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Temporal Variations in Phytoplankton Assemblages at *Dol* Net Fishing Grounds of Major Tidal Creeks of Maharashtra, India

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A B S T R A C T

Phytoplankton dynamics plays a vital role in determining the productivity of any coastal ecosystem. In this study, temporal variability in phytoplankton composition and diversity was assessed with respect to the physico-chemical parameters of water in major *dol* net fishing grounds of two spatially adjacent tidal creeks (Thane and Vasai) of Maharashtra. The phytoplankters identified belonged to 84 and 69 species in Thane and Vasai creeks, respectively. Numerical abundance of phytoplankton ranged from 8.7×10^4 cells L^{-1} to 4.3×10^5 cells L^{-1}. Diatoms were the major group in both the creeks followed by dinoflagellates. Plankton density, diversity, evenness and richness were significantly higher in winter monsoon season. Phytoplankton density is positively correlated with phosphate, nitrate, nitrite, chlorophyll-a, diatoms and dinoflagellates, and negatively correlated with total suspended solids and silicates. Canonical correspondence analysis established that temperature, salinity and nutrients regulate the temporal patterns in phytoplankton composition. This study has provided fruitful insights on the diversity, abundance and temporal variations of phytoplankton assemblages under the influence of physico-chemical parameters of water in the tidal creeks of Maharashtra.

Introduction

Tidal creeks are funnel-shaped dynamic coastal ecosystems affected by ebbing and flooding of ocean tides and characterised by continuous flushing, mixing and replenishment of nutrients (Dalrymple, 1992; Semeniuk, 1996). Moreover, these habitats support unique flora and fauna, including migrants and residents of various aquatic species (Sreekanth *et al.*, 2016). In Maharashtra, 48 tidal creeks have been reported (Vikas *et al.*, 2015) and most of these creeks are rich in fish diversity and abundance which support the traditional *dol* net fishery. *Dol* nets are location-specific stationary bag nets extensively used in the tidal creeks of Maharashtra to harvest fish. Fish production in the coastal ecosystem is believed to be influenced by the variations in phytoplankton community structure, primary production and hydrographic parameters (Roy *et al.,* 2010; Thomas *et al.*, 2016). Phytoplankton is the base trophic level in the marine food web and remains as the major source of energy flow to higher trophic levels in coastal ecosystems (Tiwari and Chauhan, 2006; Saifullah *et al*., 2014).

The spatio-temporal variability in distribution and abundance of the phytoplankton community in coastal ecosystems is regulated by a number of physico-chemical factors (Hulyal and Kaliwal, 2009; Gabriel *et al*., 2013).

The effects of seasonality in the coastal waters such as creeks and estuaries are very strong and show substantial influence on phytoplankton production and food-web dynamics (Devassy and Goes, 1988). This variability of phytoplankton, in turn, affects the diversity and abundance of other aquatic fauna including fish (Alheit *et al.,* 2005). Therefore, the community composition, biomass and temporal variations of phytoplankton need to be understood to delineate the fish production dynamics of the coastal ecosystem. Nevertheless, in the tidal-creek ecosystems, studies pertaining to phytoplankton communities in terms of diversity, composition and abundance with special reference to fishing grounds are limited.

In this study, the dynamics of phytoplankton were analysed with respect to the physico-chemical parameters of water in the major *dol* net fishing grounds of two spatially adjacent tidal creeks (Thane and Vasai) of Maharashtra. The major objectives of this study were to analyse the temporal patterns in diversity and abundance of phytoplankton communities and to elucidate the effect of the physico-chemical parameters of water on the dynamics of phytoplankton.

Materials and Methods

Study area

Thane and Vasai creeks of Maharashtra are two major tidal creeks in the shoreline of the north eastern Arabian Sea. Both the creeks are spatially adjacent and fed partially by Ulhas River. At Thane, Ulhas River splits into two branches, one flows to the west and merges with the Vasai Creek and the other flows to the south and merges with the Thane Creek. The sampling stations with an average depth of 5 m were selected along the lower stretch of both the creeks. Stations selected in Thane and Vasai creeks are indicated as Mahul station (72º 51' 40.65'' E, 18º 52' 39.08''N) and Naigaon station (72º 45' 19.18''E, 19 º 29' 21.31''N) respectively, due to the proximity to Mahul and Naigaon fishing villages. These stations represent the major *dol* net fishing grounds in the selected creeks (Fig.1). Sampling was carried out on a monthly basis from December 2015 to November 2017. In order to minimize the possible effects of tidal variations and environmental conditions, both the stations were sampled during high tide with similar tidal characteristics in the morning hours. The data collected were pooled into four pre-determined seasons; winter monsoon (December to February), spring inter-monsoon (March to May), summer monsoon (June to September) and fall inter-monsoon (October -November) as per Chatterjee *et al.*, (2012).

Estimation of phytoplankton and chlorophyll-a

The samples were collected and concentrated to 50 mL by filtering 50 L of water through plankton net (30 µm mesh size). The phytoplankton samples were preserved in 0.4% Lugol's solution for further qualitative and quantitative analyses. Identification and quantification were carried out following the standard literature and methodologies (Welch, 1948; Subhramanyan, 1959). The individual species were counted using a Sedgwick-Rafter counting cell and the numbers are expressed as cells L^{-1} (Welch, 1948). For the estimation of chlorophyll-a, water samples were concentrated using a cellulose acetate-based filter assembly of 0.45 µm pore size. The pigments were extracted from the plankton concentrate with aqueous acetone and the optical densities of the extracts were determined spectrophotometrically following the guidelines of APHA (2005). The results are expressed in mg m^{-3}.

Estimation of physico-chemical parameters of water

The physico-chemical parameters such as temperature (°C), salinity (‰), pH and turbidity (NTU) of water were recorded onsite using a mercury-in-glass thermometer, a refractometer (ERMA, Tokyo), digital pH meter (Hanna Instruments, India) and nephelometer (Eutech Instruments, Singapore), respectively. For the estimations of dissolved oxygen (DO in mg L^{-1}), biochemical oxygen demand (BOD5 in mg L^{-1}), ammonia-N (µM L^{-1}), nitrate-N (µM L^{-1}), nitrite-N (µM L^{-1}), orthophosphate (µM L^{-1}), silicate (µM L^{-1}) and total suspended solids (TSS in mg L^{-1}) the standard methodologies described in APHA (2005) guidelines were used.

Data analysis

The diversity indices for phytoplankton such as Shannon-Wiener diversity index (H'), Margalef's richness index (d) and Heip's evenness index (E) were estimated using PAST software (Hammer *et al.*, 2001). Mean values with standard error were calculated for physico-chemical parameters and the diversity indices of phytoplankton were determined using the PROC MEANS procedure of SAS (SAS Institute, 2016). To compare the phytoplankton communities, they were classified into groups such as diatoms, dinoflagellates, green algae and blue-green algae on the basis of standard taxonomic classification (Subhramanyan, 1959). Pearson's correlation coefficients were calculated for phytoplankton groups with physico-chemical parameters of water using PROC CORR procedure of SAS (SAS Institute, 2016). To visualise the spatio-temporal variations in phytoplankton species assemblages and their relationship with the environmental variables, the data were subjected to canonical correspondence analysis (CCA) using PAST software (Hammer *et al.*, 2001).

Results and Discussion

Phytoplankton composition

The phytoplankton species identified were 84 (42 families) and 69 (33 families) at Mahul and Naigaon stations, respectively. Among these, diatom was the major group in terms of abundance and diversity at both the stations. At Mahul, 55 species of diatoms comprising Bacillariophyceae (24), Mediophyceae (19) and Coscinodiscophyceae (12) were identified (Table 1). Forty-seven species of diatoms comprising Bacillariophyceae (20), Mediophyceae (16) and Coscinodiscophyceae (11) were collected at Naigaon. *Navicula*, *Pleurosigma*, *Nitzschia*, *Bacteriastrum*, *Biddulphia*, *Chaetoceros*, *Coscinodiscus*, *Triceratium*, *Thalassiothrix*, *Skeletonema*, *Fragilaria* and *Fragilariopsis* were the major genera under Bacillariophyceae while *Dinophysis*, *Prorocentrum*, *Peridinium*, *Protoperidinium*, *Gymnodinium*, *Ceratium* and *Phyrocystis* were the dominant genera under Dinophyceae. The major genera under Chlorophyceae included *Ankistrodesmus*, *Pediastrum*, *Closterium*, *Scenedemus* and *Zygnema*, and *Trichodesmium*, *Microcystis* and *Oscillatoria* were the major representatives of Cyanophyceae. Phytoplankters identified during the sampling period in Naigaon and Mahul stations with their range in the number of cells L^{-1} are presented in Table 2.

Similar to our results at the north-eastern Arabian Sea region, a total of 103 species of phytoplankters were recorded in the creek waters of western mangrove of Kachchh region (Gujarat) with 82 species of diatoms, 16 species of dinoflagellates, 3 species of blue-green algae and 2 species of green algae by Saravanakumar *et al.*, (2008). The present study indicates that the diatoms constitute the major proportion of phytoplankton community in coastal ecosystems which was supported with the earlier reports from similar ecosystems (Kadam and Tiwari, 2011; Temkar *et al.*, 2015). In the present study, to the total plankton density diatoms contributed 77% (based on cells L^{-1}), followed by dinoflagellates 13%, blue-green algae 6% and green algae 4% of the total phytoplankton density. In the creek waters of Kachchh-, 79.6% diatoms, 15.5% dinoflagellates, 2.9% blue-green algae and 1.9% green algae contributed to the abundance of phytoplankton as reported by Saravanakumar *et al.*, (2008). In coastal waters, phytoplankton community is dominated by diatoms on account of the availability of optimal quantities of solar radiation and nutrients which intensifies their multiplication and growth rates (Stowe, 1996). Temporal variations were observed in percentage contribution of phytoplankton groups with the dominance of green algae in summer monsoon, diatoms in winter monsoon and blue-green algae in spring inter-monsoon at both the stations (Fig. 3). In this study, dinoflagellates did not show any seasonality in abundance. The low density of phytoplankton in the summer monsoon observed in this study may be due to the increased precipitation, runoff and subsequent reduction in the salinity of water along the coastal waters (Mitbavkar and Anil, 2008).

Phytoplankton density

Phytoplankton density was significantly higher at Naigaon station compared to Mahul. The phytoplankton density at Mahul station ranged from 8.7×10^4 cells L^{-1} to 2.4×10^5 cells L^{-1} whereas, at Naigaon, it ranged from 1.2×10^5 cells L -1 to 4.3×10^5 cells L^{-1} (Fig. 2). Plankton production in the study area during different seasons was in a moderate range. While comparing the seasonal patterns in plankton density, winter monsoon recorded the highest values and the lowest ones were observed during summer monsoon (Fig. 2). A comparatively higher range of phytoplankton density (2.4×10^5 cells L^{-1} to 9.41×10^6 cells L^{-1}) was observed in the creek waters of Kachchh (Saravanakumar *et al.*, 2008). Temkar *et al.*, (2015) reported higher levels of phytoplankton density and diversity in the winter season and low density in summer along the coastal waters of Veraval, Gujarat. In this study, the concentrations of inorganic nutrients like nitrate, nitrite and phosphate were found to be high during winter monsoon at both the stations. The high diversity and density of phytoplankton during winter monsoon could be attributed to the favourable environment and abundance of limiting nutrients in comparison with the other seasons.

Diversity pattern

There was a significant difference in the diversity of phytoplankters between stations and the values were high in Mahul in comparison with Naigaon during all the seasons. While comparing the seasonal patterns, the diversity was the highest during winter monsoon and the lowest values were recorded during summer monsoon to both the stations. The general pattern in diversity indices was comparable with the profile of

Shannon diversity (2-3) in coastal ecosystems (Magurran, 2004). Shannon index will be the highest in situations where the ecosystem is least disturbed (Jitendra *et al.,* 2015). This corroborates the results of this study, where the values were highest during winter monsoon with low current speed and turbidity, low levels of suspended solids, etc. The abundance of limiting nutrients compared to other seasons and low environmental disturbance may be the reason for the high diversity and evenness of phytoplankters during winter monsoon season at both the stations. At the same time, the diversity gets decreased when the ecosystem is turbulent or under perturbed conditions (monsoon). Summer monsoon on the west coast creates disturbance in the coastal environment with high wind and current speeds, high rainfall and runoff, and drastic changes in the physico-chemical parameters of water. Therefore, the lower levels of phytoplankton diversity will be noticed in these seasons complementing with the observations of the current study.

Chlorophyll - a

Chlorophyll-a (Chl-a) is the active photosynthetic pigment of phytoplankton that regulates the primary production in coastal ecosystems (Yeragi and Yeragi, 2003). The concentration of Chl-a in this study ranged from 2.66 mg m^{-3} to 5.53 mg m^{-3} in Mahul Creek and from 3.54 mg m^{-3} to 6.24 mg m^{-3} in Naigaon Creek. Harnstorm *et al.,* (2009) have reported the Chl-a concentrations ranging from 1.67 mg m^{-3} to 4.87 mg m^{-3} in a tidal creek of Mangalore. In this study, a moderate concentration of chlorophyll was obtained in comparison with the earlier reports. The highest concentration of Chl-a was noticed during winter monsoon and the lowest in summer monsoon. This observation is in correspondence with the variation in phytoplankton density as at both the stations, the values of Chl-a and phytoplankton density were highest during winter monsoon. This seasonal profile of phytoplankton and Chl-a was in alliance with the recent studies in coastal ecosystems (Vase *et al.,* 2018). During summer monsoon, the dilution of seawater occurs with the freshwater influx and huge quantities of suspended solids are released into the ecosystem. This generally reduces the incidence of solar radiation that catalyses primary production. This could be a plausible explanation for the decrease in Chl-a concentration during summer monsoon (Rajasekar *et al.,* 2010).

Temporal variations and interactions of physico-chemical parameters

There were significant differences in physico-chemical parameters between seasons and stations. Temperature, salinity and pH were recorded high during spring inter-monsoon and low during summer monsoon at both the stations. This can be considered as a result of the incidence of the high amount of solar radiation during summer (spring inter-monsoon) and therefore, an increase in temperature is expected during this season. The high degree of evaporation due to high temperature could be the reason for high salinity during spring inter-monsoon (Arthur, 1972). pH was found to be in the alkaline range (7.3 to 8.2) throughout the study period at both the stations. Seasonal patterns in physico-chemical parameters were similar at both the stations. These observations were found to be in agreement with the reports from earlier studies (Sukumaran *et al.,* 2013; Shahi *et al.,* 2015). The high amount of rainfall, consequent runoffs and dilution of the creek water during summer monsoon might have reduced the temperature, salinity and pH in that season.

DO was highest during summer monsoon and lowest during spring inter-monsoon at both the stations. Research reports from earlier attempts show that low salinity and low temperature could be the reason for higher solubility of oxygen in water (Levinton, 2001; Saravanakumar *et al.*, 2008; Puthiya *et al.*, 2009). In this study, low values of DO were observed in correspondence with high temperature and high salinity levels.

The Pearson correlation analysis has also shown a significant negative correlation of DO with salinity and temperature. Comparatively higher value of BOD noted at Naigaon station than Mahul indicates higher consumption of oxygen and higher organic pollution. This higher organic pollution might be the reason for low phytoplankton diversity and richness at Naigaon compared to Mahul. In this study, a significant negative correlation was observed between BOD and DO in both the stations. An increase in BOD causes a reduction in dissolved oxygen concentration in coastal ecosystems. The high BOD values indicate organic pollution and thus, a higher consumption of oxygen by microbes for decomposing the organic compounds (Lekshmi *et al.*, 2018).

Fig.1 Map showing the sampling locations

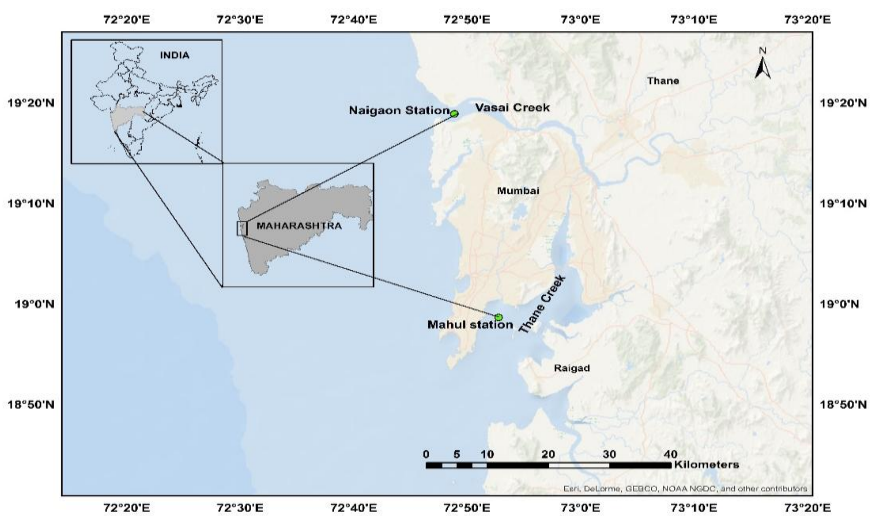

Fig.2 Spatio-temporal variation in phytoplankton density

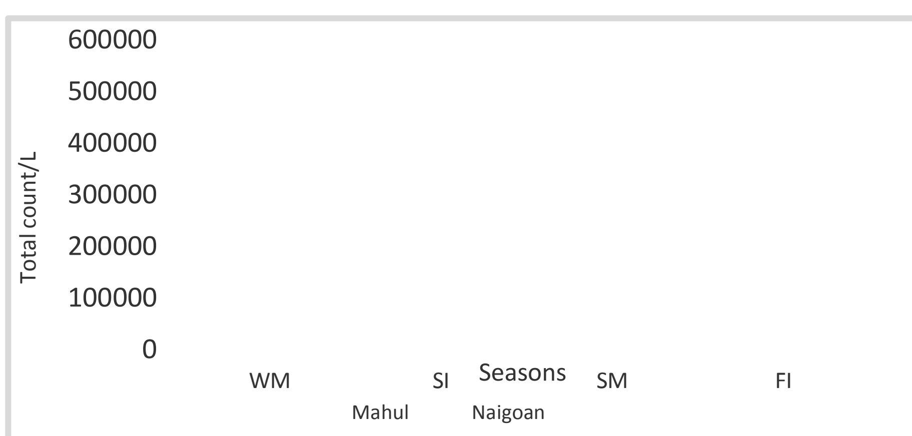

Fig.3 Spatio-temporal variations in percentage composition of phytoplankton

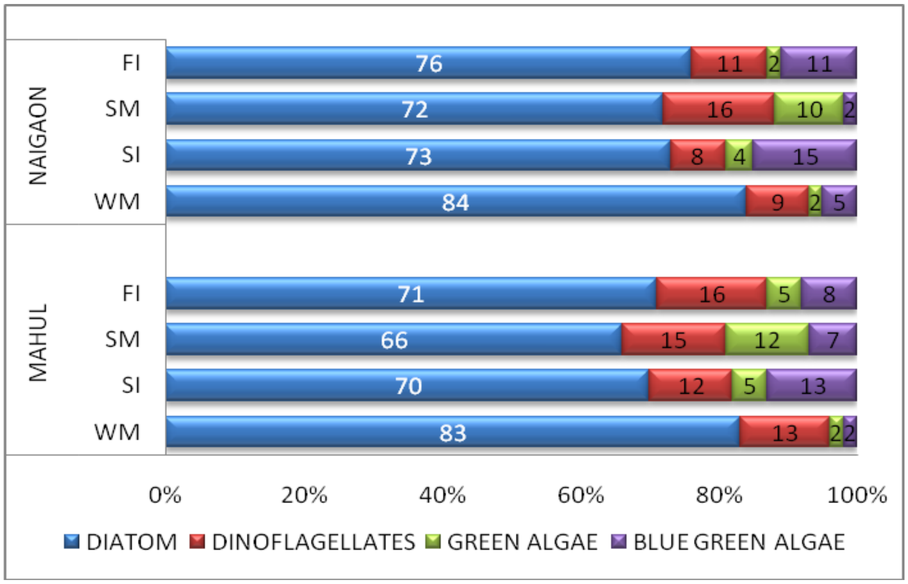

Fig.4 CCA plot for physico-chemical variables, plankton group and seasons

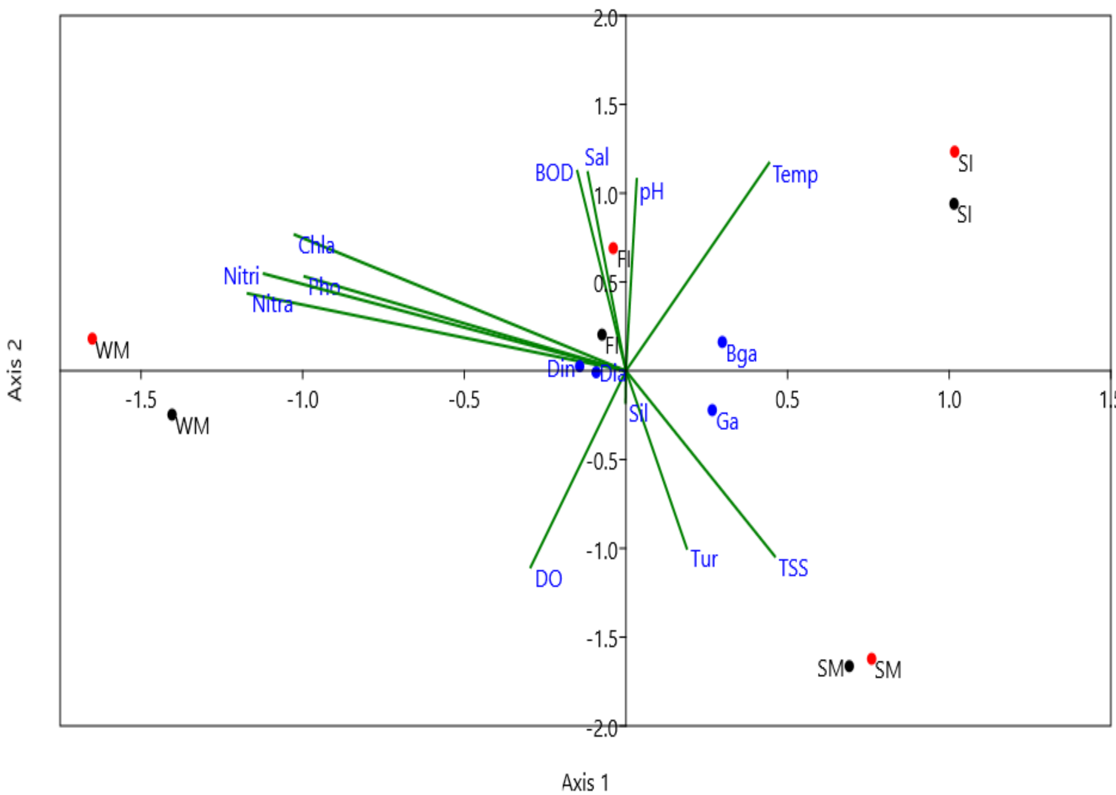

Table.1 Phytoplankton groups observed from the dolnet fishing grounds of Vasai and Thane creek

Mahul (Thane creek)				Naigoan (Vasai creek)			
Groups	Class	No.families	Species	Groups	Class	No.families	Species
Diatoms	Bacillariophyceae	9	24	Diatoms	Bacillariophyceae	7	20
	Mediophyceae	8	19		Mediophyceae	8	16
	Coscinodiscophyceae	5	12		Coscinodiscophyceae	4	11
Dinoflagellates	Dinophyceae	8	14	Dinoflagellates	Dinophyceae	7	12
Green algae	Chlorophyceae	5	6	Green algae	Chlorophyceae	4	6
	Zygnematophyceae	1	2		Zygnematophyceae	0	0
	Ulvophyceae	1	1	Blue-green algae	Cyanophyceae	3	4
Blue-green algae	Cyanophyceae	5	6				
Total		42	84	Total		33	69

Table.2 Phytoplankton taxa identified and its range (Cells L^{-1})

Family	**Phytoplankton Species**	**Range (Cells L^{-1})**	
Diatoms		Mahul	Naigoan
Amphipleuraceae	*Amphiprora sp.*	0-1500	0-2200
Naviculaceae	*Naviculatransitans*	0-14590	0-10200
Naviculaceae	*Naviculalongissima*	0-6900	0-17900
Naviculaceae	*Naviculadistans*	0-5400	0-16700
Pinnulariaceae	*Pinnulariarectangulata*	0-3700	Nil
Plerosigmataceae	*Pleurosigmaangulatum*	0-11300	0-23200
Plerosigmataceae	*Pleurosigmanormanii*	0-22600	0-31400
Plerosigmataceae	*Pleurosigmaelongatum*	0-10100	Nil
Naviculaceae	*Gyrosigmabalticum*	0-2100	0-21650
Bacillariaceae	*Pseudonitzschiaseriata*	0-16700	0-16700
Bacillariaceae	*Nitzschiaclosterium*	0-2300	0-11000
Bacillariaceae	*Nitzschaiseriata*	0-36000	0-62500
Bacillariaceae	*Nitzschiapungens*	0-6000	0-9450
Bacillariaceae	*Nitzschialongisima*	0-14200	Nil
Bacillariaceae	*Nitzschiaangularis*	0-6340	0-13400
Bacillariaceae	*Nitzschia sigma*	0-2865	Nil
Thalassionemataceae	*Thalasionemanitzschioides*	0-12600	0-5800
Thalassionemataceae	*Thalassiothrixfrauenfeldii*	0-1350	0-6200
Surirellaceae	*Surirellafluminensis*	0-7500	0-12450
Catenulaceae	*Amphora sp*	0-22000	0-25000
Thalassionemataceae	*Thallassiothrixlongissima*	0-680	0-19670
Bacillariaceae	*Fragilariopsissp*	0-5400	400-32500
Fragilariaceae	*Fragilariaoceanica*	0-23300	0-14300
Fragilariaceae	*Synedraformosa*	0-18000	0-7700
Biddulphiaceae	*Biddulphiasinensis*	0-1340	0-9650
Streptothecaceae	*Streptothecasp*	0-22200	0-19200
Biddulphiaceae	*Biddulphiamobilensis*	0-4600	0-6600
Biddulphiaceae	*Biddulphiapulchina*	0-7100	0-15800

Leptocylindraceae	*Leptocylindrusdanicus*	0-2300	0-6430
Chaetocerotaceae	*Bacteriastrumhyalinum*	0-2300	0-9800
Chaetocerotaceae	*Bacteriastrumdelicatum*	0-2300	Nil
Chaetocerotaceae	*Chaetocerostortissimus*	0-21500	0-13700
Chaetocerotaceae	*Chaetocerosaffinis*	0-1700	0-23000
Chaetocerotaceae	*Chaetocerosbrevis*	0-9300	0-7300
Chaetocerotaceae	*Chaetoceroscurvisetus*	0-10300	400-28700
Chaetocerotaceae	*Chaetocerosdiversus*	0-2300	0-3400
Thalassiosiraceae	*Thalassiosirasubtilis*	0-1550	0-12500
Thalassiosiraceae	*Thalassiosiraeccentrica*	0-5600	Nil
Thalassiosiraceae	*Planktoniellaspp*	0-6200	0-14600
Skeletonemataceae	*Skeletonema sp.*	0-16200	1350-39800
Stephanodiscaceae	*Cyclotellastriata*	0-11700	0-1600
Lithodesmiaceae	*Ditylumbrightwellii*	0-3350	0-6350
Biddulphiaceae	*Biddulphiabiddulphiana*	0-780	Nil
Hemidiscaceae	*Hemidiscussp*	0-2300	Nil
Coscinodiscaceae	*Coscinodiscusgranii*	0-3500	2400-30200
Rhizosoleniaceae	*Guinardiasp*	0-1800	0-6700
Rhizosolenaceae	*Rhizosoleniaserieta*	0-3000	0-8670
Rhizosolenaceae	*Rhizosoleniasetigera*	0-6500	0-12300
Rhizosoleniaceae	*Rhizosoleniastolterfothii*	0-1550	0-8050
Triceratiaceae	*Triceratiumdubium*	0-16350	0-12400
Triceratiaceae	*Triceratiumreticulatum*	0-9400	0-13100
Triceratiaceae	*Triceratiumalternans*	0-1220	0-7300
Melosiraceae	*Melosirasp*	0-7560	340-9560
Melosiraceae	*Melosiraundulata*	0-5600	0-13600
Coscinodiscaceae	*Coscinodiscuslorenzianus*	0-7600	0-3200
Dinoflagellates			
Dinophyceae	*Dinophysistripos*	0-24500	0-15400
Dinophyceae	*Dinophysisbicaudata*	0-9700	0-9700
Dinophysaceae	*Dinophysiscaudata*	0-4400	0-5000
Prorocentraceae	*Prorocentrum lima*	0-1540	0-12400
Prorocentraceae	*Prorocentrummicans*	0-5800	Nil
Peridiniaceae	*Peridiniumsp*	0-7700	0-9440
Peridiniaceae	*Peridiniumbiconicum*	0-400	0-4300
Protoperidiniaceae	*Protoperidiniumspp*	0-16500	Nil
Pyrocystaceae	*Pyrocystisfusiformis*	0-4500	0-12300
Ceratiaceae	*Ceratiumfurca*	0-5400	0-12500
Pyrophacaceae	*Pyrophacushorologium*	0-5020	0-5020
Ceratiaceae	*Ceratiumlineatum*	0-25400	0-6500
Gymnodiniaceae	*Gymnodiniumsp*	0-6400	0-11680
Gonyaulacaceae	*Gonyaulaxspinifera*	0-3200	0-7400
Green algae			
Selenestraceae	*Ankistodesmussp*	0-2700	0-5467
Hydrodictyaceae	*Pediastrumsp*	0-4300	0-3300
Chlorellaceae	*Actinastrumsp*	0-4000	0-4210

Scenedesmaceae	*Scenedesmussp*	0-7120	0-3000
Zygnematacae	*Zygnemasp*	0-3500	0-6600
Ulotrichaceae	*Ulothrixsp*	0-6450	Nil
Selenastraceae	*Ankistrodesmussp*	0-3400	0-11400
Dunaliellaceae	*Dunaliellasalina*	0-3200	Nil
Closteriaceae	*Closteriumsp*	0-12370	Nil
Blue-green algae			
Microcoleaceae	*Trichodesmiumerythraeum*	0-9670	0-32340
Microcystaceae	*Microcystissp*	0-300	0-13210
Oscillatoriaceae	*Oscillatoriasp*	0-3200	0-29650
Chroococcaceae	*Chrococcussp*	0-3250	0-3200
Merismopediaceae	*MerismopediaSp*	0-9700	Nil
Nostocaceae	*Anabaena sp*	0-4400	Nil

Table.3 Mean± standard error values of physico-chemical parameters and plankton diversity indices between seasons

	Mahul				**Naigoan**			
Parameter	WM	SI	SM	FI	WM	SI	SM	FI
Temperature	26.82±0.10	29.87±0.233	25.5±0.13	27.5±0.25	27.16±0.089	30.13±0.29	26.16±0.225	27.75±0.45
Salinity	31.15 ± 0.311	33. 13±0.218	25.42±0.72	28.82±1.17	30.78±0.926	32.22±0.67	24.82±0.74	28.36±0.2
pH	7.9±0.05	8.2±0.058	7.42±0.09	7.76±0.1	7.87±0.033	8.1±0.03	7.35±0.087	7.6±0.1
DO	5.66±0.13	4.22±0.055	5.86±0.20	5.41±0.4	4.59±0.50	3.91±0.23	5.51±0.10	4.46±0.09
BOD	2.6±0.09	2.92±0.058	1.68±0.13	2.3±0.2	2.93±0.145	3.37±0.25	2.02±0.07	2.45±0.25
Chl-a	5.53±0.28	4.22±0.09	2.66±0.21	4.76±0.25	6.24±0.368	4.6±0.27	3.54±0.29	5.14±0.14
Turbidity	48.13±8.03	38.31±2.35	70.89±3.95	58.55±9.15	55.63±8.87	46.44±7.87	87.93±7.38	67.55±6.39
TSS	64.39±12.97	59.70±4.07	124.7±21.62	74.45±6.75	76.12±2.66	75.03±10.29	167.2±15.13	94.45±46.75
Phosphate	4.25±0.28	1.67±0.17	1.39±0.097	3.66±0.39	6.97±1.48	3.89±0.45	1.89±0.23	5.99±0.32
Nitrate	19.40±2.12	9.40±1.16	7.18±0.83	14.26±0.98	28.4±7.25	15.94±1.17	10.78±2.58	19.76±3.51
Nitrite	2.25±0.58	0.92±0.062	0.49±0.11	1.24±0.09	2.45±0.46	1.12±0.189	0.57±0.153	2.19±0.25
Silicate	5.85±0.137	4.82±0.31	7.91±1.88	14.31±0.62	7.02±0.25	7.15±1.75	11.62±1.89	17.32±0.62
Ammonia	0.46±0.054	1.71±0.04	0.19±0.05	0.66±0.07	0.92±0.20	3.45±0.43	0.37±0.06	0.88±0.03
Plankton density	497.83±26.12	337.18±9.33	296.59±8.23	391.5489±14.84	656.54±50.05	456.95±10.56	349.17±16.21	507.07±21.78
Diatom	456.23±22	287.37±26.36	242.07±9.5	329.54±29	604.48±55	401.05±16	304.98±16	447.51±8
Dinoflagellate	170.36±3	101.09±42.10	108.70±21	154.74±9	195.95±55	123.97±19	134.06±16	153.04±32
Green algae	53.26±6.1	77.02±6.95	92.94±14	74.54±51	42.33±12	77.49±18	93.89±11	53.59±35
Blue green algae	55.77±20	108.55±11.86	82.64±5.6	103.24±20	146.35±28	162.37±48	51.02±10	142.84±33
Dominance	0.04±0.01	0.06±0.002	0.09±0.01	0.058±0.01	0.04±0.01	0.051±0.01	0.082±0.02	0.06±0.01
Diversity	3.37±0.04	3.2±0.001	2.86±0.13	3.2±0.04	3.30±0.68	3.22±0.05	2.78±0.18	3.17±0.30
Evenness	0.56±0.01	0.516±0.017	0.47±0.58	0.52±0.03	0.671±0.05	0.65±0.53	0.545±0.08	0.53±0.03
Margalef	4.67±0.23	4.13±0.15	3.44±0.23	4.41±0.05	3.84±0.30	3.05±0.18	2.93±0.32	3.55±0.16

Square root was taken for the plankton groups and dens

Table.4 Correlation matrix of various physico-chemical parameters with plankton groups in Mahul

	SST	pH	Sal	DO	BOD	Chl.a	Tur	TSS	Pho	Nitra	Nitri	Sil	Am	Pd	Dia	Dino	GA
Ph	0.58*																
Sal	0.36	0.91**															
DO	-0.85**	-0.74**	-0.61*														
BOD	0.68*	0.87**	0.81**	-0.87**													
Chla	-0.15	0.51	0.79**	-0.16	0.43												
Tur	-0.87**	-0.35	-0.17	0.66*	-0.49	0.18											
TSS	-0.26	-0.83**	-0.91**	0.48	-0.69*	-0.77**	0.22										
Pho	-0.55	-0.30	0.05	0.49	-0.28	0.56*	0.37	-0.15									
Nitra	-0.74**	-0.24	0.11	0.54	-0.34	0.63*	0.70*	-0.13	0.84**								
Nitri	-0.74**	-0.16	0.13	0.47	-0.31	0.61*	0.78**	-0.08	0.66*	0.92**							
Sil	-0.29	-0.78**	-0.93**	0.57*	-0.79**	-0.85**	0.21	0.90**	-0.21	-0.21	-0.14						
Am	0.78**	0.90**	0.81**	-0.85**	0.84**	0.38	-0.56*	-0.66*	-0.38	-0.40	-0.31	-0.67*					
Pd	-0.53	0.27	0.54	0.20	0.10	0.87**	0.60*	-0.57	0.59*	0.82**	0.88**	-0.55*	0.04				
Dia	-0.56*	0.31	0.55	0.24	0.10	0.83**	0.59*	-0.58*	0.50	0.74**	0.76**	-0.57*	0.03	0.95**			
Dino	-0.24	0.07	0.28	0.01	0.09	0.54	0.37	-0.09	0.42	0.63*	0.74**	-0.27	0.01	0.67*	0.43		
GA	0.49	-0.36	-0.49	0.15	-0.42	-0.45	-0.40	0.36	-0.03	-0.34	-0.33	0.53	-0.11	-0.53	-0.55	-0.43	
BGA	0.60*	0.54	0.11	-0.39	0.23	-0.06	-0.54	0.04	0.09	-0.23	-0.34	-0.09	0.38	-0.36	-0.52	0.05	0.29

(Sal-salinity; Tur-turbidity; TSS-Total suspended solids; Pho-phospate; Nitra-nitrate; Nitri-nitrite; Sil-silicate; Am-ammonia; PD-plankton density; DIAT-diatom, DINO-dinoflagellate, GA-green algae, BGA-blue green algae)

Table.5 Correlation matrix of various physico-chemical parameters with plankton groups in Naigaon

	SST	pH	Sal	DO	BOD	Chla	Tur	TSS	Pho	Nitra	Nitri	Sil	Am	Pd	DIAT	DINO	GA
pH	0.56																
Sal	0.50	0.92**															
DO	-0.56*	-0.81**	-0.72**														
BOD	0.54	0.82**	0.73**	-0.82**													
Chla	-0.24	0.48	0.55	-0.40	0.30												
Tur	-0.66*	-0.06	0.07	0.22	-0.25	0.71*											
TSS	-0.12	-0.80**	-0.84**	0.71**	-0.73**	-0.82	-0.34										
Pho	-0.59*	-0.27	-0.30	0.29	-0.39	0.54*	0.68*	-0.08									
Nitra	-0.79**	-0.62*	-0.64*	0.61*	-0.61	0.60*	0.60*	0.25	0.89								
Nitri	-0.79**	-0.68*	-0.59*	0.76**	-0.78**	0.49*	0.66*	0.33	0.77	0.90**							
Sil	-0.35	-0.86**	-0.94**	0.77**	-0.76**	-0.70**	-0.15	0.94**	0.13	0.48	0.49						
Am	0.82**	0.85**	0.84**	-0.77**	0.78**	0.18	-0.35	-0.59*	-0.55	-0.82**	-0.80**	-0.74**					
PD	-0.43	0.32	0.38	-0.10	0.10	0.90**	0.84**	-0.62*	0.54*	0.66**	0.58*	-0.46	-0.03				
DIAT	-0.49	0.29	0.33	-0.07	0.12	0.88**	0.82**	-0.61*	0.51	0.45	0.39	-0.53	-0.07	0.99**			
DINO	-0.37	0.07	0.08	0.21	-0.21	0.59	0.77**	-0.17	0.52	0.42	0.50	-0.06	-0.27	0.82**	0.78**		
GA	0.62*	0.01	-0.07	-0.09	0.08	-0.50	-0.36	0.30	-0.52	-0.49	-0.38	0.13	0.40	-0.51	-0.59*	-0.31	
BGA	0.55*	0.42	0.58*	-0.48	0.15	0.55	0.31	-0.49	0.12	-0.20	-0.08	-0.59*	0.43	0.33	0.21	0.18	0.20

(Sal-salinity; Tur-turbidity; TSS-Total suspended solids; Pho-phospate; Nitra-nitrate; Nitri-nitrite; Sil-silicate; Am-ammonia; PD-plankton density; DIAT-diatom, DINO-dinoflagellate, GA-green algae, BGA-blue green algae)

Table.6 Canonical coefficients of physico-chemical parameters and plankton groups

Variables	Axis 1 (74.1%)	Axis 2 (24.09)
Diatom	-0.092	-0.008
Dinoflagelate	-0.143	0.025
Green algae	0.267	-0.222
Blue green algae	0.298	0.162
Temperature	0.340	0.900
Salinity	-0.091	0.859
pH	0.026	0.829
DO	-0.227	-0.850
BOD	-0.116	0.864
TSS	0.354	-0.803
Turbidity	0.145	-0.769
Chl-a	-0.788	0.589
Silicate	-0.001	-0.137
Phosphate	-0.765	0.408
Nitrate	-0.900	0.335
Nitrite	-0.861	0.420

The Concentration of total suspended solids (TSS) and turbidity demonstrated peak values during summer monsoon and low values during spring inter-monsoon. This can be viewed as a result of high terrestrial runoff and discharge of suspended particles into the creek ecosystems in summer monsoon which increases TSS and turbidity (Vinayachandran *et al.,* 2002). While comparing the results of phytoplankton and TSS, a negative correlation was observed between TSS and the density of phytoplankton at both the stations (Table 4 & 5). The higher amount of TSS reduces the penetration of solar radiation, and this leads to the reduction in growth and abundance of phytoplankton (Rai and Rajashekar, 2014).

Phosphate, nitrate and nitrite were highest during winter monsoon and lowest during summer monsoon at both the stations (Table 3). Higher concentration of ammonia was recorded during spring inter-monsoon which got reduced significantly during summer monsoon season. Similar observations were reported for nitrate and ammonia by Vase *et al.,* (2018) along Veraval coast. Nitrate concentrations were varying from 7.18 µM L^{-1} to 28.4 µM L^{-1}. A comparatively lower range of nitrate concentration (2.2 µM L^{-1} – 6.87 µM L^{-1}) was described from the coastal waters of Veraval by Vase *et al.,* (2018). The values of phosphate ranged from 1.39 µM L^{-1} to 6.97 µM L^{-1} in this study. However, Shahi *et al.,* (2015) stated a wider range of phosphate concentration (3.6 – 46.8 µM L^{-1}) in the coastal waters of Mumbai. Nitrate, nitrite and phosphate concentrations at both the stations showed significant positive correlations with plankton density and Chl-a (Table 4 and 5).

It has been mentioned that as long as the limiting nutrients such as nitrate and phosphate prevail in an aquatic ecosystem, the primary productivity and concentration of Chl-a will be very high (Lekshmi *et al.,* 2018). This might have resulted in the positive correlation of Chl-a and plankton density with limiting nutrients such as phosphates, nitrates and nitrites. These results emphasize the essential nature of these nutrients for phytoplankton productivity in a tidal creek ecosystem.

Silicate concentrations were the highest during the fall inter-monsoon season at both the stations. A significant negative correlation of silicate was noticed at both the creeks with diatom density and salinity (Table 4 and 5). The increased availability of silicate during the low saline phase indicates the incursion of fresh water from land runoff carrying silicates during monsoon and its accumulation during post-monsoon seasons as reported in earlier research reports (Kamalkanth *et al.,* 2012). Moreover, the greater consumption of silicate by diatoms could be the possible reason for its low availability during winter monsoon. This observation was corroborated by the greater density of diatoms during winter monsoon.

The changes in the availability of nutrients in coastal ecosystems depends on their concentrations in the freshwater influx that mixes with seawater, land runoff, uptake of nutrients by phytoplankton, upwelling, chemical interactions and microbial decomposition (Satpathy *et al.,* 2009; Shahi *et al.,* 2015).

The availability of these nutrients in the coastal ecosystems regulates the growth and density of phytoplankton (Mochemadkar *et al.,* 2013). Comparatively, the higher availability of limiting nutrients during winter monsoon might have enhanced the phytoplankton production at both the stations. Vase *et al.,* (2018) reported that in the north eastern Arabian Sea, the higher concentrations of nutrients and higher productivity during the winter monsoon season is the end result of winter convective mixing and maturity of runoff nutrients during post-monsoon due to low current speed and low environmental perturbations. This mixing pattern, low environmental disturbance and the maturity of nutrients could be a major cause for the higher levels of limiting nutrients during winter monsoon in this study.

Canonical correspondence analysis (CCA) was carried out to determine the temporal variability in plankton groups in correspondence with the physico-chemical parameters of water. The canonical coefficients of environmental variables and plankton groups with the first two axes of CCA are given in Table 6. The results of CCA reveal that the seasonal variations in physico-chemical parameters are the major influencing factors for the distribution and abundance of phytoplankton. At both the stations (black dot representing Mahul and a red dot representing Naigaon), the abundance of diatoms and dinoflagellates was observed to be the highest during winter monsoon followed by fall inter-monsoon (Fig 4). At the higher levels of limiting nutrients during winter monsoon and fall inter-monsoon, the plankton density in terms of diatoms and dinoflagellates increased substantially. Therefore, a general consensus can be inferred from the CCA analysis that the major factors influencing plankton density of diatom and dinoflagellates are the concentrations of limiting nutrients such as nitrate, nitrite and phosphate.

The abundance of blue-green algae was observed during spring inter-monsoon at both the stations which coincided with high temperature and pH. Thajuddin and Subramanian (2005) stated that compared to the other phytoplankton groups, blue-green algae require relatively high pH and temperature for ideal growth. Green algae were high at both the stations during summer monsoon when TSS and turbidity were high, and salinity and pH were low. It is reported that green algae tolerate extreme environmental changes compared to the other phytoplankton groups (Silva *et al.,* 2004). Therefore, the abundance of green algae during summer monsoon is correlated to their tolerance to stressful conditions like high TSS and turbidity during the summer monsoon.

From the CCA analysis, the major environmental factors which regulate the population of phytoplankton in various seasons were identified as nutrients, temperature, salinity and pH.

The present study recapitulates the temporal fluctuations in physico-chemical parameters, phytoplankton abundance and diversity in Thane and Vasai tidal creeks of Maharashtra. Phytoplankton assemblages are highly dynamic depending primarily on the nutrient availability which is clearly explained by correlation analysis and CCA in the present study. The availability of nutrients in exact proportions and optimal environmental conditions generate high diversity and density of phytoplankton during winter monsoon. As phytoplankton form the base for coastal food webs, fish abundance and diversity are interlinked to plankton dynamics. Thus, the overall study gives a good outline of the seasonal dynamic relationship between phytoplankton and environmental parameters. Hence, the results from this study provide insight for further ecological assessment of the tidal creek coastal ecosystems and contribute towards ecosystem-based fisheries management in the region.

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