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Baseline

Elucidation of seasonal variations of physicochemical and biological parameters with statistical analysis methods in Puducherry coastal waters

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ABSTRACT

The present investigation aimed to study the effect of monsoonal and anthropogenic influences on the water quality parameters of Puducherry coastal waters. Surface water sampling was performed at three fixed stations in four distinct seasons during 2011. Physical water quality parameters such as salinity and TSM showed strong seasonal and spatial variability. Evaporation and monsoonal runoff seem to be the major controlling forces for these parameters in the coastal waters. Seasonal distribution of the parameters showed a random pattern for nitrate and a well-defined pattern for silicate. Chl-*a* was minimum during monsoon when high TSM was encountered in the system. Moreover, factors that regulated the phytoplankton biomass varied with seasons. Moreover, TSM was strongly correlated with silicate. The relationship between Chl-*a* and nutrients were more consistent throughout the year, and much weaker correlations were noticed between Chl-*a* and TSM. Cluster analysis depicted the existence of a marked seasonal heterogeneity.

Coastal marine ecosystems are the most ecologically and economically productive regions on the planet, providing more than US$10 trillion in annual resources or ~40% of the global ecosystem goods and services (Costanza et al., 1997). Approximately 40% of the world population lives within 100 km of a coastline, subjecting these regions to a multitude of anthropogenic stressors including intense nutrient loading (de Jonge et al., 2002; Valiela, 2006). The coastal water quality, which is affected by both natural and anthropogenic influences (Jarvie et al., 1998), and particularly the near shore waters and estuaries, exhibits considerable variation depending upon the regional environmental setup such as rainfall, quantum of fresh water inflow, tidal incursion, and biological activities (Satpathy et al., 2011).

The phytoplankton are a crucial source of food for a diverse range of large and more familiar aquatic organisms such as invertebrates, fin and shell fish, and whales (Onyema et al., 2007). Growth and abundance of phytoplankton are primarily regulated by the combination of both biotic and abiotic interactions in coastal ecosystems (Dayala et al., 2014); this ultimately regulates the food web and biodiversity. Wastewater discharges are the major sources of organic and inorganic pollutants (including nutrients) in the coastal water ecosystems (Specchiulli et al., 2010). In addition to nutrients, physical properties such as salinity (McLusky, 1971), turbidity, and light availability (Cloern, 1987) also play major roles in the regulation of phytoplankton growth and their distribution in coastal waters. Moreover, top-down control by zooplankton can constrain phytoplankton concentrations within certain levels (Reid et al., 1990).

Because coastal water quality changes with time and space, continuous monitoring of water quality is necessary for the effective management of coastal water (Wu et al., 2010). There seems to be a great difficulty in analyzing the quality of water depending on the robust and sophisticated data sets provided by the monitoring programs, and therefore, some reduction methods are generally opted to make the data sets significant and easily accessible. In such cases, multivariate statistical analyses, such as factor analysis and cluster analysis (CA), have been effectively used to evaluate the temporal and spatial characteristics of coastal water and river water quality (Vega et al., 1998; Simeonov et al., 2003; Simeonov et al., 2004; Singh et al., 2004; Panda et al., 2006; Shirodkar et al., 2009; Wu et al., 2010). In the present study, multivariate analyses, i.e. CA and correlation analysis, were used to elucidate seasonal variations of physical, chemical and biological parameters in Puducherry coastal waters. The statistical approach gave an idea of the inter-relationship between various parameters that control the water quality. It also provides an insight into not only factors that chiefly affect the phytoplankton biomass but also those that are affected by variations in phytoplankton biomass.

Considering the influence of physical parameters on the productiv-

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ity potential of coastal waters, numerous studies have been made along the east coast of India to evaluate their seasonal and spatial behavior (Jayaraman, 1951, 1954; Sankaranarayanan and Reddy, 1968; Naqvi et al., 1978; Rajendran et al., 1980; Panigrahy et al., 1984; Sasmal et al., 1986; Choudhary and Panigrahy, 1991). Paramasivam and Kannan (2005) reported that factors related to water quality such as temperature, pH, salinity, dissolved oxygen, total organic carbon, and nutrients are particularly important for determining the biota and ecosystem functions in coastal waters. Information on general hydrography and biology from Puducherry coastal waters are available (Ananthan, 1995; Satheeshkumar and Khan, 2009, 2012). Moreover, earlier studies have been conducted along the Puducherry coast, particularly on mangrove-adjacent areas (Saravanan, 2005), river-adjacent areas (Vijayakumar et al., 2012, 2014), and sediment metal-related works (Ananthan et al., 2005; Solai et al., 2010). However, there is a paucity of information on the spatial and seasonal distributions of physicochemical and biological parameters that determine water quality and how they are influenced by external factors such as rainfall in the Puducherry coast. The present study aimed to evaluate the climatic influence (monsoonal runoff) and effects of physical, chemical, and biological variables on phytoplankton biomass (in terms of chlorophyll-*a* [Chl-*a*]) in the coastal waters of Puducherry located in the southeast coast of India.

The present study area is located in the Puducherry region, which is the largest among the four isolated domains of the union territory of Puducherry and is located on the east coast of India (Nathan et al., 2012). The Puducherry coast is surrounded by the Bay of Bengal on the east and by Tamil Nadu state on the other three sides. Stations were selected at the Puducherry coast, covering a distance of 5 km from shore (Fig. 1). The study area experiences a tropical subhumid type of climate with an annual mean temperature of 25 °C and average annual precipitation of 1200 mm (Solai et al., 2010). This region is an agriculture area, and around 56% of the land is used for crop production (Nathan et al., 2012). Puducherry has a population of 7,35,000 and generates wastewater of about 45,000 Kilo Liter per Day (KLD). The entire wastewater is discharged into the sea through backwaters and creeks in an untreated form. Puducherry has six major industries that manufacture paper, alcoholic beverages, chemicals, and pharmaceuticals. The total treated wastewater discharged from industries is about 7000 KLD (http://www.icmam.gov.in/comaps/pon.pdf).

For the present study, three stations were selected in Puducherry coastal waters from three different zones, namely (i) shore (0.5 km), (ii) inshore (2 km), and (iii) offshore (5 km) (Fig. 1), covering a 5-km distance from shore. The temporal sampling was conducted quarterly during 2011 for seasonal analysis such as postmonsoon (March 24th), summer (June 17th), premonsoon (September 23rd), and monsoon (December 14th).

Field data such as temperature, salinity, dissolved oxygen (DO), and pH were measured in the forenoon. Surface water temperatures were measured using a mercury thermometer. Salinity was estimated using a handheld refractometer (Atago, Japan), and pH was measured using a digital pH meter. Transparency in the water column was measured with the help of secchi disc. For the analysis of nutrients, surface water samples were collected in clean polyethylene bottles, kept in an ice box, and transported immediately to the laboratory. The water samples were analyzed for ammonia, dissolved inorganic phosphate, nitrate, nitrite, and reactive silicate by adopting the standard methods described by Grasshoff et al. (1999). Water samples for Chl-*a* determination were filtered through Whatman GF/F (47 mm) glass fiber filters, and pigment extraction was performed using 90% acetone. Chl-*a* pigment concentrations were measured by using UV–visible spectrophotometer (Strickland and Parsons, 1972). DO and biological oxygen demand (BOD) were estimated by the modified Winkler's method (Strickland and Parsons, 1972) and are expressed as mg/L. For total suspended matter (TSM) estimation, about 150 mL of water samples were filtered through pre-weighed 0.22 μm polycarbonate filters (Millipore), dried at 40 °C, and reweighed. The difference between the two weights was taken as the TSM content (mg/L). Mesozooplankton samples were collected by horizontally towing a bongo net with 200 μm mesh. The volume of water filtered by the net was measured using a calibrated flow meter (Hydrobios, USA) mounted at the mouth of the net. Mesozooplankton biomass was estimated by the standard displacement volume method (Harris et al., 2000), and the biomass was expressed in milli liter per cubic meter (mL/m^3).

Multivariate analysis included CA and correlation analysis on the present water quality data to understand the inter-relationships between different variables. Seasonal associations of nutrients (silicate), TSM, DO, phytoplankton biomass, and zooplankton biomass were examined by hierarchical CA using the Euclidean distance similarity index as an estimate of similarity among seasons using the software Primer 5.2.8. The clusters are divided by their unique characteristics, and often, it helps to interpret the data (Vega et al., 1998). The correlation coefficient (Spearman) among physicochemical and biological parameters was computed. Data were analyzed using the statistical software Statistica 8.0. Spearman rank-order correlation, which gives an idea of the inter-relation between various water quality parameters, was considered to be not significant when the value of the probability of significance (p) was > 0.05. Grapher (version 3) was used for the graphical representation of the data.

Rainfall is an important cyclic phenomenon in tropical countries and brings vital changes in the hydrological characteristics of coastal marine environments (Satheeshkumar and Khan, 2012). In India, the rainfall is largely influenced by two monsoons: (1) the southwest monsoon on the west coast and northern and northeastern India and (2) the northeast monsoon on the southeast coast (Paramasivam and Kannan, 2005). The average rainfall is about 149.31 mm/year and is prolonged from April to December. Major rainfall occurs during October to December (northeast monsoon), while a weak spell of southwest monsoon brings rain during June to September (http://knoema.com/icrqbyg/monthly-rainfall-data-district-wise-for-2004-2013) (Fig. 2). According to reports on the Tamil Nadu coastal region, the quality and distribution of rainfall is crucial in determining the condition of the coastal waters (Satpathy et al., 2011; Muthulakshmi et al., 2012).

The spatial and seasonal variations of water quality parameters (Fig. 2; Fig. 3 and Fig. 4) with their mean and standard deviation along the Puducherry coast are summarized in Table 1. Most of the parameters showed greater seasonal variability than spatial variability.

The maximum surface water temperature (28.5 °C) was recorded during the summer season (Table 1). Hydrographical parameters such as salinity, transparency, and TSM have shown significant spatial and seasonal variability in Puducherry coastal waters (Fig. 2 & Table 1). These variations can be attributed to the typical features of the tropical regions, e.g., intense cloud cover and reduced effect of solar radiations. Salinity was higher during summer (33.8 ± 1.1 PSU) than during other seasons, which may be because of the higher degree of evaporation in the study area (Fig. 2). The lowest salinity was found during the monsoon period (32.4 ± 0.1 PSU) due to heavy rainfall at the coast. A similar trend in the salinity values was also observed from various parts in the southeast coast of India (Seenivasan, 1998; Palanichamy and Rajendran, 2000; Sulochana and Muniyandi, 2005; Prabu et al., 2008; Damotharan et al., 2010). Spatially, salinity values were lower toward the shore and gradually increased toward offshore. Turbidity measures the presence of material in water that affects the transparency or light scattering of the water (Gadhia et al., 2012). A higher TSM value was recorded during monsoon (65.4 ± 20.4 mg/L) and a low value during postmonsoon (21.7 ± 4.4 mg/L) (Fig. 2). During the monsoon season, silt, clay, and other suspended particles contribute to the turbidity values, while during other seasons, settlement of silt and clay result low turbidity (Manikannan et al., 2011). Bathusha and Saseetharan (2007), Garg et al. (2006), Prasad and Patil (2008), Saravanakumar et al. (2008), and Upadhyay et al. (2010) have also reported high turbidity

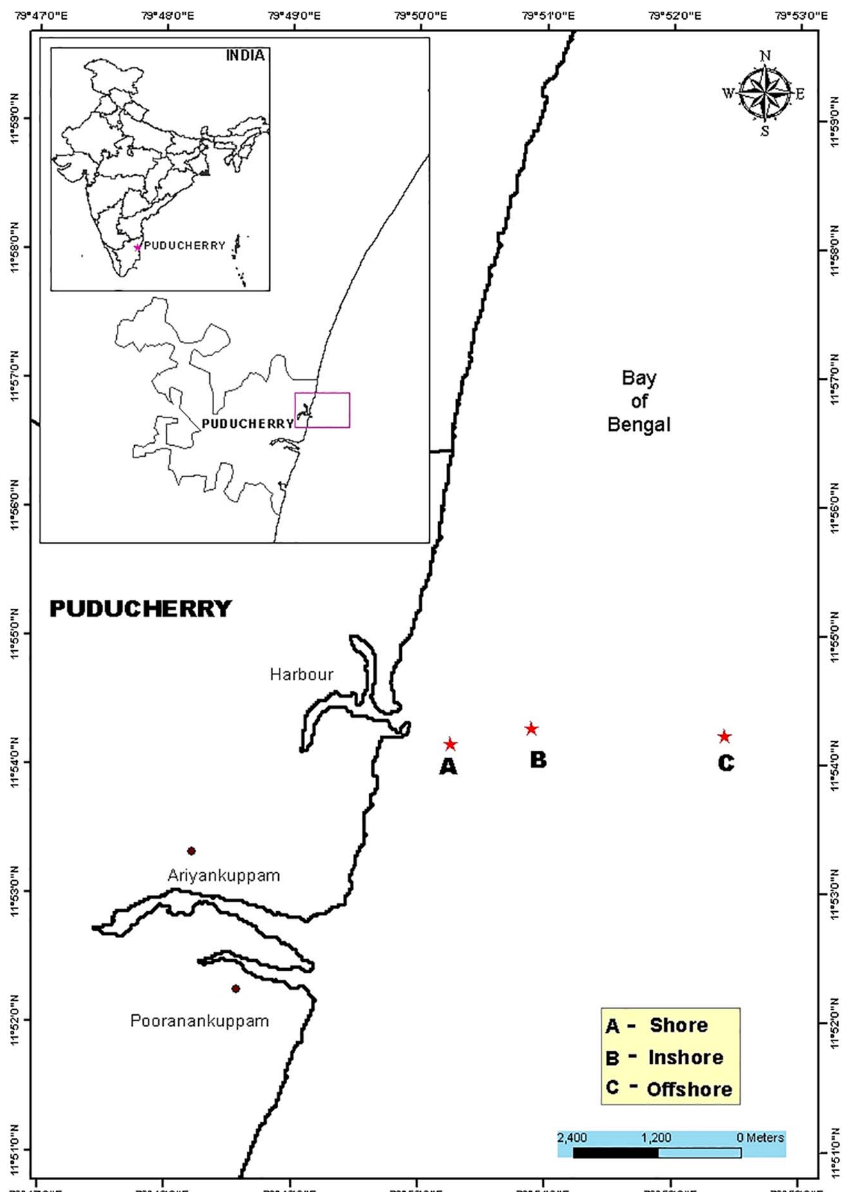

Fig. 1. Figure showing station locations in the Puducherry coastal waters.

during rainy season. Transparency of the coastal waters ranged from 2.5 to 11 m, with higher transparency in summer (8.3 ± 2.5 m) and lower in monsoon (2.8 ± 0.3 m). The high transparency of the water column in the nonmonsoon season, compared to that in the monsoon season (Table 1), can be because of rainfall. Turbidity showed a decreasing trend toward the offshore direction because of decreasing TSM concentrations. Variations in pH among seasons and stations were not significant. The pH ranged from 8.1 to 8.4 and was also lower in monsoon (8.2). In general, fluctuations in pH during different seasons of the year is attributed to factors including 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 materials, as stated by Karuppasamy and Perumal, 2000; Rajasegar, 2003. In the present study, high pH values were found during summer and premonsoon because of the influence of seawater penetration and high biological activity.

In the coastal environment, the supply of nutrients is mainly influenced by the amount of fresh water inflow, rate of the rainfall, invasion of tidal pattern, and biological activities (Kathiravan et al., 2014). Terrestrial runoff from the industrial, agricultural, residential, and urban areas may also increase the nutrient loads to the nearby shore and inland waters in the ocean (Preethi Latha et al., 2014). The assessment of nutrient levels showed more seasonal variations than spatial variability. Variations of nitrogenous nutrient concentrations in Puducherry coastal water ranged from 0.1 to 1.3 μM of ammonia, 0.2 to 1.0 μM of nitrite, and 7.6 to 11.8 μM of nitrate. Ammonia showed high concentrations during the premonsoon season, and its irregular trend observed during the study period could be due to its oxidation to other forms coupled with reduction of nitrite to ammonia in coastal waters. Nitrate showed neither seasonal nor spatial variability because of influx of surplus discharge of industrial and domestic sewage (Fig. 3) (http://www.icmam.gov.in/comaps/pon.pdf). Nitrate showed low concentrations during the monsoon season (8.6 ± 0.7 μM) because of the monsoonal dilution effect. The nitrogenous nutrient concentrations in coastal waters indicated that the nutrients originated from local anthropogenic input and biological activity rather than monsoonal runoff. The spatial and seasonal variations of total nitrogen (TN) show a random pattern similar to that of nitrate (Table 1). The difference between dissolved inorganic nitrogen (ammonia + nitrite + nitrate)

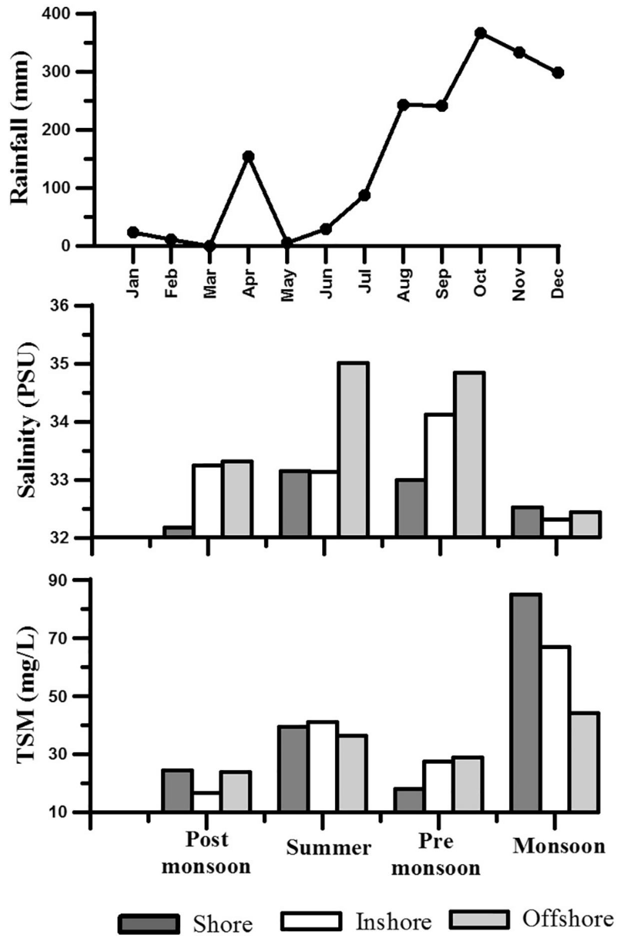

Fig. 2. Monthly distribution of rainfall and seasonal distribution of salinity and TSM in Puducherry coastal waters.

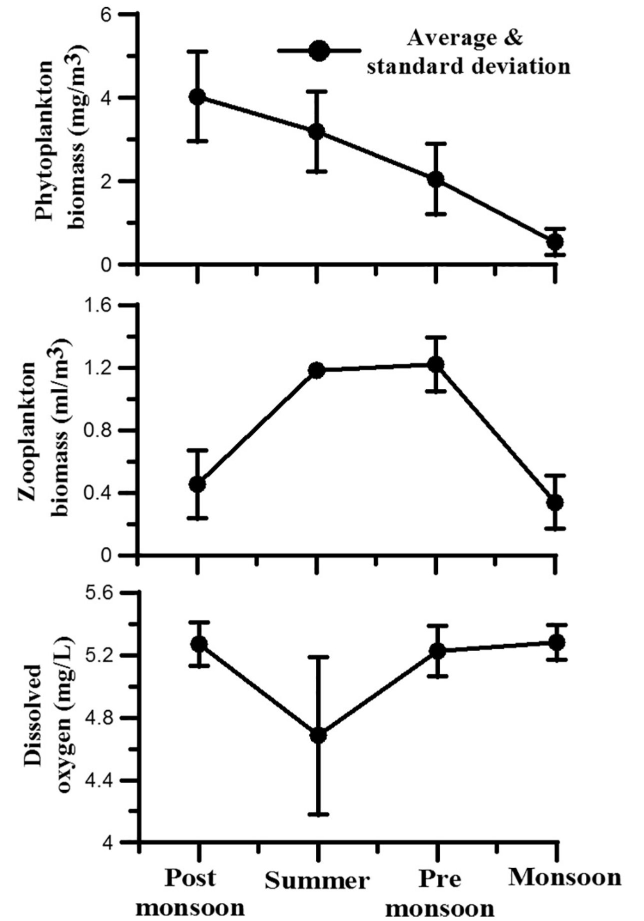

Fig. 4. Seasonal distribution of phytoplankton biomass (Chl-*a*), zooplankton biomass and Dissolved oxygen in Puducherry coastal waters.

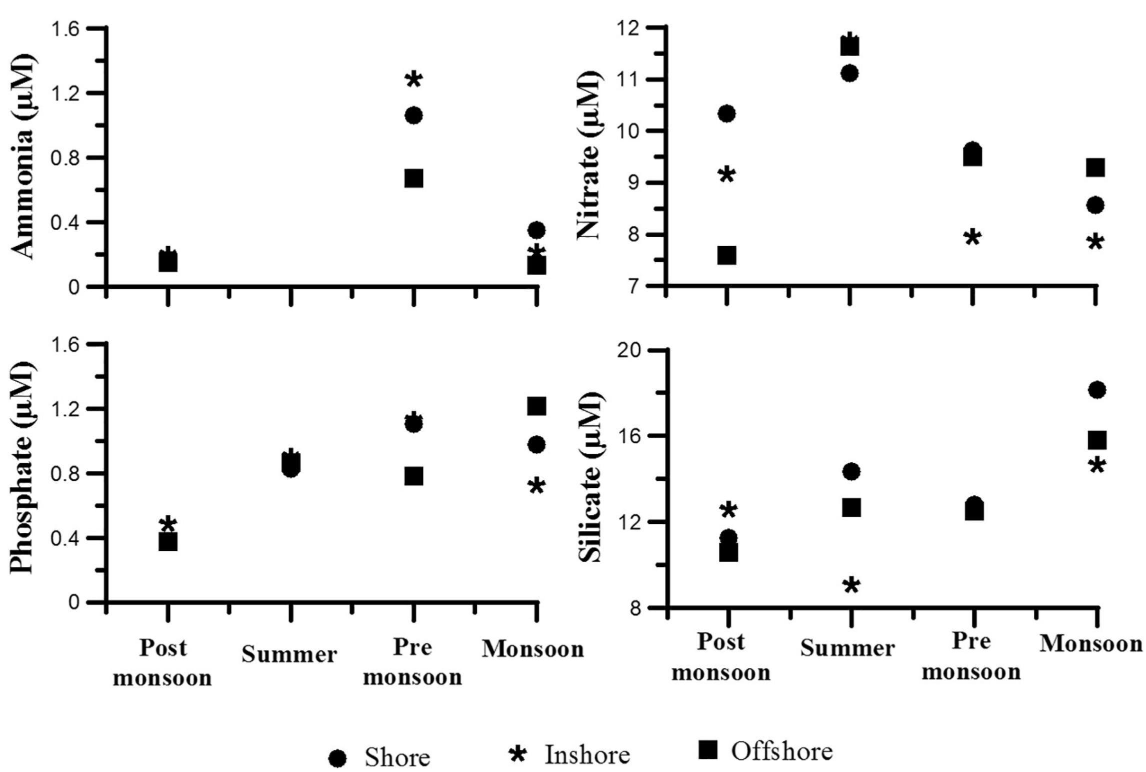

Fig. 3. Seasonal distribution of ammonia, nitrate, phosphate and silicate in Puducherry coastal waters.

Table 1
Variations of environmental properties in Puducherry coastal waters during distinct seasons (postmonsoon, summer, premonsoon, and monsoon) and shore to offshore.

Parameter	Seasons	Ave ± SD	Stations	Ave ± SD	Parameter	Seasons	Ave ± SD	Stations	Ave ± SD
Temperature	Post monsoon	28.0 ± 0.0	Shore	28.2 ± 0.3		Post monsoon	0.5 ± 0	Shore	0.6 ± 0.3
(°C)	Summer	28.5 ± 0.0	Inshore	28.5 ± 0.5	Nitrite	Summer	0.3 ± 0	Inshore	0.6 ± 0.3
	Premonsoon		Offshore	28.2 ± 0.3	(μM)	Premonsoon	0.7 ± 0.3	Offshore	0.4 ± 0.1
	Monsoon	28.3 ± 0.6				Monsoon	0.6 ± 0.3		
Salinity	Post monsoon	32.9 ± 0.6	shore	32.7 ± 0.4		Post monsoon	9 ± 1.4	Shore	9.9 ± 1.1
(PSU)	Summer	33.8 ± 1.1	Inshore	33.2 ± 0.7	Nitrate	Summer	11.5 ± 0.3	Inshore	9.2 ± 1.8
	Premonsoon	34 ± 0.9	Offshore	33.9 ± 1.2	(μM)	Premonsoon	9 ± 0.9	Offshore	9.5 ± 1.7
	Monsoon	32.4 ± 0.1				Monsoon	8.6 ± 0.7		
Total suspended matter	Post monsoon	21.7 ± 4.4	shore	41.9 ± 30.1		Post monsoon	0.4 ± 0.1	Shore	1 ± 0.1
(mg/L)	Summer	39.1 ± 2.4	Inshore	38.1 ± 21.8	Phosphate	Summer	0.9 ± 0	Inshore	0.8 ± 0.3
	Premonsoon	24.8 ± 5.8	Offshore	33.3 ± 8.9	(μM)	Premonsoon	1 ± 0.2	Offshore	0.8 ± 0.3
	Monsoon	65.4 ± 20.4				Monsoon	1 ± 0.2		
Transparency	Post monsoon	5.8 ± 1.1	Shore	4.1 ± 1.7		Post monsoon	11.5 ± 1	Shore	14.1 ± 3
(m)	Summer	8.3 ± 2.5	Inshore	5.4 ± 2.3	Silicate	Summer	12 ± 2.7	Inshore	12.2 ± 2.3
	Premonsoon	4 ± 1	Offshore	6.3 ± 4.2	(μM)	Premonsoon	12.6 ± 0.2	Offshore	12.9 ± 2.1
	Monsoon	2.8 ± 0.3				Monsoon	16.2 ± 1.8		
pH	Post monsoon	8.2 ± 0.1	Shore	8.2 ± 0	Total	Post monsoon	19.9 ± 0.9	Shore	23.3 ± 2.5
	Summer	8.3 ± 0.1	Inshore	8.2 ± 0.1	Nitrogen (TN)	Summer	23.6 ± 1.8	Inshore	22.7 ± 2.6
	Premonsoon	8.3 ± 0.1	Offshore	8.3 ± 0.1	(μM)	Premonsoon	24.5 ± 1.1	Offshore	23.2 ± 2.3
	Monsoon	8.2 ± 0				Monsoon	24.3 ± 1.3		
Dissolved oxygen	Post monsoon	5.3 ± 0.1	Shore	4.9 ± 0.6	Total	Post monsoon		Shore	1.5 ± 0.2
(mg/L)	Summer	4.7 ± 0.5	Inshore	5.2 ± 0.1	Phosphorous (TP)	Summer	1.2 ± 0.2	Inshore	1.4 ± 0.4
	Premonsoon	5.2 ± 0.2	Offshore	5.3 ± 0.1	(μM)	Premonsoon	1.5 ± 0.4	Offshore	1.4 ± 0.5
	Monsoon	5.3 ± 0.1				Monsoon	1.6 ± 0.3		
Biological oxygen demand	Post monsoon	1.1 ± 0.4	Shore	0.8 ± 0.5	Phytoplankton	Post monsoon	4 ± 1.1	Shore	3.2 ± 1.9
(mg/L)	Summer	0.4 ± 0.1	Inshore	0.8 ± 0.4	Biomass (Chl-*a*)	Summer	3.2 ± 1	Inshore	2.3 ± 1.6
	Premonsoon	0.9 ± 0.4	Offshore	0.8 ± 0.4	(mg/m^3)	Premonsoon	2.1 ± 0.8	Offshore	1.9 ± 1.5
	Monsoon	0.7 ± 0.2				Monsoon	0.5 ± 0.3		
Ammonia	Post monsoon	0.2 ± 0	Shore	0.4 ± 0.4	Zooplankton	Post monsoon	0.5 ± 0.2	Shore	0.6 ± 0.4
(μM)	Summer		Inshore	0.6 ± 0.6	Biomass	Summer	1.2	Inshore	0.7 ± 0.6
	Premonsoon	1 ± 0.3	Offshore	0.3 ± 0.3	(ml/L)	Premonsoon	1.2 ± 0.2	Offshore	0.8 ± 0.5
	Monsoon	0.2 ± 0.1				Monsoon	0.3 ± 0.2		

and TN was much higher in all seasons, indicating that a higher value of the organic form of nitrogen is contributed through industrial and domestic sewage. The phosphate concentrations ranged from 0.4 to 1.2 μM, and unlike nitrate, phosphate concentrations showed little seasonal variations, which was not significant. During the monsoon season, high concentrations of phosphate (1 ± 0.2 μM) have been observed compared to that in other seasons due to heavy rainfall and land runoff. The recorded low phosphate values during nonmonsoon seasons (postmonsoon, summer, and premonsoon) (Fig. 3) could be attributed to the limited flow of freshwater, high salinity, and utilization of phosphate by phytoplankton. The total phosphate (TP) in Puducherry coastal waters ranged from 1.0 to 1.9 μM. The seasonal variation of TP was very similar to that of dissolved inorganic phosphorous (Table 1). Silicate showed significant seasonal variations; the concentrations ranged from 9.1 to 18.1 μM from postmonsoon to monsoon season. The seasonal variations show that silicate concentration was maximum during the monsoon season (11.5 ± 1 μM). This might be because during the monsoon season, there was input of more siliceous sediment gathered from its catchments (Pai and Reddy, 1981; Sharma and Ghose, 1987; Gouda and Panigrahy, 1992; Bhattacharya et al., 2002). The nutrient concentrations were slightly higher in shore waters than inshore and offshore because of direct effluent discharge by proximity.

DO and BOD did not show any typical seasonal cycle like other hydrological parameters. DO values varied from 4.3 to 5.8 mg/L, with slightly higher values in the monsoon season (5.3 ± 0.1). This may be because of the cumulative effect of higher wind velocity, rainfall, and the resultant freshwater mixing during the monsoon season (Das et al., 1997). DO levels were high, and no clear seasonal variation was observed throughout the study period. (Fig. 4). In aquatic systems, oxygenation is the result of an imbalance between the process of photosynthesis, degradation of organic matter, reaeration (Granier et al., 2000), and physicochemical properties of water (Aston, 1980). The BOD ranged between 0.3 and 1.5 mg/L in coastal waters, which was well within the permissible limits. Higher BOD was found during postmonsoon as compared to other seasons (Table 1). This might be due to phytoplankton productivity, which increases DO concentrations, and the high productivity leads to the production of more organic matter, thus resulting in more microbiological activity, which in turn increases the BOD.

Changes in phytoplankton biomass (Chl-*a*) and zooplankton biomass in Puducherry coastal waters.

The Present study recorded higher Chl-*a* concentrations during the nonmonsoon period (postmonsoon, summer and premonsoon) than during the monsoon season (Fig. 4). Similarly, during the monsoon season, minimum concentrations of chlorophyll have also been reported by several authors (Raghuprasad, 1958; Sridhar et al., 2006). During the monsoon season, the sharp decline in Chl-*a* concentration caused by the changes in hydrographic parameters due to a large volume of freshwater influx through land runoff increased turbidity and decreased pH. However, in other seasons, the increased chlorophyll values in the ecosystem might be because of improvement in salinity and nutrients structure (Palleyi et al., 2008). High concentration of Chl-*a* would result in high values of phytoplankton production (Prabhahar, 2000). Higher Chl-*a* concentrations in shore region indicates there is good availability of nutrients for the growth and proliferation of phytoplankton. There is no remarkable spatial difference observed in phytoplankton biomass and zooplankton biomass of Puducherry coastal waters. The zooplankton biomass ranged between 0.2 and 2.4 mL/m^3 during the study period, with the highest being recorded during summer and premonsoon (1.2 mL/m^3) and lowest during the monsoon season (0.3 mL/m^3) (Fig. 4). The seasonal abundance of zooplankton is determined by the availability of phytoplankton and the onset of phytoplankton growth in combination with an increase in the seawater temperature (Bot et al., 1996). The zooplankton biomass's decline in the monsoon season coincides with the declination of the phytoplankton

Table 2
Rank correlation matrix (Spearman's) of biological properties with physical and chemical parameters in Puducherry coastal waters. TSM indicates total suspended matter and BOD indicates biological oxygen demand. * indicates significance level of p ($p < 0.05$).

	Salinity	TSM	Transparency	pH	BOD	Ammonia	Nitrite	Nitrate	Phosphate	Phytoplankton biomass
TSM	− 0.6 (11)									
Transparency	0.6 (11)	− 0.5 (10)								
pH	0.8 (12) *									
DO				0.6 (11)						− 0.6 (10)
BOD			0.7 (8)							
Ammonia										
Nitrite			− 0.7 (11)*			0.7 (12)*				
Nitrate		0.5 (10)	0.7 (11)*				0.7 (12)*			
Phosphate		0.5 (10)								
Silicate	− 0.6 (11)*	0.7 (11)*	− 0.6 (11)*		− 0.5 (10)					− 0.6 (11)*
TN		0.6 (11)*	− 0.7 (10)*	0.5 (12)					0.8 (11)	− 0.6 (11)
TP			− 0.6 (9)		0.8 (7)		0.5 (9)	− 0.5 (9)	0.8 (9)	− 0.5 (8)
Phytoplankton biomass	0.5 (10)	− 0.5 (11)	0.7 (9)*				− 0.6 (10)	0.6 (10)*	− 0.7 (9)*	
Zooplankton biomass	0.5 (11)		0.6 (10)	0.5 (11)		0.7 (9) *		0.6 (11) *	0.5 (9)	− 0.7 (6)

biomass. The seasonal cycles of phytoplankton and zooplankton, which are controlled by the availability of light and nutrients, represent probably one of the most obvious properties of the pelagic system (Bot et al., 1996). Local differences caused, for example, by the input of nutrients in coastal areas or by hydrodynamic circumstances may alter this cycle (Bot et al., 1996).

Trend analysis and correlation between different water quality parameters require an intensive understanding of both the external driving forces and internal biogeochemical processes taking place in the coastal regions. We evaluated Spearman rank order correlations between observed variables for the surface water of Puducherry coastal waters during 2011, which are presented in Table 2. This helped understand the strength of relationships among the analyzed variables and which variables co-vary with other variables. Some extreme outliers were excluded from the respective parameters to determine the strength of the relationship, and the number of points utilized is given in table itself. Dissolved nitrogen species exhibited significant positive correlations among themselves (Table 2). A strong significant positive correlation was noticed between salinity and pH ($p < 0.05$). Coastal water pH was found to vary with salinity (Saraswat et al., 2011). TSM showed good relation with almost all nutrients and significant relation with silicate ($p < 0.05$). It showed a common source for all nutrients and organic loads. Silicate showed negative loading with salinity ($p < 0.05$), so it is clear that the high loading of silicate with respect to salinity showed the major source of silicate is from the flow of land runoff. Negative correlation between salinity and TSM and positive correlation between TSM and silicate ($p < 0.05$) indicate the effect of monsoonal runoff on these ecosystems. Less significant correlations were noticed in the case of TSM vs. phosphate and nitrate (Table 2). This lack of significant correlations indicates the influx of anthropogenic inputs and waste discharges containing nitrogen and phosphorous compounds. Significant relations were observed between transparency and nutrients and between transparency and phytoplankton biomass, which indicates that nutrients are utilized by phytoplankton when light availability is high (Table 2).

Linear regression analysis was performed between phytoplankton biomass and some important parameters such as TSM, nitrate, phosphate, silicate, DO, and zooplankton biomass to determine controlling factors of phytoplankton biomass. Negative correlation was observed between TSM and phytoplankton biomass (Fig. 5), which was, however, not significant because during seasons when there was no significant input of TSM, grazers and nutrients limited the phytoplankton biomass. Moreover, the role of phytoplankton in the increased TSM values (Kaliyamurthy, 1973) during summer cannot be overlooked as phytoplankton production in nonmonsoon seasons is generally high compared to that in the monsoon season. Comparatively low concentrations of silicate and phosphate observed during nonmonsoon seasons could be due to phytoplankton uptake, which was indicated by a strong negative correlation ($p < 0.05$) (Fig. 5). However, such a process does not reflect in the case of the nitrate because of the influence of effluent load through different point sources in Puducherry coastal waters. Chl-*a* exhibited a negative correlation with DO ($p < 0.05$) (Fig. 5). A similar type of observations was reported by Pip (1988) in Shoal Lake. A decrease in the DO content of coastal waters due to phytoplankton respiration could be the reason for this negative correlation. During nonmonsoon seasons, a negative correlation was observed between phytoplankton biomass and zooplankton biomass ($p < 0.05$). This result suggests that during the nonmonsoon period, the phytoplankton biomass was greatly influenced by zooplankton biomass because of grazing. A positive correlation was observed between zooplankton biomass and ammonia ($p < 0.05$) in Puducherry coastal waters (Table 2). The possible sources of ammonia input into the waters were land runoff, zooplankton excretion, or demineralization of organic matter (Ketchum, 1962).

Significant variations in parameters were observed among the seasons because of the prevalence of different hydrographic environment in different seasons (Ei-Gindy and Dorghan, 1992). The relationships among the seasons were obtained through CAs, with Bray-Curtis as a similarity measure, and were synthesized into dendrogram and multidimensional scaling (MDS) plots. Some of the important water quality parameters such as TSM, silicate, phytoplankton biomass, DO, and zooplankton biomass were used as variables and were sequentially associated, displaying the information. During the study period, CA generated a dendrogram, grouping the sampling seasons into two groups for each variable, and is presented in Fig. 7. TSM, silicate, and phytoplankton biomass dendrograms showed two groups; one group contained nonmonsoon seasons such as postmonsoon, summer, and premonsoon, whereas the other group contained monsoon (Fig. 6), which showed completely different characteristics from other seasons, being associated with higher levels of nutrients (silicate) and TSM and low phytoplankton biomass. Although high nutrient levels were observed during monsoon, the highest phytoplankton biomass was noticed during nonmonsoon periods, suggesting that low suspended matter is conducive for phytoplankton growth. The DO dendrogram showed more similarity between seasons than between other variables, which were also divided into two clusters Fig. 6. One group contained three seasons (postmonsoon, summer, and premonsoon) and the other contained summer. During postmonsoon and premonsoon seasons, elevated DO content was due to high phytoplankton biomass (photosynthetic process), and during monsoon, it might be due to precipitation (the down pour of oxygen-rich waters) and land runoff.

MDS can support more information about the distribution of water

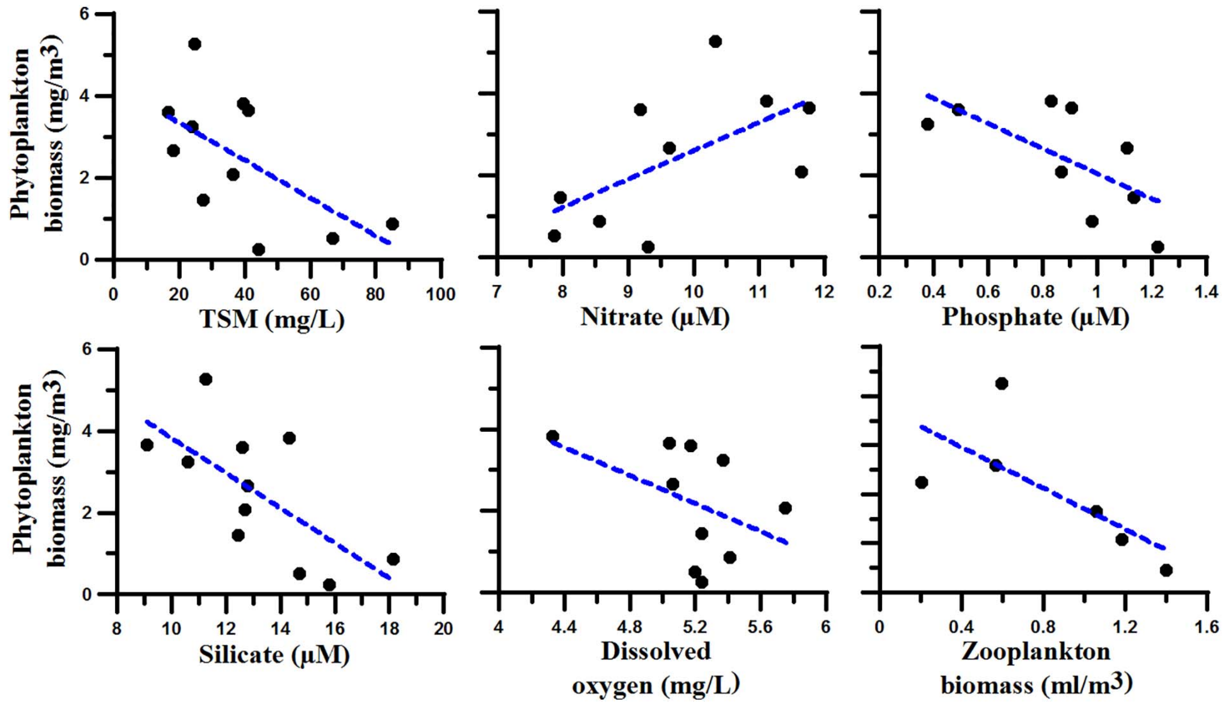

Fig. 5. Correlation between phytoplankton biomass (Chl-*a*) and other environmental parameters (TSM, Nitrate, Phosphate, Silicate, Dissolved oxygen and Zooplankton biomass) in Puducherry coastal waters.

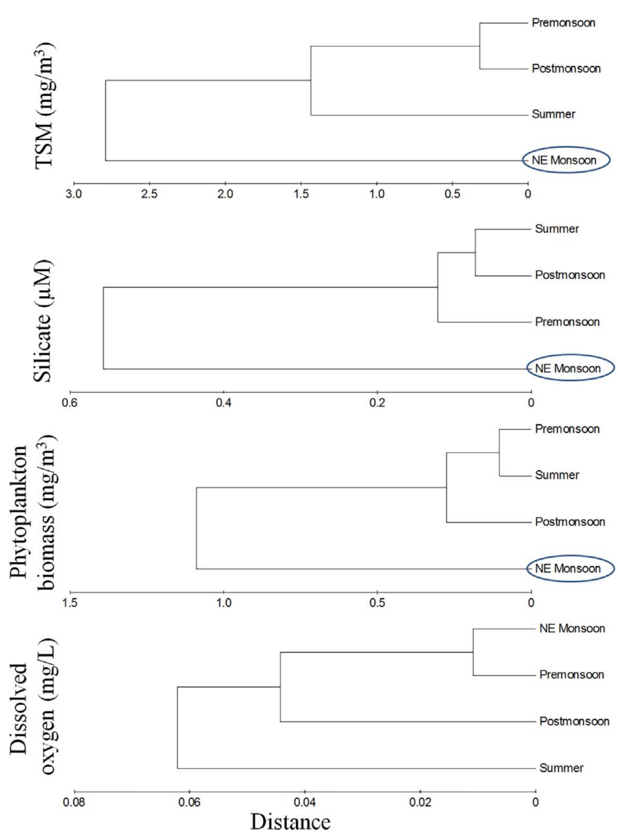

Fig. 6. Dendrogram are showing similarity among seasons in environmental variables (TSM, Silicate, Phytoplankton biomass and Dissolved oxygen) in Puducherry coastal waters.

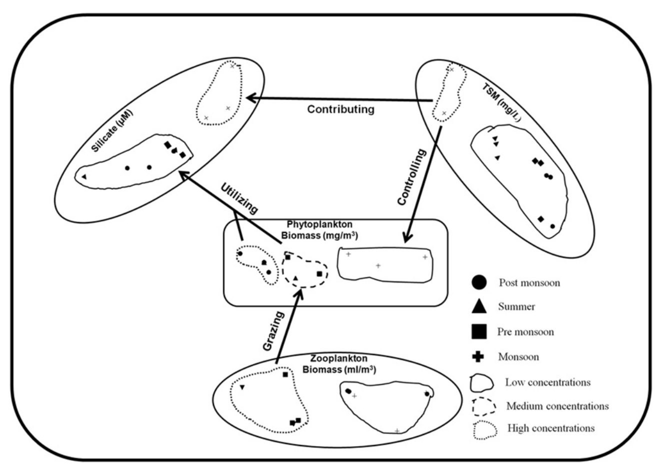

Fig. 7. Schematic diagrams showing heterogeneous controlling factors on phytoplankton biomass during different seasons in Puducherry coastal waters. These MDS plots are showing 0.01 (stress) for TSM, Phytoplankton biomass and Zooplankton biomass whereas 0 shows for silicate. Outliner values were removed to know the similarities and dissimilarities among seasons in each variable.

quality parameters and controlling factors of each parameter. Controlling factors of phytoplankton biomass in Puducherry coastal waters, evaluated by MDS, were used to identify which parameter is controlling phytoplankton biomass and visualize similarities and dissimilarities among seasons for these parameters. Our results reveled that seasonality has an important influence on phytoplankton biomass in Puducherry coastal waters. From Fig. 7, it is clear that TSM, silicate, and zooplankton are the most important parameters causing these dissimilarities in phytoplankton biomass in Puducherry coastal waters. In Fig. 7, all (TSM, silicate, and zooplankton) variables formed two groups, except phytoplankton biomass, which was split as three groups, namely high, moderate, and low concentrations. Phytoplankton biomass was low during monsoon, which was mainly controlled by high TSM concentrations. A slightly lower concentration of silicate was observed in Puducherry coastal waters at all station during nonmonsoon seasons. This may be related to a high biological productivity and the abiological removal of dissolved silicate by adsorption onto suspended sediments (De Souza et al., 1981). However, this phenomenon is not observed during monsoon. Because biological productivity is minimum during the monsoon, removal of silicate might also be minimum (Sundaray et al., 2006). Although all conditions are favorable for phytoplankton, they showed moderate biomass during premonsoon because of zooplankton grazing. It can be inferred from the above observations that there seemed to be no marked difference in the characteristics of coastal water during postmonsoon, summer, and premonsoon periods, whereas during the monsoon season, the coastal waters behaved entirely different water mass. Therefore, monsoonal pattern can be considered one of the most significant factor determining the physicochemical and biological characteristics of the coastal environment at this location.

Seasonality has an important effect on the trophic status of water. A significant seasonal variation was observed in all physicochemical and biological parameters observed during the study period, i.e., postmonsoon, summer, premonsoon, and monsoon periods were characterized by different physicochemical and biological properties. A significant difference in the physicochemical and biological characteristics of coastal waters was observed during the monsoon compared to the other seasons in the year. The highest concentrations for all the nutrients and DO was observed during the monsoon season, while salinity, phytoplankton biomass, and zooplankton biomass were at their minimum level during monsoon. The above observations were supported by statistical analyses, which showed two temporally distinct water masses: one belonging to the monsoon season and the other to the postmonsoon, summer, and premonsoon seasons. This indicates that in Puducherry coastal waters, irrespective of the enormous supply of nutrients to the region during monsoon, the phytoplankton biomass declined because of nonavailability of light due to increased TSM. Hence. there is need for more frequent study of the area. This will reveal more trends and regimes while contributing to the science and literature of the area.

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