Phytoplankton diversity in the Parangipettai coastal waters, southeast coast of India

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Abstract

An investigation was carried out during June 2005 to May 2007 on hydrography, composition and community structure of phytoplankton including chlorophyll *a* in Parangipettai coastal waters (southeast coast of India). Air and surface water temperatures varied from 25.5 to 31.2 °C and from 25 to 29.3°C, respectively. Salinity values varied from 5 to 33.1‰ and the pH ranged between 7.2 and 8.3. Dissolved oxygen content varied from 3.1 to 7.9 mg l^{-1} while the light extinction coefficient values (LEC) ranged between 1.8 and 11.0 cm. The range of inorganic nutrients viz., nitrate, nitrite, phosphate and silicate were: 6.5 - 27.0 µM; 1.0 - 8.9 µM; 0.1 - 3.0 µM and 15.0 - 140 µM, respectively. The range of chlorophyll *a* was: 2.0 - 7.5 µg l^{-1}. Presently, 117 phytoplankton species representing different classes viz: Bacillariophyceae (66); Dinophyceae (22); Cyanophyceae (19); Chlorophyceae (7) and Chrysophyceae (3) were recorded. The phytoplankton cell abundance varied from 0.14 to 132 cells ml^{-1}, with peak diversity (3.52 bits ind.$^{-1}$) during summer season. The maximum abundance was found during summer season coinciding with the stable hydrographical conditions. Canonical Correspondence Analysis was applied in this study for discriminating environmental factors effecting on phytoplankton community at species level.

Introduction

Estuaries are transition areas between land and sea forming aquatic ecosystems that are characterized by a variety of interrelated biotic and abiotic structural components and intensive chemical, physical and biological processes (David *et al.*, 2005; Marques *et al.*, 2006). Estuarine variability is reflected in the dynamics of the biological populations, particularly planktonic ones. Spatio-temporal variation and habitat types are among the most important factors affecting patterns of species abundance, composition and size structure of estuarine plankton (Hoffmeyer, 2004). Assemblages can also vary depending on the geographical locations and on geological, hydrological and ecological factors (David *et al.*, 2005). The relationship between distribution of plankton communities and physical and/or chemical variables has been studied in several estuaries, and frequently salinity and temperature have been shown to be the most important parameters affecting the distribution and abundance of plankton (Mouny and Dauvin, 2002; Tackx *et al.*, 2004; Marques *et al.*, 2006).

Phytoplankton initiates the marine food chain, by serving as food to primary consumers like zooplankton, shellfish and finfish

(Sun *et al.*, 2001; Liu *et al.*, 2004; Zhang *et al.*, 2005; Saravanakumar *et al.*, 2008a; Rajkumar *et al.*, 2009; Vengadesh Perumal *et al.*, 2009). Biomass and productivity of phytoplankton in different size ranges are important factors regulating the productivity of higher tropic-level organisms. The pelagic algal communities make important contributions to the smooth functioning of estuarine ecosystem (Kawabata *et al.*, 1993). Phytoplankton species distribution shows wide spatio-temporal variations due to the differential effect of hydrographical factors on individual species and serve as good indicators of water quality including pollution (Rajashree Gouda and Panigrahy, 1996; Sun *et al.*, 2001; Liu *et al.*, 2004).

Physico-chemical parameters, species composition and seasonal variation in phytoplankton abundance has been studied in other regions of Indian coastal waters (Perumal *et al.*, 1999; Govindasamy *et al.*, 2000; Rajasegar *et al.*, 2000; Rajasegar, 2003; Geetha Madhav and Kondalarao, 2004; Thillai Rajasekar *et al.*, 2005; Asha and Diwakar, 2007; Ashok Prabhu *et al.*, 2008; Saravanakumar *et al.*, 2008a; Rajkumar *et al.*, 2009; Vengadesh Perumal *et al.*, 2009).

The present study deals with the species composition and community structure of phytoplankton from Parangipettai coastal waters in relation to hydrography.

Materials and Methods

Two sampling stations situated in the Vellar estuary and the neritic region of Bay of Bengal near Parangipettai along the southeast coast of India (11° 29' N latitude; 79° 46' E longitude) were chosen as study area. The station 1 is in Bay of Bengal, where the depth is about 5 m, with sandy bottom and station 2 is located opposite to the Marine Biological Station of Annamalai University with depth of 2.5 m and muddy bottom.

Monthly sampling was carried out to record the physico-chemical parameters and phytoplankton characteristics. Rainfall data was obtained from Parangipettai meteorological department (Government of India). Field data like temperature, salinity, dissolved oxygen and pH were measured during forenoon. Atmospheric and surface water temperatures were measured using standard mercury filled centigrade thermometer. Light penetration in the water column was measured with the help of a Secchi disc and the light extinction coefficient (LEC) was calculated using the Pool and Atkins (1929) formula. Salinity was estimated with the help of a hand refractometer (Atago, Japan) and pH was measured using Elico pH meter (Model LC-120). Dissolved oxygen was estimated by the modified Winkler's method, described by Strickland and Parsons (1972). For the analysis of nutrients, surface water samples were collected in clean polyethylene bottles and kept in an ice box and transported immediately to the laboratory. The water samples were filtered using a Millipore filtering system (MFS) and analyzed for dissolved inorganic phosphate, nitrate, nitrite and reactive silicate by adopting the standard methods described by Strickland and Parsons (1972).

Phytoplankton was sampled from the surface water, by towing a phytoplankton net (mouth diameter 0.35 m) made of bolting silk cloth (No. 30, Mesh size–48 µm), for half an hour. The collected samples were preserved in 5% neutralized formalin for further analysis. For the quantitative analysis of phytoplankton, the settlement method described by Sukhanova (1978) was adopted. Numerical plankton analysis was carried out using an inverted microscope. Phytoplankton were identified using the standard work of Tomas (1997). The phytoplankton analysed were assigned to major groups *viz.* diatoms, dinoflagellates, blue green algae and green algae. Chlorophyll *a* concentration was measured according to Strickland and Parsons (1972). Biodiversity indices such as species diversity, richness and evenness were calculated according to Shannon and Weaver (1949), Gleason (1922) and Pielou (1966).

Correlation coefficients (r) were calculated between phytoplankton cell abundance and physico-chemical parameters, while the analysis of variance (F) tests were made for hydrological parameters in relation to stations and seasons. All these statistical analyses were performed using SPSS statistical software (Version 11.5 for Windows, SPSS, Chicago, IL, USA).

CANOCO 4.53 version software was used for Canonical Correspondence Analysis (CCA) (ter Braak, 1986), performing a form of step-wise regression. Using the CCA routine implemented in CANOCO linking phytoplankton communities with environmental variables (rainfall, air and surface water temperature, salinity, pH, dissolved oxygen, light extinction coefficient, nitrate, nitrite, phosphate, silicate, chlorophyll *a*). CCA for all collections was performed on selected species, on the basis of their Dominance Index (*Y*) and in the light of known environmental data. A Monte Carlo permutation test (unrestricted) was used to determine the significance of species - environment relationships for all the collections made at Station 1 and 2 separately. Phytoplankton Dominance Index (*Y*) in each collection was calculated using the formula:

$$Y = \frac{n_i}{N} f_i$$

where n_i is the number of the individuals of species *i*, f_i is the frequency of species *i* that occurred in any particular sample and *N* is the total number of species.

Results and Discussion

Monthly rainfall ranging from 5 to 2050 mm was recorded from June 2005 to May 2006. No rainfall was recorded during June, 2005 or from February to April, 2006 or in January or in March, 2007 (Fig. 1a). Air and surface water temperatures varied from 25.5 to 31.2°C and from 25 to 29.3°C, respectively (Fig. 1 b and c). Salinity values varied from 5 to 33.1‰ and the pH ranged between 7.2 and 8.3 (Fig. 1 d and e). Variation in dissolved oxygen content ranged between 3.1 to 7.9 mg l⁻¹ while the light extinction

coefficient values ranged between 1.8 and 11.0 cm (Fig. 1 f and g). The range of inorganic nutrients viz., nitrate, nitrite, phosphate and silicate were: 6.5-27.0 µM; 1.0-8.9 µM; 0.1-3.0 µM and 15-140 µM, respectively (Fig. 1 h-k). The range of chlorophyll a content was 2.0-7.5 µg l⁻¹ (Fig. 1 l).

Out of 117 species, 66 species of diatoms (Bacillariophyceae), 22 species of dinoflagellates (Dinophyceae), 19 species of blue greens (Cyanophyceae), 7 species of greens (Chlorophyceae) and 3 species of silicoflagellates (Chrysophyceae) were found (Table 1). In terms of percentage, the composition of phytoplankton was principally made up of diatoms. *Odontella sinensis*, *Thalassionema frauenfeldii*, *Skeletonema costatum*, *Bacteriastrum comosum* and *Trichodesmium erythraeum* were the most abundant diatoms. The ranges of phytoplankton abundance were: 0.140 – 130 cells ml⁻¹ (Station 1) and 0.198 – 132 cells ml⁻¹ (Station 2)

(Fig. 2a). The range of species diversity, richness and evenness at Stations 1 and 2 were: 0.76 - 3.52, 0.50 - 0.96 and 060 - 0.96, respectively (Fig. 2 b-d). Like Thillai Rajasekar *et al.* (2005) we observed the number of phytoplankton species increased consistently towards the outer region of the Bay of Bengal, where the salinity was high.

At Station 1, the first axis of CCA had an eigenvalue of 0.246. Monte Carlo permutation tests (with forward selection) were used to identify which environmental variables (out of 11) explained the variance significantly (p < 0.05 level) (Table 2). Based on p value= 0.454, monthly sampling collection pattern is given in Fig. 3, and based on p value = 0.532, phytoplankton distribution and species abundance pattern is given in Fig. 4. The first CCA axis separated pH, rainfall, nitrite and silicate, most of these collections fell into the monsoon and postmonsoon seasons. The second axis separated dissolved oxygen, silicate, light extinction coefficient, most
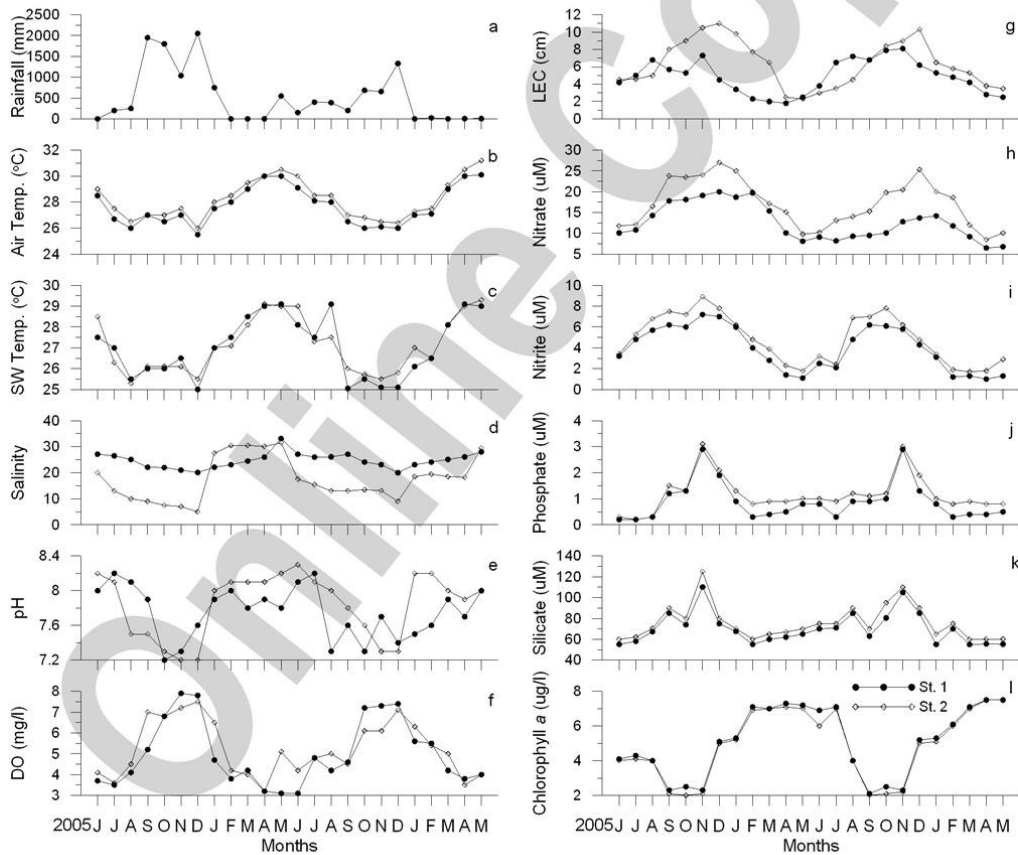

Fig. 1 (a-l) : Seasonal variations of physico-chemical parameters and chlorophyll a during 2005 to 2007 at stations 1 and 2

Table- 1 : List of phytoplankton species recorded during June 2005 to May 2007 at stations 1 and 2

Species Name	Station - 1				Station - 2			
	Sp. No.	n_i	f_i	Y	Sp. No.	n_i	f_i	Y
Amphora coffeaeformis	15	0.022998	0.625	0.014374		–	–	–
A. marina	44	0.00368	0.375	0.00138		–	–	–
A. ovalis	65	0.001883	0.166667	0.000314	30	0.010024	0.458333	0.004594
Asterionellopsis glacialis	8	0.031592	0.875	0.027643	28	0.01561	0.375	0.005854
Bacillaria paxillifera	10	0.032663	0.708333	0.023136	2	0.067909	0.958333	0.06508
Bacteriastrum comosum	28	0.010148	0.458333	0.004651	25	0.013225	0.541667	0.007164
B. delicatulum	98	–	–	–	71	0.000648	0.041667	2.7E-05
B. hyalinum	81	0.000594	0.083333	4.95E-05		–	–	–
Bellerochea malleus	5	0.041434	0.75	0.031076	4	0.05956	0.75	0.04467
Chaetoceros affinis	25	0.017553	0.291667	0.00512	37	0.012227	0.208333	0.002547
C. diversus	69	0.002011	0.125	0.000251	68	0.000648	0.083333	5.4E-05
C. indicus	95	3.2E-05	0.041667	1.33E-06				
C. lorenzianus	17	0.026993	0.375	0.010122	39	0.013079	0.125	0.001635
C. curvisetus	24	0.024451	0.25	0.006113		–	–	–
Coscinodiscus centralis	3	0.040588	1	0.040588	1	0.071143	0.958333	0.068179
C. gigas	47	0.010057	0.125	0.001257		–	–	–
C. granii	51	0.003374	0.291667	0.000984				
C. jonesianus	99	–	–	–	43	0.003337	0.291667	0.000973
C. radiatus	101	–	–	–	9	0.026421	0.75	0.019816
Cyclotella meneghiniann	36	0.005481	0.5	0.00274	34	0.007612	0.458333	0.003489
C. stelligera	102	–	–	–	22	0.013606	0.583333	0.007937
C. striata	43	0.006089	0.25	0.001522		–	–	–
Cylindrotheca closterium	46	0.005129	0.25	0.001282	40	0.006084	0.25	0.001521
Ditylum brightwellii	18	0.016031	0.583333	0.009352		–	–	–
D. sol	96	3.2E-05	0.041667	1.33E-06		–	–	–
Eucampia zodiacus	21	0.010503	0.625	0.006564	26	0.012108	0.541667	0.006559
Fragilaria intermedia	71	0.001189	0.208333	0.000248		–	–	–
Fragilariopsis oceanica	94	4.57E-05	0.041667	1.9E-06		–	–	–
Gyrosigma balticum	31	0.012251	0.333333	0.004084	36	0.007604	0.375	0.002852
Helicothaeca tamensis	90	0.000274	0.041667	1.14E-05		–	–	–
Isochrysis galbana	103	–	–	–	63	0.000994	0.083333	8.28E-05
Lauderia annulata	61	0.003017	0.125	0.000377	55	0.002679	0.083333	0.000223
Leptocylindrus danicus	2	0.054013	0.791667	0.042761	6	0.049449	0.791667	0.039147
Lithodesmium undulatum	86	0.00064	0.041667	2.67E-05		–	–	–
Paralia granulata	67	0.00133	0.208333	0.000277		–	–	–
P. sulcata	91	0.000114	0.083333	9.52E-06		–	–	–
Navicula granulata	42	0.005655	0.291667	0.001649	69	0.000564	0.083333	4.7E-05
N. longa	104	–	–	–	31	0.008209	0.458333	0.003763
N. indica	63	0.001061	0.333333	0.000354	67	0.001555	0.041667	6.48E-05
N. salinarium	92	0.000137	0.041667	5.71E-06		–	–	–
Nitzschia longissima	48	0.009554	0.125	0.001194		–	–	–
N. acuta	105	–	–	–	56	0.001771	0.125	0.000221
Odontella sinensis	1	0.048976	0.875	0.042854	3	0.059763	0.833333	0.049803
O. mobiliensis	6	0.045712	0.666667	0.030475	5	0.064555	0.666667	0.043036
Palmeria hardmaniana	14	0.021622	0.708333	0.015315	18	0.014129	0.625	0.00883
Paralia sulcata	79	0.00096	0.083333	8E-05		–	–	–
Planktoniella sol	4	0.041488	0.75	0.031116	15	0.01412	0.833333	0.011767
Pleurosigma angulatum	56	0.003273	0.208333	0.000682		–	–	–
P. elongatum	34	0.014326	0.25	0.003582	52	0.003094	0.083333	0.000258
P. normanii	106	–	–	–	73	0.000363	0.041667	1.51E-05
Proboscia alata	11	0.030035	0.666667	0.020023	12	0.026702	0.666667	0.017801
P. hebetate	59	0.0032	0.125	0.0004	70	0.000735	0.041667	3.06E-05
P. imbricata	64	0.001554	0.208333	0.000324	61	0.001339	0.125	0.000167
P. robusta	107	–	–	–	72	0.000432	0.041667	1.8E-05
P. styliformis	23	0.016567	0.375	0.006213	49	0.005237	0.083333	0.000436

Species	No.	n_i	f_i	Y	No.	n_i	f_i	Y
Skeletonema costatum	16	0.027222	0.458333	0.012477	35	0.019862	0.166667	0.00331
Stephanophyxis palmeriana	76	0.000855	0.166667	0.000142	–	–	–	–
Thalassionema nitzschioides	9	0.029809	0.833333	0.024841	11	0.022221	0.833333	0.018518
T. frauenfeldii	12	0.024354	0.666667	0.016236	10	0.027803	0.666667	0.018536
Thalassiothrix longissima	78	0.000731	0.125	9.14E-05	65	0.000951	0.083333	7.92E-05
Thalassiosira eccentrica	39	0.007801	0.291667	0.002275	59	0.002074	0.083333	0.000173
T. subtilis	37	0.006322	0.416667	0.002634	44	0.003543	0.25	0.000886
T. decipiens	26	0.015176	0.333333	0.005059	17	0.019515	0.541667	0.01057
Triceratium favus	27	0.016913	0.291667	0.004933	48	0.005782	0.125	0.000723
T. reticulatum	60	0.0032	0.125	0.0004	–	–	–	–
Amphisolenia bidentata	83	0.000485	0.083333	4.04E-05		–	–	–
Ceratium breve	70	0.002011	0.125	0.000251		–	–	–
C. furca	19	0.018239	0.458333	0.00836	8	0.036159	0.708333	0.025613
C. lineatum	97	1.83E-05	0.041667	7.62E-07		–	–	–
C. macroceros	52	0.00384	0.25	0.00096	57	0.001737	0.125	0.000217
C. trichoceros	20	0.017873	0.458333	0.008192	16	0.017628	0.625	0.011018
C. tripos	35	0.009696	0.333333	0.003232	45	0.005314	0.166667	0.000886
Dinophysis caudata	58	0.003657	0.125	0.000457	75	0.000302	0.041667	1.26E-05
Gonyaulux digensis	88	0.000215	0.083333	1.79E-05		–	–	–
Karenia breve	57	0.00309	0.166667	0.000515		–	–	–
Noctiluca scintillans	38	0.005988	0.416667	0.002495	38	0.005405	0.416667	0.002252
Ornithocercus steinii	49	0.005531	0.208333	0.001152		–	–	–
Prorocentrum micans		–	–	–	21	0.015935	0.5	0.007967
Protoperidinium excentricum	87	0.000457	0.041667	1.9E-05	46	0.002895	0.25	0.000724
P. venustum	66	0.001783	0.166667	0.000297	76	0.000302	0.041667	1.26E-05
P. depressum	22	0.010893	0.583333	0.006354	27	0.008978	0.666667	0.005986
P. oceanicum	73	0.001029	0.208333	0.000214	64	0.000644	0.125	8.05E-05
P. pentagonium	55	0.002816	0.25	0.000704	62	0.001383	0.083333	0.000115
Pyrocystis fusiformis		–	–	–	54	0.001512	0.166667	0.000252
P. elegans	85	0.000411	0.083333	3.43E-05		–	–	–
Anabena variabilis	32	0.006391	0.583333	0.003728	33	0.006049	0.583333	0.003529
A. ambigua	33	0.008	0.458333	0.003666	29	0.0103	0.541667	0.005579
A. circinalis		–	–	–	23	0.014604	0.5	0.007302
A. milleri		–	–	–	53	0.001542	0.166667	0.000257
Cylindrosperm majus	40	0.006095	0.291667	0.001778	32	0.009462	0.375	0.003548
Chroococcs tenax		–	–	–	74	0.000346	0.041667	1.44E-05
Lyngbya aestuarii	29	0.010084	0.458333	0.004622	20	0.016073	0.5	0.008036
L. major	62	0.002926	0.125	0.000366		–	–	–
L. majuscule	82	0.000594	0.083333	4.95E-05	58	0.001469	0.125	0.000184
Microcystis littoralis		–	–	–	66	0.000864	0.083333	7.2E-05
M. aeruginosa	80	0.001371	0.041667	5.71E-05		–	–	–
Oscillatoria salina	13	0.019606	0.791667	0.015521	7	0.031827	0.833333	0.026522
O. agardhii	89	0.000375	0.041667	1.56E-05		–	–	–
Phormidium tenue	30	0.007734	0.541667	0.00419	24	0.013355	0.541667	0.007234
P. molle	93	0.000137	0.041667	5.71E-06		–	–	–
Spirulina subsalsa	54	0.003108	0.291667	0.000907		–	–	–
S. major	77	0.000937	0.125	0.000117	60	0.001033	0.166667	0.000172
Synechococcus sp.	53	0.00384	0.25	0.00096	47	0.003474	0.208333	0.000724
Trichodesmium erythraeum	7	0.064024	0.458333	0.029344	13	0.049558	0.333333	0.016519
Chlorella vulgaris	41	0.003468	0.5	0.001734	41	0.003845	0.375	0.001442
Deamidium swartzii	74	0.001189	0.166667	0.000198		–	–	–
Tetrastrum sp.		–	–	–	14	0.019881	0.666667	0.013254
Ulothrix sp.	50	0.003355	0.333333	0.001118	51	0.001577	0.208333	0.000329
Pediastrum simplex	45	0.003145	0.416667	0.00131	19	0.012919	0.625	0.008074
Volvox sp.	68	0.000902	0.291667	0.000263		–	–	–
Euglena acus	84	0.000297	0.125	3.71E-05		–	–	–
Emiliania sp.	72	0.000983	0.25	0.000246	42	0.004105	0.291667	0.001197
Dictyocha sp.	75	0.000713	0.25	0.000178	50	0.001237	0.333333	0.000412

(Species number is using in CCA, n_i is the number of the species individuals, f_i is the frequency of species, Y is the Dominant Index)
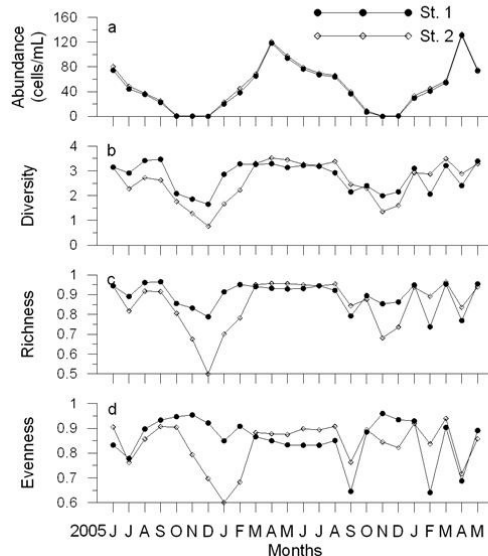
Fig. 2 (a-d) : Seasonal variations of phytoplankton abundance, diversity, richness and evenness during 2005 to 2007 at stations 1 and 2

of the collections were in summer and monsoon. Only one environmental parameter salinity was in the third CCA axis, and heavily impacted in postmonsoon. While the other environmental parameters further separated temperature (air and water) and phosphate along with monthly sampling collections were summer (Fig. 3). From Fig. 4, it is clear that *Planktoniella sol* was heavily affected by phosphate. *Skeletonema costatum, Chaetoceros affinis, Ceratium furca, C. trichoceros, Protoperidinium depressum* and *Lyngbya aestuarii* were associated with high salinity. *Thalassionema nitzschioides, Proboscia alata* and *Bellerochea malleus* relied heavily on rainfall, pH, nitrite and nitrate. *Thalassiothrix frauenfeldii, Amphora coffeaeformis* and *Bacillaria paxillifera* were sensitive to light intensity.

At Station 2, the first axis of CCA had an eigenvalue of 0.402 (Table 2). Based on p value= 0.452, monthly sampling collection pattern is given in Fig. 5, and based on p value= 0.154, phytoplankton distribution and species abundance pattern is given in Fig. 6. First CCA axis separated temperature (air and water) and phosphate, and most of these collections were fall into the summer, while the second CCA axis separated no parameter. The third CCA axis separated rainfall, dissolved oxygen, silicate, nitrite and light extinction coefficient, most of these collections were in premonsoon. The fourth CCA axis separated salinity, nitrate and pH, and most of the collections were in the monsoon and the postmonsoon (Fig. 5). According to the species - environmental plot, *T. frauenfeldii* was heavily affected by light intensity, and may thrive at high light intensity more than the other algal species. *Anabena circinalis* was greatly

affected by nitrite, while the *P. alata* and *C. furca* were by nitrate only (Fig. 6). *Coscinodiscus radiatus* and *O. sinensis* were living well in high rainfall season during the monsoon. *Phormidium tenue* and *Pediastrum simplex* were greatly affected by pH. *Odontella sinensis, O. mobiliensis* and *P. sol* were mostly presented in high dissolved oxygen and silicate contents during monsoon season.

Rainfall is the most important cyclic phenomenon in tropical countries as it brings important changes in the hydrographical characteristics of the estuarine environment. In the present study, the peak values of rainfall were recorded during the monsoon month of December 2005.

The surface water temperature showed an increasing trend from December to April and is influenced by the intensity of solar

Table- 2: Results of the CCA: Eigen values, species–environment correlations and percentage variance for estuarine mouth and Vellar estuary Phytoplankton abundance data; weighted correlation coefficient between environmental variables and CCA axes

| Axes	1	2	3	4
Station 1				
Eigen values	0.246	0.151	0.089	0.075
Species–environment correlations	0.835	0.72	0.855	0.914
Cumulative percentage variance				
of species data	17.782	28.682	35.124	40.55
of species–environment	32.812	52.925	64.812	74.823
Correlation coefficient				
Rainfall	-0.155	0.027	0.035	0.075
Atmospheric temperature	0.155	-0.177	0.556	-0.362
Surface water temperature	0.052	0.273	-0.218	0.005
Salinity	0.38	-0.014	0.063	0.008
pH	0.194	0.157	0.033	-0.019
Dissolved oxygen	0.196	-0.124	0.165	0.062
Light extinction co-efficient	0.187	-0.338	0.171	-0.033
Nitrate	0.572	-0.002	-0.101	0.025
Nitrite	0.02	0.582	0.479	0.006
Phosphate	-0.015	0.374	-0.205	-0.091
Silicate	0.177	-0.299	-0.133	-0.333
Station 2				
Eigen values	0.402	0.205	0.185	0.172
Species–environment correlations	0.949	0.977	0.905	0.946
Cumulative percentage variance				
of species data	21.553	32.54	42.48	51.733
of species–environment	29.583	44.665	58.307	71.008
Correlation coefficient				
Rainfall	0.249	-0.134	0.53	-0.651
Atmospheric temperature	0.362	-2.375	-2.106	2.72
Surface water temperature	0.302	2.094	0.801	-2.22
Salinity	-0.651	0.934	1.607	-0.285
pH	-0.212	-0.662	-0.339	0.255
Dissolved oxygen	-0.826	-0.004	-0.01	0.992
Light extinction co-efficient	0.276	-0.661	0.699	-0.049
Nitrate	0.405	0.414	-2.009	0.4
Nitrite	-0.236	-0.234	0.068	-0.078
Phosphate	0.57	0.373	0.119	0.17
Silicate	-0.504	-0.157	-0.296	-0.002
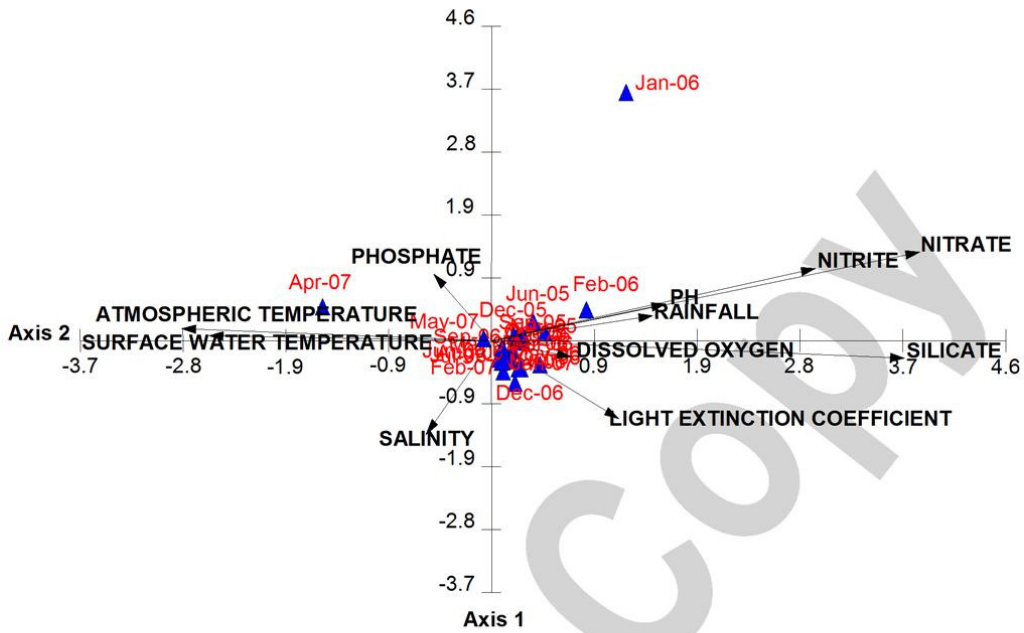
Fig. 3: CCA showing scatter plot for 24 monthly sampling *vs* environmental variables at station 1
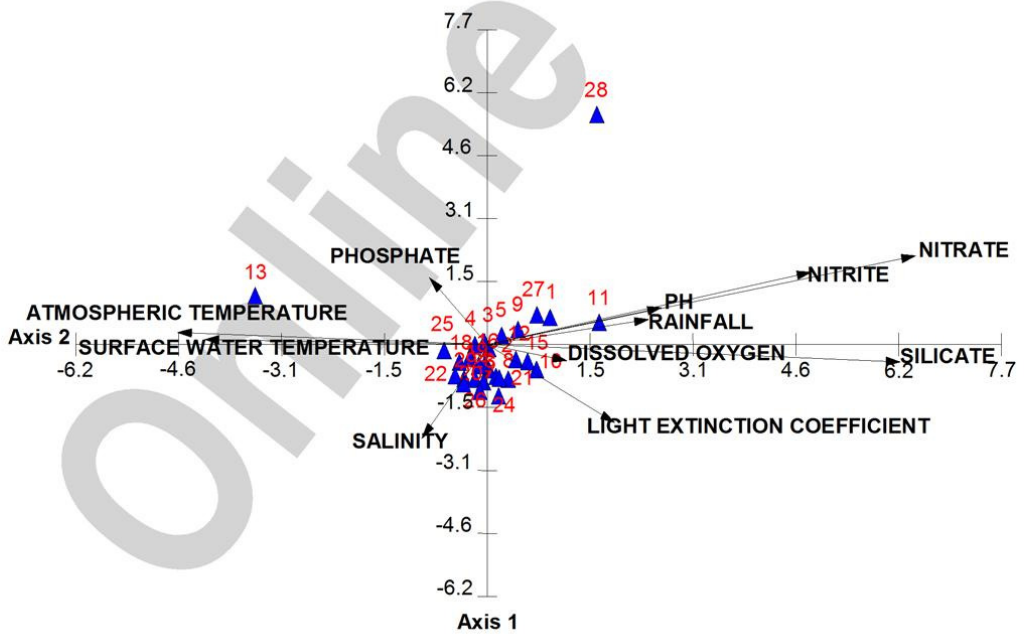

Fig. 4: CCA showing scatter plot for phytoplankton species *vs* environmental variables at station 1 (Species number refer to Table 1)
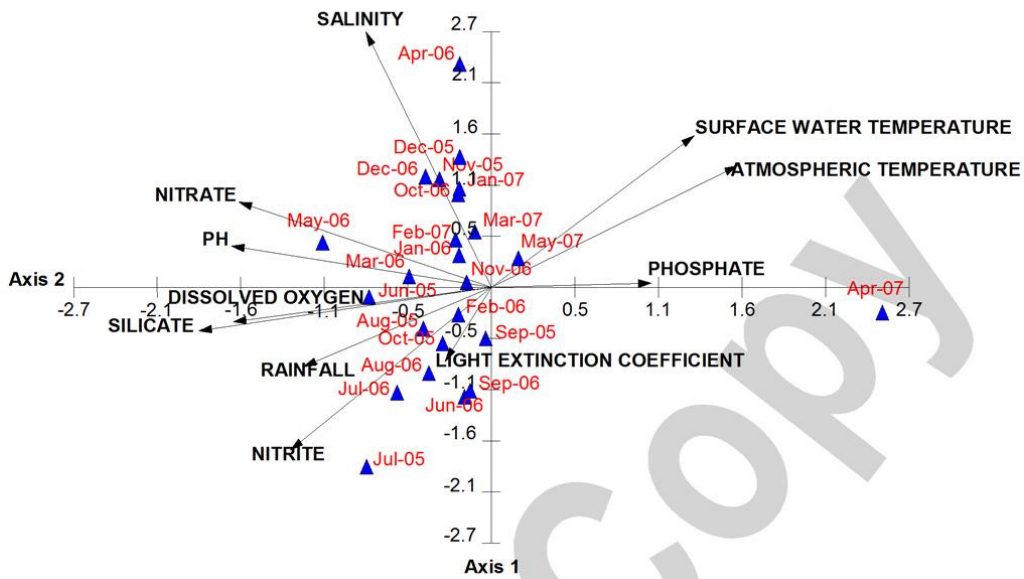
Fig. 5: CCA showing scatter plot for 24 monthly sampling *vs* environmental variables at station 2
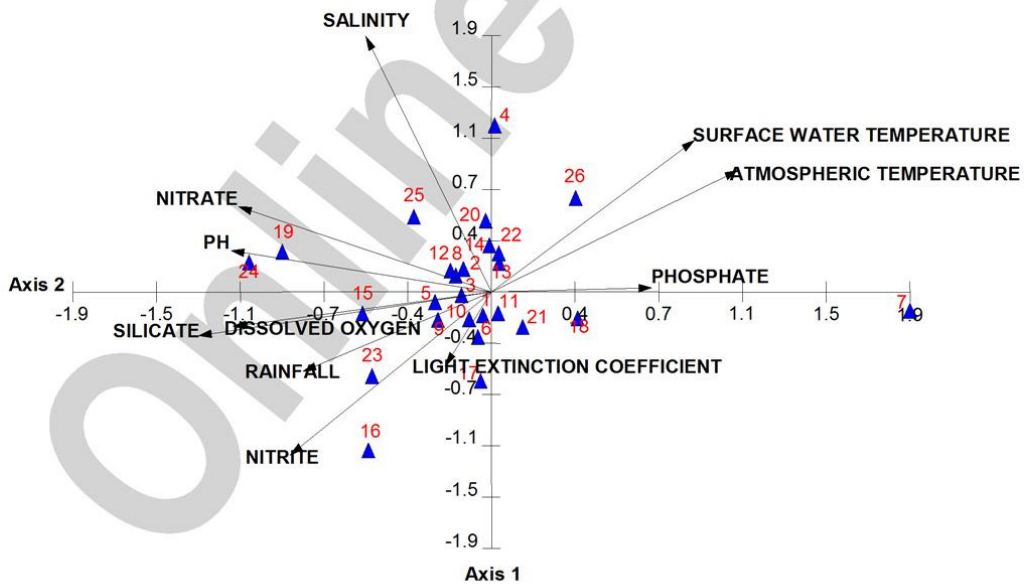

Fig. 6: CCA showing scatter plot for phytoplankton species *vs* environmental variables at station 2 (Species number refer to Table 1)

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radiation, evaporation, freshwater influx and cooling and mixing by the ebb and flow from adjoining neritic waters (Govindasamy *et al.*, 2000; Saravanakumar *et al.*, 2008b). The low value observed in November was due to strong land sea breeze and precipitation and the recorded high summer value could be attributed to high solar radiation (Govindasamy *et al.*, 2000; Ashok Prabu *et al.*, 2008; Rajkumar *et al.*, 2009).

The salinity was found to be high during postmonsoon and summer seasons and low during the monsoon season at both the stations. The recorded higher values could be attributed to the low amount of rainfall, higher rate of evaporation and also due to neritic water dominance (Balasubramanian and Kannan, 2005; Asha and Diwakar, 2007). During the monsoon season, the rainfall and the freshwater inflow from the land moderately reduced the salinity.

Light extinction coefficient values were high during monsoon season due to the higher concentration of dissolved organic matter and suspended sediments. Further, inundation by freshwater discharge and bottom sediment could also be the important factors in governing light penetration (Rajkumar *et al.*, 2009). The observed low summer value could be due to clean water condition and low runoff (Vengadesh Perumal *et al.*, 2009).

pH remained throughout the study period at both stations with maximum values during the pre-monsoon, post-monsoon and summer and the minimum during monsoon. Generally, its seasonal variation is attributed to factors like removal of CO_2 by photosynthesis through bicarbonate degradation, dilution of seawater by freshwater influx, low primary productivity, reduction of salinity and temperature and decomposition of organic matter (Bragadeeswaran *et al.*, 2007). The recorded high pH in summer might be due to the influence of seawater penetration and high biological activity (Govindasamy *et al.*, 2000) as well as to the occurrence of high photosynthetic activity (aravanakumar *et al.*, 2008b).

It is well known that the temperature and salinity affect the dissolution of oxygen (Saravanakumar *et al.*, 2008b). In the present investigation, higher values of dissolved oxygen were recorded during monsoon season which might be due to the cumulative effect of higher wind velocity coupled with heavy rainfall and the resultant freshwater mixing (Rajasegar, 2003). Paramasivam and Kannan (2005) attributed the seasonal variation of dissolved oxygen, mainly freshwater flow and impact of terrigenous sediments.

The observed high monsoonal phosphate value might be due to the regeneration and release of total phosphorus from bottom mud into the water column by turbulence and mixing (Saravanakumar *et al.*, 2008b). Moreover, the bulk of weatherings of rocks release soluble alkali metal phosphates (in the upstream area) that are carried into the estuaries (Govindasamy *et al.*, 2000). Super phosphates applied in the agricultural fields as fertilizers and alkyl phosphates used in household detergents can be other sources of inorganic phosphates (Bragadeeswaran *et al.*, 2007). The low summer

value could be attributed to the limited flow of freshwater, high salinity and utilization of phosphate by phytoplankton (Rajasegar, 2003). The variation may also be due to the processes like adsorption and desorption of phosphates and to the buffering action of sediment (Rajasegar, 2003).

The recorded highest monsoonal nitrate value could be mainly due to the organic materials received from the catchment area during ebb tide (Ashok Prabu *et al.*, 2008). Another possible way of nitrate input could be through oxidation of ammonia to nitrite (Rajasegar, 2003). The recorded low values during non-monsoon period may be due to its utilization by phytoplankton as evidenced by high photosynthetic activity and the dominance of neritic seawater having a negligible amount of nitrate (Bragadeeswaran *et al.*, 2007).

The silicate content was higher than that of the other nutrients and the recorded high monsoon values may be due to heavy inflow of freshwater derived from land drainage carrying silicate leach out from rocks and also from the bottom sediment (Rajasegar, 2003; Saravanakumar *et al.*, 2008b). The removal of silicates by adsorption and co-precipitation of soluble silicate with humic compounds and iron (Rajasegar, 2003). The observed low post-monsoon and summer values could be attributed to uptake of silicates by phytoplankton for their biological activity (Ashok Prabhu *et al.*, 2008).

A higher value of chlorophyll *a* was recorded during summer and the low value was observed during premonsoon and monsoon seasons. The reduction in chlorophyll *a* during monsoon season may be due to high freshwater discharge, causing turbidity and less availability of light (Godhantaraman, 2002; Thillai Rajasekar *et al.*, 2005).

Phytoplankton species composition was comparatively more at station 2 than at station 1. Generally, diatoms were found to be dominant in Vellar estuarine waters, which could well thrive in widely changing hydrographical conditions (Mani, 1992; Tiwari and Nair, 1998; Rajasegar *et al.*, 2000; Saravanakumar *et al.*, 2008a).

The observed high abundance and species diversity during summer and premonsoon seasons was associated with a predominance of diatoms viz: *B. malleus, C. lorenzianus, C. curvisetus, Leptocylindrus danicus, T. frauenfeldii, O. sinensis, O. mobiliensis, P. sol, C. centralis, S. costatum* and *T. erythraeum*.

The abundance of phytoplankton was lowest during monsoon months, associated with freshwater forms including *Anabaena* sp., *Oscillatoria* sp., *Chlorella* sp., *Lyngbya aestuarii, L. major, L. majuscule, Spirogyra* sp. *Volvox* sp. *Spirulina major* and *Microcystis* sp. The phytoplankton counts were high during southwest monsoon season (June-September) as reported in some of the previous studies in Bay of Bengal (Marichamy *et al.*, 1985).

The observed high phytoplankton abundance during the summer could be attributed to more stable hydrographical conditions prevailed during that period (Thillai Rajasekar *et al.*, 2005). Station

2 showed comparatively high abundance due to high nutrient concentrations (Rajashree Gouda and Panigrahy, 1996; Rajasegar *et al.*, 2000).

Species such as *B. comosum, O. sinensis, S. costatum, T. frauenfeldii, T. nitzschioides* and *T. erythraeum* were noticed during the entire study period, implying their euryhaline and eurythermal nature. Most phytoplankton species occurred on a seasonal basis. Species from the genera, *Bellerochea, Chaetoceros, Coscinodiscus, Leptocylindrus, Odontella, Skeletonema, Thalassiothrix,* and *Trichodesmium* occurred at high numbers during all seasons except monsoon season in both the stations, perhaps indicating their thermophilic nature. A few phytoplankton species (*C. radiatus, B. malleus, O. sinensis, P. alata* and *T. nitzschioides*) were particularly abundant during the monsoon season, indicating that these species are adapted to low temperature conditions. Thus, the seasonal occurrence of phytoplankton species may be closely associated with the species-specific environmental conditions that required to encystment or excystment. The occurrence of species from the genera: *Bellerochea, Chaetoceros, Proboscia, Planktonella, Pleurosigma* and *Nitzschia* in Bay of Bengal were conspicuous. The observed higher number and variety of phytoplankton species in the Station 1 might be influenced by the tidal ingression of species from the adjacent sea, i.e., the Bay of Bengal (Mani, 1992).

The diatom forms the bulk, with 75% of the census, followed by the dinoflagellates with 15% (Rajkumar *et al.*, 2009). Natural phytoplankton communities were dominated by *N. closterium, Pleurosigma* spp., *T. nitzschioides* and *T. frauenfeldii* (Mani, 1992). Thirty one species were bloom formers with a predominance of P. alata, attaining a maximum bloom concentration of 2.9×10^7 cells ml^{-1} (Mani *et al.*, 1986). Phytoplankton biomass, productivity and size are closely tied to diversity and to the abundance of higher trophic levels. The marine water had significantly richer nannophytoplankton than the estuary. Phytoplankton may make only small contributions to total productivity in estuarine waters, they may be critical to supporting higher trophic levels (Robertson and Blabber, 1992). This may be particularly true because of the high nutritional quality of phytoplankton relative to estuarine detritus. Phytoplankton are responsible for 5-10 µm size contributed 33-51% of total chlorophyll a and 20-22% of the total gross production in the Vellar estuarine system of South India (Kawabata *et al.*, 1993). Selvam et al. (1992) found phytoplankton productivity to be four times higher in mangrove or estuarine waters than in adjacent marine waters in south India.

Like abundance, the observed species richness values from both the stations were highest during the pre and postmonsoon seasons, and the low richness was recorded during the monsoon and postmonsoon seasons, as found by Rajasegar *et al.* (2000). Higher and lower species richness recorded during premonsoon and postmonsoon seasons respectively could be correlated with the recorded lower and higher salinity values, as reported by Mani (1992).

CCA ordination revealed the different environmental requirements and niche differentiation among phytoplankton taxa. Comparing the sampling number or species vs environmental parameters at different stations, station 1 was more stable than that of station 2 (Fig. 3-6). The sampling collections and species dots were more scattered at station 2 (estuary) than at station 1 (Bay of Bengal) (cf. Fig. 3 vs 4, 5 vs 6). The dominant species *O. sinensis* at Station 1 was associated with a high-phosphate, low-nitrate regime offshore, while at station 2 it grew in high-nitrate, high-phosphate and highly turbid waters.

Parangipettai coastal water is subjected to seasonal fluctuations in physico-chemical parameters depending upon the seasonal tidal amplitude and freshwater influx resulting in a continuous exchange of organic, inorganic, plant and animal matters. This coastal water is rich in resources allowing phytoplankton to attain high abundance and diversity. CCA discriminated well environmental factors affecting the phytoplankton community at species level. Our findings support those of Sun et al. (2007) that it is a good tool to aid comprehension of how the phytoplankton distribution in time and space in marine ecosystems provided that the species and environment data matrix is suitable. Diatoms formed the dominant group. Among the bloom-forming species of phytoplankton, the *cyanobacterium, T. erythraeum* are also abundant. It is concluded that Parangipettai coastal waters are fertile with abundant, diverse and productive phytoplankton.

Acknowledgments

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