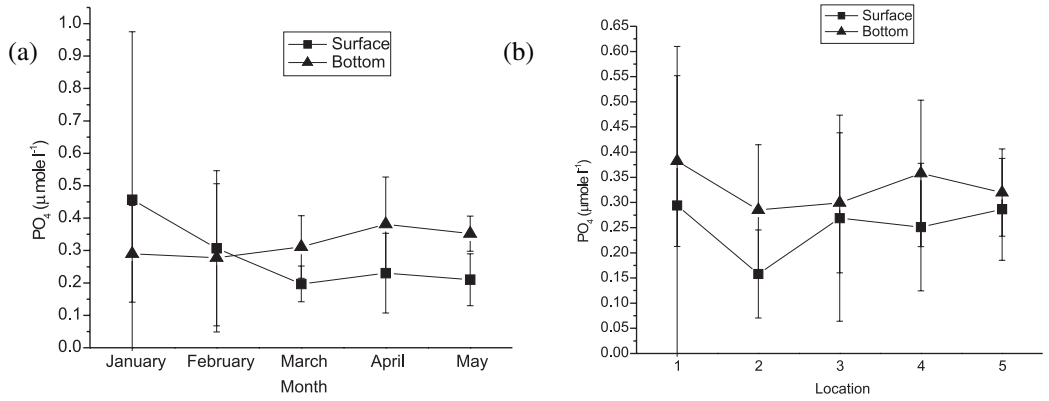

Figure 7: Monthly (a) and station-wise (b) variation of phosphate in the surface and bottom waters.

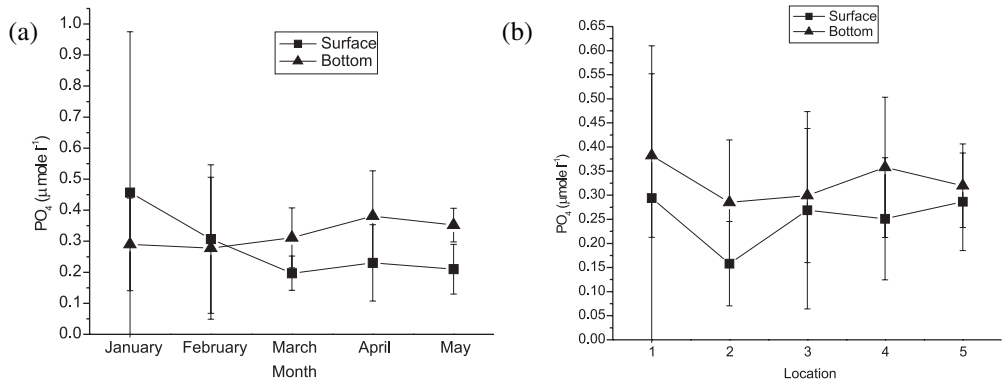

Figure 8: Monthly (a) and station-wise (b) variation of TP in the surface and bottom waters.

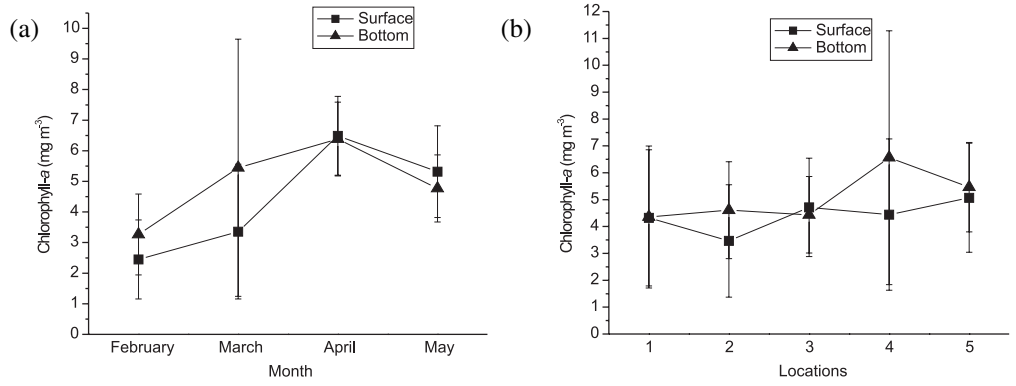

Figure 9: Monthly (a) and station-wise (b) variation of chlorophyll-*a* in the surface and bottom waters.

respectively. Due to operational difficulties January sample couldn't be estimated for chlorophyll-*a*. Relatively high values for surface (8.29 mg m^{-3}) and bottom (15.95 mg m^{-3}) were observed during April and March respectively at the 4th location. The bottom chlorophyll-*a* values were relatively high during February and March, whereas during the next two months higher surface values were noticed (Figure 9a). The station-wise average values didn't show any significant variation in chlorophyll-*a* content for surface waters however, a marginal variation between surface and bottom was observed (Figure 9b). Stations 4 and 5 were found to be marginally high in chlorophyll-*a* concentration compared to other locations.

Primary productivity potential of the marine environments depends upon the phytoplankters, which alone contributes ~90% of the total marine primary production. Thus, chlorophyll-*a,* which constitutes the chief photosynthetic pigment of phytoplankters, is an index that would provide the primary production potential upon which the biodiversity, biomass and carrying capacity of that system depends. Chlorophyll-*a* concentration increased gradually from February to April when it reached the peak and again decreased in May during the present study. This showed that the phytoplankton productivity was relatively high during the early summer and summer. A similar observation has been made from this area (Ganapati and Rao, 1958; Prasanna Kumar et al., 2002) and also from other coastal waters of India (Prasannakumar et al., 2000; Madhupratap et al. 2001; Sarma et al. 2006). High phytoplankton production during this period could be attributed to the upwelling that brings the nutrient rich deeper water to the surface, which is a regular phenomenon in this area (Murthy and Varadachari, 1968; La Fond, 1957). The average of the surface waters chlorophyll-*a* concentration was found to be 4.34 mg m^{-3} during the present study, which is lower compared to the previously recorded value of 6.15 mg m^{-3} (Satpathy, 1996b). This showed that the phytoplankton productivity of this region has been decreased in the recent years especially after the Tsunami, irrespective of the post-Tsunami increase in nutrient concentrations. The above observation depicted that phytoplankton growth and production in the marine environment is not solely dependent upon the nutrient level, rather it depends upon a proper combination of physicochemical and biological parameters, which might have been altered by the devastating effect of Tsunami leading to observed low phytoplankton production during the post-Tsunami period. It is worthwhile to mention here that turbidity of the coastal waters appears to have increased during post-Tsunami and thus possibly affected the light penetration thereby leading to reduction in the primary production. In the present study, the chlorophyll-*a* concentration increased with the increasing salinity from February to April, which can be seen from the strong positive correlation ($p \geq 0.001$) of the station-wise values of chlorophyll-*a* with salinity. This showed that the onset of favourable conditions for the growth of phytoplankton was initiated during the post-monsoon months and became conducive during the summer when the primary productivity reached its peak. A strong positive correlation ($p \geq 0.001$) between chlorophyll-*a* and turbidity observed in the station-wise values showed that the phytoplankton cell density that might have increased gradually from post-monsoon to summer leading to increase in chlorophyll-*a* concentration, contributed to the turbidity of the water column.

Cluster Analysis

Cluster analysis of month-wise average of water quality parameters showed four clusters (Figure 10a) revealing clearly the nature of the coastal waters at different time periods. The month of January, which is considered as the later part of NE monsoon behaved separately from all the other time periods and formed a clearly differentiated group (cluster formed by JanS and JanB). Second cluster was formed by February and March (FebS, FebB, MarS and MarB). This showed that February and March together behaved as a same time period when the physicochemical properties were almost similar. April, the month of onset of summer, and May, generally considered as the pre-monsoon (SW monsoon) or summer was distinctly separate from each other in terms of their physicochemical properties and thus, formed two separate clusters. When station-wise average values were considered, the surface and bottom averages form four clusters as well (Figure 10b). The first cluster is formed by surface of 1st location (1S) with bottom of 1st (1B), 2nd (2B) and 3rd (3B) locations, which showed these stations were alike. Surface of 2nd (2S) and 3rd (3S) location, which are in fact the transitional zone between the Sadras and Edaiyur backwaters and relatively free from any external influence, formed the second cluster. Third cluster is formed by surface of 4th (4S) and surface (5S) & bottom (5B) of 5th locations, which could be attributed to the influence of the Edaiyur backwater on these locations. The 4th bottom (4B) individually formed one cluster showing that it behaved separately from others and the peculiarity of this location is that, both the power plant effluents as well as the Edaiyur backwater influence

Table 6: Eigenvalues (monthly average values)

	F1	*F2*	*F3*
Eigenvalue	4.672	3.622	1.740
Variability (%)	38.931	30.184	14.499
Cumulative %	38.931	69.115	83.614

Table 7: Factor loadings (monthly average values)

	F1	*F2*	*F3*
pH	-0.789	-0.411	-0.419
Salinity	0.764	-0.102	-0.523
Turbidity	0.666	0.107	-0.243
DO	-0.800	0.312	0.334
Nitrite	0.448	0.667	0.576
Nitrate	0.877	0.290	0.225
Ammonia	-0.202	0.749	-0.378
TN	0.940	0.028	0.015
Silicate	-0.214	0.888	-0.020
Phosphate	-0.402	0.722	0.308
TP	-0.393	0.667	-0.565
Chlorophyll-*a*	0.352	0.700	-0.426

Table 8: Eigenvalues (station-wise average values)

	F1	*F2*	*F3*	*F4*
Eigenvalue	5.172	2.610	1.793	0.920
Variability (%)	43.101	21.754	14.943	7.670
Cumulative %	43.101	64.854	79.797	87.467

Table 9: Factor loadings (station-wise average values)

	F1	*F2*	*F3*	*F4*
pH	0.013	0.342	0.699	0.548
Salinity	0.646	0.481	0.403	-0.379
Turbidity	0.779	-0.439	0.203	-0.318
DO	-0.918	-0.192	0.117	-0.178
Nitrite	0.927	-0.152	-0.245	0.044
Nitrate	0.368	0.718	-0.474	-0.177
Ammonia	-0.218	-0.580	0.340	0.060
TN	0.157	0.869	-0.199	0.192
Silicate	0.567	-0.483	-0.572	0.261
Phosphate	0.867	-0.381	-0.104	0.261
TP	0.690	0.149	0.356	0.252
Chlorophyll-*a*	0.830	-0.040	0.428	-0.265

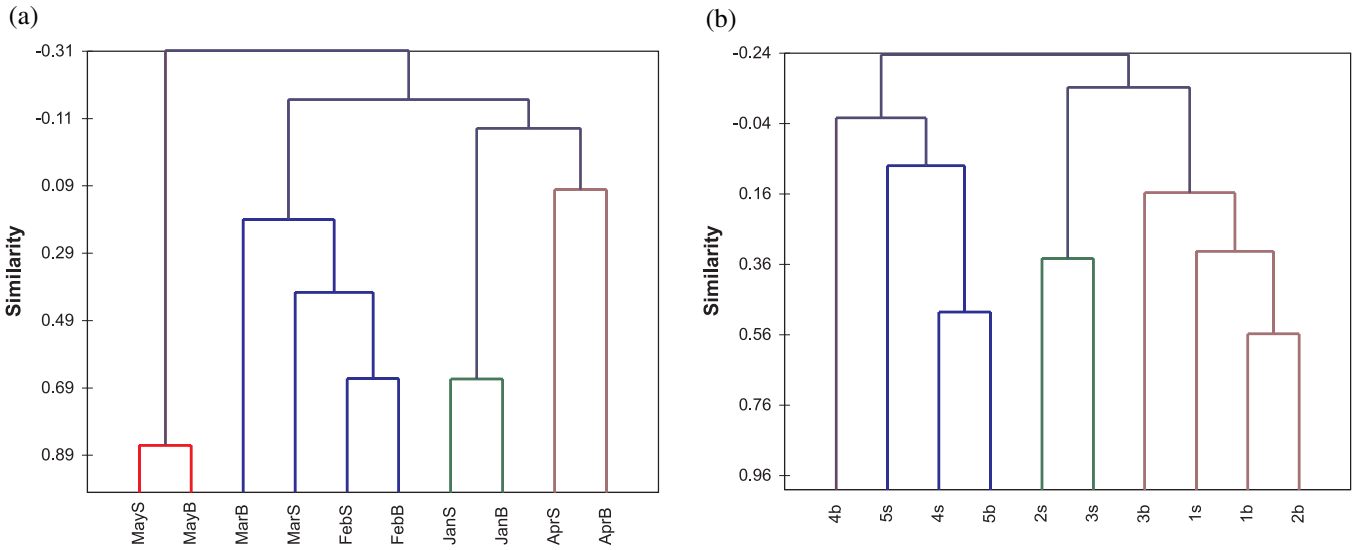

Figure 10: Dendrogram showing the clusters formed by surface and bottom samples for Months (10a) and for different locations (10b)

its hydrology. However, the depth profile and the current patterns that determine the turbulence and vertical mixing could be the factor behind such behaviour of these locations.

Principal Component Analysis (PCA)

PCA of the month-wise average values developed three principal components (PC) which explain 10.03% of water quality variability in Kalpakkam coastal waters as can be determined from the eigenvalues (Table 6). Negative factor loadings of pH, DO, ammonia, silicate, phosphate and TP can be seen in PC-1 (Table 7). In PC-2 positive loadings of almost all the parameters can be seen except pH and salinity, whereas in PC-3 positive loadings of DO, nitrite, nitrate, TN and phosphate were noticed. PCA of the station-wise average of parameters

also developed three PCs (Table 8). Positive factor loading for all the parameters except DO and ammonia can be seen in PC-1, whereas, except pH, salinity, nitrate, TN and TP, all other parameters are negatively loaded in PC –2 (Table 9). All the other parameters except nitrite, nitrate, TN, silicate and phosphate were negatively loaded in PC-3.

Conclusion

It is evident from the present study that Tsunami had considerable impact on the changes in water quality. An increase in nitrate, phosphate, silicate and turbidity and conversely decrease in chlorophyll-*a* concentration was noticed during post-Tsunami period. The observed changes resulted a great adverse impact on the primary productivity of this coastal environment. Of course, the distribution of dissolved inorganic nutrients in this tropical coast is also very much influenced by additional factors including tidal (hydrodynamic processes) (Bowman, 1977; Ho, 1977), physical stirring by currents and benthic invertebrates (Hammond et al., 1977; Hammond and Fuller, 1979; Mc Caffery et al., 1980) as well as abundant rainfalls due to NE monsoon and sewage transport by Sadras backwater.

The present work is a sustainable management plan considering basically four components: (i) baseline and monitoring studies, (ii) water quality criteria establishment, (iii) identification of sources, pathways and quality of nutrients and (iv) pollution control abatement and rehabilitation.

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