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Spatiotemporal distribution in phytoplankton community with distinct salinity regimes along the Mandovi estuary, Goa, India

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Abstract: Seasonal variations in the composition and abundance of phytoplankton were investigated fortnightly at 3 different regions along the Mandovi estuary from June 2007 to May 2008 in relation to salinity and nutrients. A total of 209 species belonging to 7 divisions were identified during the study period. The highest phytoplankton cell density (5.17×10^4 cells L^{-1}) and biomass (7.68 mg m^{-3} chlorophyll *a*) were observed in the upper sections during the nonmonsoon period, while the highest diversity (3.46) was observed in the upper section during the monsoon period. Bacillariophyta was the dominant phytoplankton group at 71% of the total species identified. This group was dominated by Pennales (88) over Centrales (60) at all 3 stations. Contributions of Dinophyta, Chlorophyta, Cyanophyta, Haptophyta, Chromophyta, and Chrysophyta to the total species were 25%, 0.5%, 1%, 0.5%, 1%, and 1%, respectively. Dinophyta did not show significant variations in percentage distribution among the 3 sections and seasons. Twenty-six dominant species of phytoplankton, representing all seasons with cell density of >1000 cells L^{-1}, showed spatial adaptability patterns with respect to salinity. *Protoperidinium acbromaticum* and *Alexandrium ostenfeldii* were found to grow only during nonmonsoon periods in upper sections and were reported for first time in the present study. Euryhaline *Skeletonema costatum* and *Thalassiothrix frauenfeldii* were present throughout the study period. A total of 36 harmful algal bloom-forming species, with 11 toxin-producing species, have been identified. The presence of *Streptotheca thamensis* acts as an indicator to evaluate water quality.

Key words: Chlorophyll, monsoon, dinoflagellates, nutrients, diatoms

1. Introduction

Estuaries and their associated river systems form an integral part of inshore waters. Despite extreme conditions, estuaries are fertile and provide excellent nursery grounds for a variety of commercially important fishes and prawns. The Mandovi estuary, on the west coast of India, is one of the life lines of Goa, stretching up to 40 km inland. Although partially landlocked, the Mandovi estuary is exposed to constant flushing and flooding by the semidiurnal tides, which considerably influences the environmental features of the area. The flow in the estuarine system is regulated by the incoming tide at the adjacent Zuari estuary, which reaches the Mandovi River through the Cumbarjua canal. The flow is reversed during the outgoing tide (Shetye et al., 2007; Vijith et al., 2009).

Summer (dry) and monsoon (wet) are the 2 distinct seasons that determine the extent of saline and fresh water. During peak monsoon season, the estuary is predominantly fresh water, which later slowly becomes saline. Salinity is an important factor governing the growth of phytoplankton (Qasim et al., 1972; Shetye et al., 2007). The decline in salinity is accompanied by an increase in nutrients during the onset of monsoon season, which is an important factor controlling the distribution, abundance, and productivity of phytoplankton (Devassy and Goes, 1988; Krishna Kumari et al., 2002). Generally, tropical estuaries with moderately low salinities support a greater phytoplankton population (Desikachary and Rao, 1972; Qasim et al., 1972) than those with a higher salinity, as was observed in the adjacent Zuari estuary (Bhargava and Dwivedi, 1976).

In the present investigation we examined the hypothesis that the gradients in salinity and nutrients due to tidal and monsoonal seasonality along the Mandovi estuary affect the temporal dynamics of phytoplankton species' composition, abundance, and spatial distribution. Therefore, this study will contribute to understanding the role of environmental variables in studying the estuarine phytoplankton communities.

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2. Materials and methods

2.1. Sampling site and sampling protocols

Surface and bottom water samples were collected fortnightly using a Niskin sampler from 3 stations: 1) Verem (lower section = mouth of the estuary), 2) Ribandar (middle section), and 3) Old Goa (upper section) (Figure 1), for a period of 1 year from June 2007 to May 2008. The data were then pooled into seasons depending on the rainfall pattern: monsoon (June–November 2007) and nonmonsoon (December 2007 to May 2008). Water samples for phytoplankton taxonomy were placed in 500-mL plastic bottles and fixed with 2% Lugol's iodine. Samples were allowed to settle for 2 weeks and concentrated to 5–10 mL by carefully siphoning the top layer of the sample with silicon tubing, one end of which was covered with 10-µm Nitex mesh, which then went deeper inside the bottle without disturbing the bottom layer. Using a Sedgwick Rafter chamber, 1 mL of each concentrate was counted under an Olympus 86 inverted microscope (Model IX 50) at 200× magnification. Phytoplankton cell identification was based on standard taxonomic keys (Tomas, 1997) and on previous phytoplankton taxonomic data from the study area (Devassy and Goes, 1988). SEM samples of *Pseudo-nitzschia* species were processed using the $KMnO_4$/HCL oxidation method (Miller and Scholin, 1998). Results (averages of duplicate counts) are expressed as cell numbers × 10^4 L^{-1}. Depth variations were around 10 m, so the column was integrated and then average values for each month were used.

Phytoplankton biomass, estimated as chlorophyll (Chl) *a*, was measured by filtering 500-mL water samples onto 47-mm glass-fiber filters (grade 91 GF/F, Whatman, USA), which were then extracted overnight in 10 mL of 90% acetone in the cold and dark. Sample extracts were then filtered through PTFE filters (0.2 µm, Millipore, USA) to remove GF/F filter debris. Chl *a* was estimated (duplicate samples) by high-performance liquid chromatography (Agilent 94 1100 series) and separated on a C-18 reverse-phase column using the eluent gradient program of Wright et al. (1991).

Salinity was measured with a salinometer (Atago S/Mill97, Japan; salinity range of 0–100 psu, resolution of 1 psu at 10–20 °C). Nutrients were estimated using the methods outlined by Strickland and Parsons (1972).

2.2. Statistical methods for data analysis

Data processing was done using PRIMER version 5.2.8 (Clarke and Warwick, 1994), where species diversity (H′) was calculated according to Shannon and Weaver (1963):

$$H = \sum_{i=1}^{S} Pi \ \log_2(Pi) \ ,$$

where P_i is the n_i/N proportion of the sample belonging to the *i*th species, S is the number of species, and *N* is the total number of individuals of all the species in a sample.

The normality of the data was verified using the Kolmogorov–Smirnov test and homogeneity of variance using Leven's test in STATISTICA 6. As the data were unable to satisfy the assumptions of the parametric test, they were later transformed into the log form to achieve normality. Log-transformed data were then used to carry out Pearson's correlation test between biological and environmental characters within the 2 seasons.

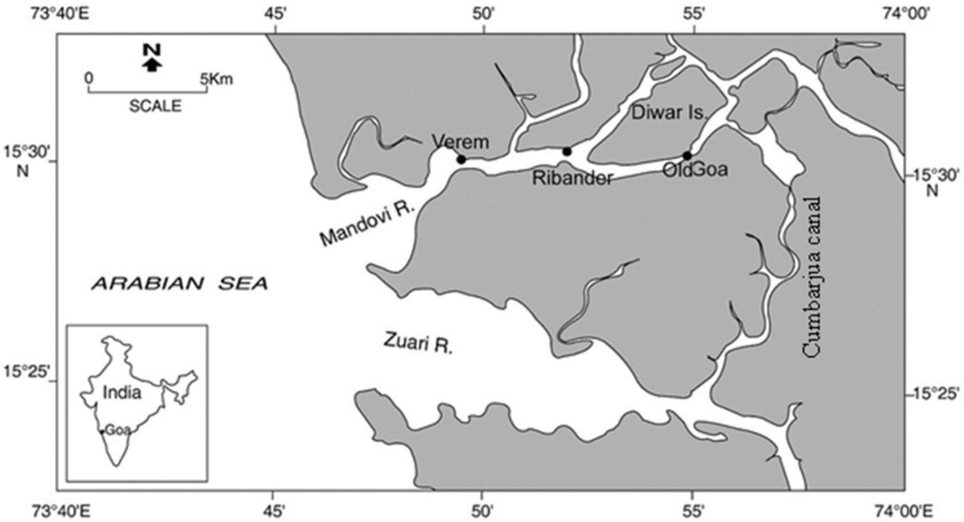

Figure 1. Map showing sampling stations Verem, Ribandar, and Old Goa in the Mandovi estuary, Goa, on the west coast of India.

3. Results

3.1. Physical and chemical parameters

Seasonal variations in the physicochemical parameters are presented in Figures 2A–2E. The highest concentration of nitrate (18.76 µM) was found in August, in the middle of the monsoon period, at the lower section (Verem). The silicate concentration was highest (129.7 µM) at the upper section (Old Goa). Salinity was high at the lower section and low at the upper section. The seasonal variations in the physical and chemical parameters at the different stations are shown.

3.2. Phytoplankton

The total phytoplankton population cell density and biomass varied seasonally in the Mandovi estuary. Phytoplankton cell density was greater during the nonmonsoon period. The highest cell density (5.17×10^4 cells L^{-1}) and biomass

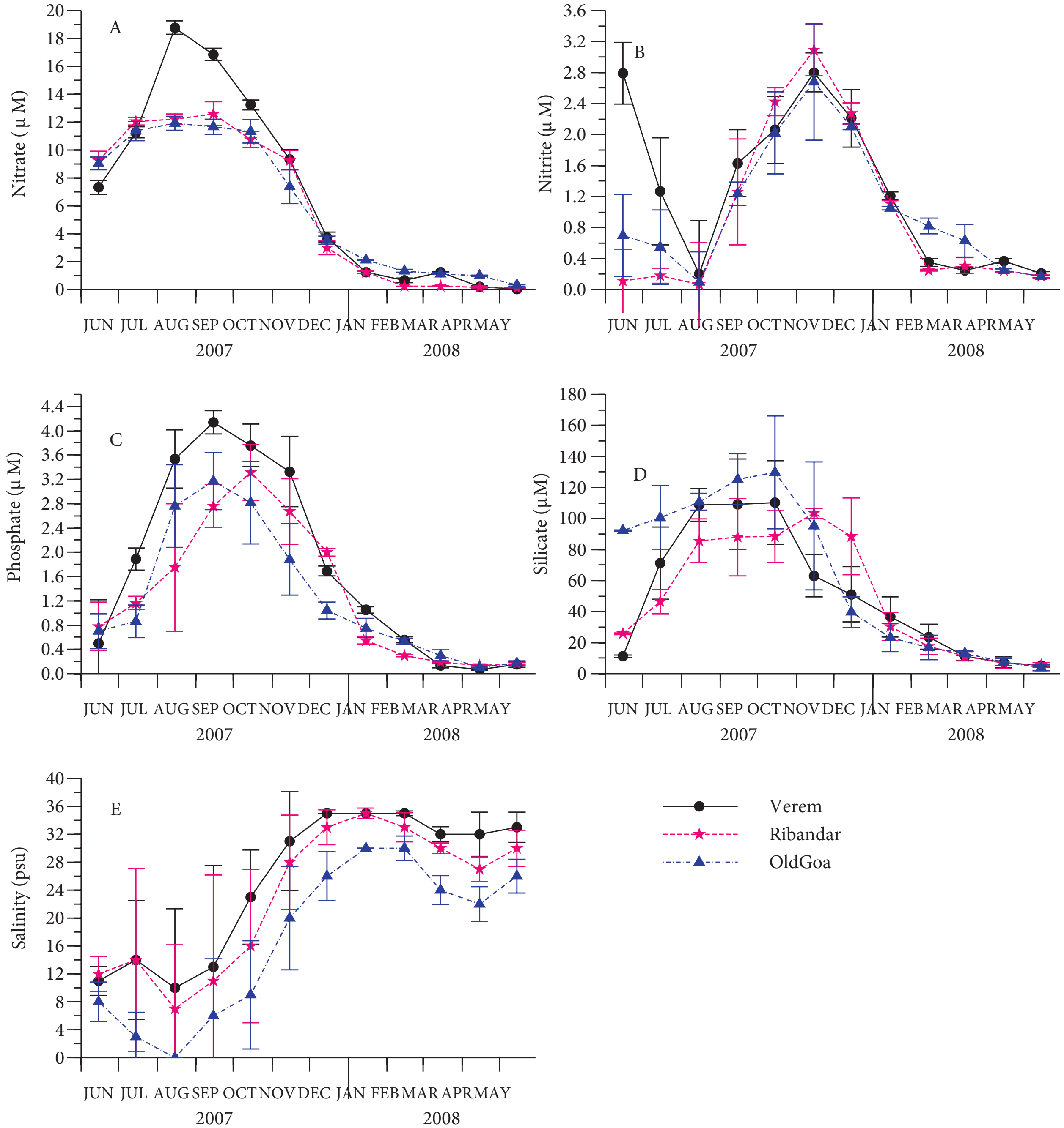

Figure 2. Seasonal variations in the physicochemical parameters in the Mandovi estuary during June 2007–May 2008. A- Nitrate, B- nitrite, C- phosphate, D- silicate, E- salinity.

(7.68 mg Chl *a* m^{-3}) were observed in March, at the upper section. During the monsoon season, the highest cell density (0.60×10^4 L^{-1}) was observed at the lower section in October, while the highest biomass (4.62 mg m^{-3}) was seen at the middle section (Ribandar) in June (Figures 3A and 3B). The phytoplankton concentration and biomass showed a significant positive correlation with salinity (Table 1), signifying the role of salinity as an important control factor in this estuary. A total of 209 species with 80 genera belonging to 7 divisions were identified. The lower section consisted of 156 species, 66 genera, and 7 divisions, while the middle section consisted of 143 species, 65 genera, and 6 divisions. The upper section represented 149 species, 70 genera, and 6 divisions. A list of phytoplankton is given in Table 2. During the study period, diversity ranged between 2.61 and 3.46. The highest diversity was found at the lower section in August. The lowest value was observed at the middle section in April (Figure 3C).

Total diatom cell density was highest during the nonmonsoon period in March at all 3 sections (Figures 4A–4C). Lower sections had a maximum value of 2.10 $\times$ 10^4 cells L^{-1} during the nonmonsoon period; a value of 0.56×10^4 cells L^{-1} was observed in September during the monsoon period (Figure 4A). Middle sections had a maximum value of 3.62×10^4 cells L^{-1} in March, while a value of 0.55×10^4 cells L^{-1} was seen in October (Figure 4B). In the case of upper section, a maximum of 4.92 $\times$ 10^4 cells L^{-1} was observed in March (Figure 4C). During the monsoon period, a maximum value of 0.45×10^4 cells L^{-1} was seen in November. In the case of dinoflagellate total density at lower sections, values peaked at 0.31×10^4 cells L^{-1} in September and at 0.17×10^4 cells L^{-1} during the nonmonsoon period in December (Figure 4D). During the monsoon season in middle sections, the maximum value was 0.15×10^4 cells L^{-1} in August (Figure 4E). In upper sections, dinoflagellate cell density (0.24×10^4 cells L^{-1}) was the highest during the nonmonsoon period in March, while 0.17×10^4 cells L^{-1} were observed in July during the monsoon period (Figure 4F).

Bacillariophyta was the dominant division, accounting for 71% (148 species, 56 genera) of the total population. It was negatively correlated with nutrients and positively correlated with salinity (Table 1). Dinophyta was the second-most dominant group, with 25% (53 species, 18 genera) of the total; it showed a positive correlation with nutrients. The remaining divisions were Chlorophyta

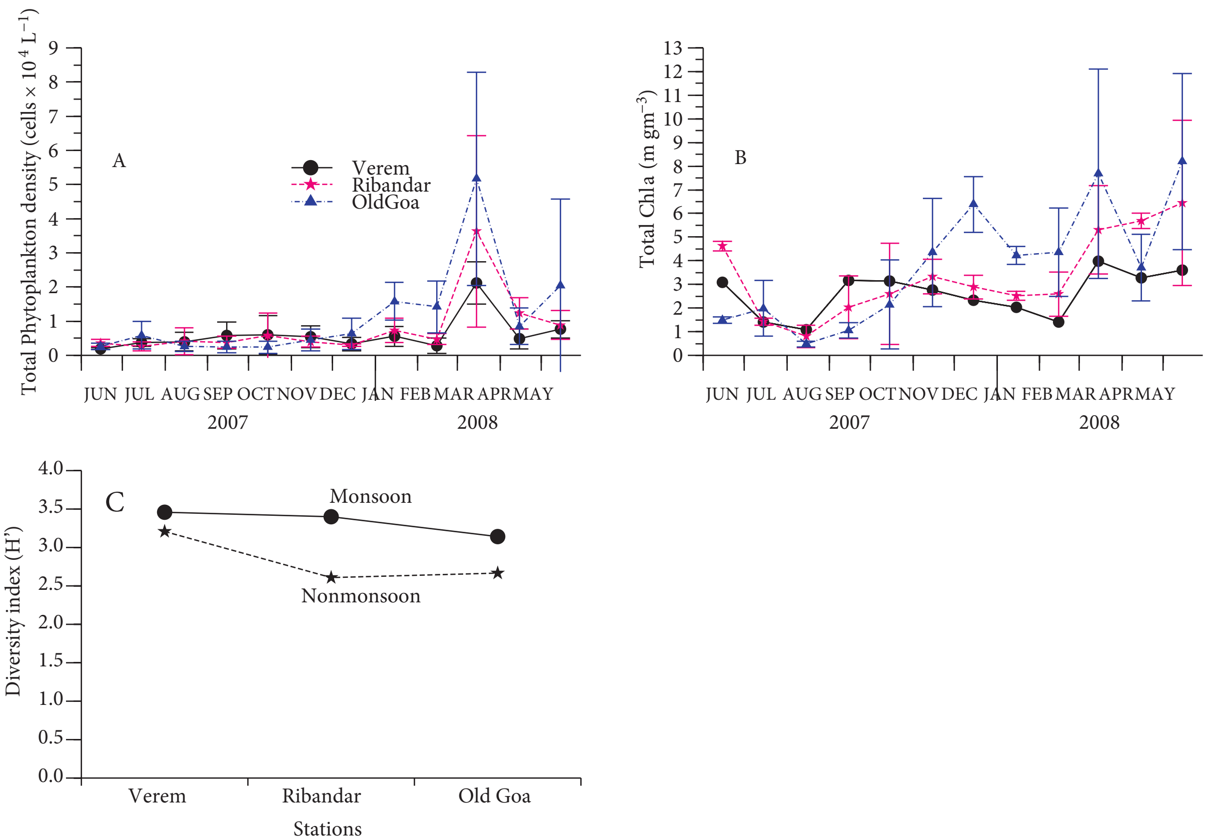

Figure 3. Seasonal variations in total phytoplankton cell density, biomass, and diversity at 3 different stations in Mandovi estuary during June 2007–May 2008. A- Total phytoplankton cell density, B- biomass, C- diversity.

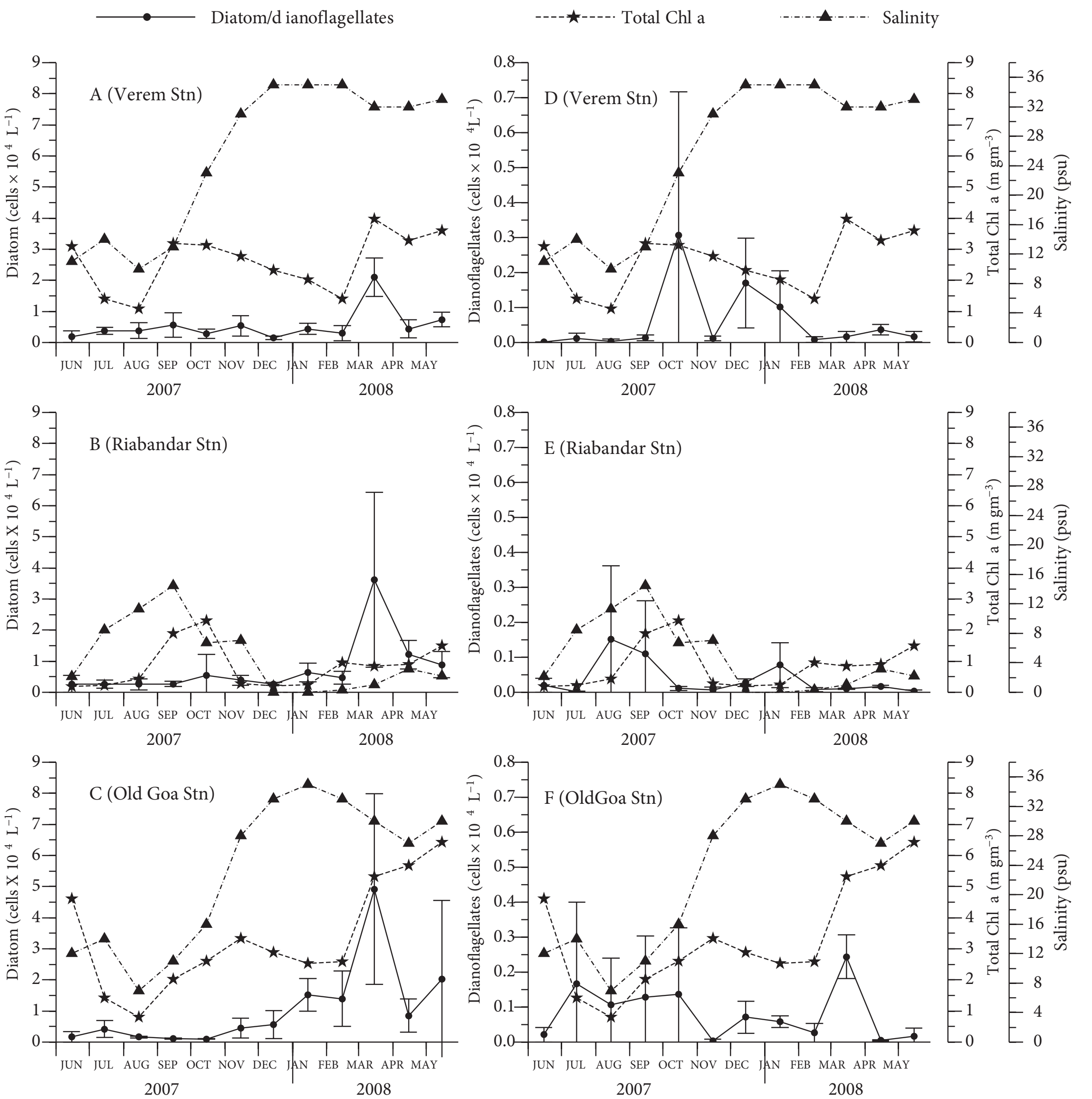

Figure 4. Seasonal variations in total diatom cell density and dinoflagellate cell density with respect to salinity and Chlorophyll *a* at 3 different stations in the Mandovi estuary during the year June 2007–May 2008. A, B, C- Total diatom cell density; and D, E, F- total dinoflagellate cell density.

Table 1. Statistically significant Pearson correlations ($P < 0.05$; bold = significant) among total phytoplankton density, chlorophyll *a* (Chl *a*) concentration, diatom abundance, dinoflagellate abundance, and other algae abundance.

Parameter	Nitrate	Nitrite	Phosphate	Silicate	Salinity
Total density	**–0.25**	**–0.21**	**–0.24**	**–0.25**	**0.22**
Chl *a*	**–0.47**	–0.16	**–0.45**	**–0.50**	**0.27**
Diatoms	**–0.39**	**–0.28**	**–0.33**	**–0.39**	**0.26**
Dinoflagellates	0.11	0.09	0.08	**0.17**	**–0.18**
Other algae	0.11	0.01	**0.21**	0.07	0.01

Table 2. Check list of phytoplankton species encountered during the present investigation (June 2007–May 2008). Present = +; absent = -, and potentially harmful and toxic species = *.

Phytoplankton			
Division Bacillariophyta	Verem	Ribandar	Old Goa
Centrics			
Family Asterolampraceae			
Asteromphalus cleveanus Grunow	+	+	+
A. flabellatus (Brébisson) Greville	+	+	+
A. heptactis (Brébisson) Ralfs	+	+	-
Asterolampra marylandica Ehrenberg	-	+	-
Asteromphalus sp.	+	+	+
Family Chaetocerotaceae			
Bacteriastrum furcatum Shadbolt	+	+	+
Chaetoceros breve F.Schütt	+	+	+
C. coarctatus Lauder	+	-	-
**C. curvisetus* Cleve	+	+	+
C. decipiens Cleve	+	-	-
C. diversus Cleve	+	+	-
C. exospermum Meunier	-	+	+
C. fragile Meunier	+	-	-
C. laciniosus F.Schütt	+	+	+
C. lorenzianus Grunow	+	+	+
C. messanense Castrcane	+	+	+
C. radicans F.Schütt	-	+	-
C. subtilis Cleve	+	+	-
Family Coscinodiscaceae			
**Coscinodiscus centralis* Ehrenberg	+	+	+
C. granii Gough	+	+	+
C. occulus Ehrenberg	-	+	+
C. radiatus Ehrenberg	+	+	+
C. marginatus Ehrenberg	+	+	+
C. nitidus Ehrenberg	+	+	+
C. nodulifer A.W.F.Schmidt	-	+	-
**C. wailesii* Gran & Angst	+	+	+
Family Biddulphiaceae			
Odontella aurita (Lyngbye) C.Agardh	+	+	+
O. regia (Schultze) Ostenfeld	+	+	+
**O. mobiliensis* (J.W.Bailey) Grunow	+	+	+
**O. sinensis* Greville	+	+	+
Family Hemidiscaceae			
Actinocyclus octonarius Ehrenberg	+	+	+

Table 2. (Continued).

Roperia tesselata (Roper) Grunow ex Pelletan	+	-	-
Family Heliopeltaceae			
Actinoptychus senarius Ehrenberg	+	+	+
Family Hemiaulaceae			
Cerataulina pelagica (Cleve) Hendey	+	+	+
**Eucampia zoadicus* Ehrenberg	+	+	+
Hemiaulus sinensis Greville	-	+	+
Family Leptocylindraceae			
* *Leptocylindrus minimus* Gran	+	+	+
**Leptocylindrus danicus* Cleve	+	+	+
Corethron criophilum Castracane	+	+	+
Family Lithodesmiaceae			
**Ditylum brightwellii* (T.West) Grunow	+	+	+
Streptotheca thamensis Shrubsole	+	+	+
Family Melosiraceae			
Groentvedia elliptica Hendey	-	-	+
Melosira moniliformis (O.F.Müller) C.Agardh	+	+	+
Stephanopyxis palmeriana Greville Grunow	+	-	-
Family Paraliaceae			
Paralia sulcata Ehrenberg & Cleve	+	+	-
Family Rhizosolaniaceae			
**Proboscia alata* (Brightwell) Sundstrom	+	-	-
**Rhizosolenia delicatula* Cleve	+	+	-
R. hebetata Bail	+	+	-
R. imbricata Brightwell	+	+	+
**R. setigera* Brightwell	+	+	+
**R. stolterforthii* H.Perag	+	+	
Family Hyalodiscaceae			
Podosira stelligera (J.W.Bailey) A.Mann	-	-	+
Family Thalassiosiraceae			
Detonula pumila (Castracane) Gran	+	+	-
**Skeletonema costatum* (Greville) Cleve	+	+	+
Thalassiosira condensata Cleve	+	-	-
T. eccentrica (Ehrenberg) Cleve	+	+	+
**T. rotula* Meunier	+	-	-
Family Triceraceaceae			
Triceratium favus Ehrenberg	+	+	+
Pennate			
Family Achnanthaceae			
Achananthes longipes Agardh	+	+	+

Table 2. (Continued).

Cocconies disculus (Schumann) Cleve	+	+	+
C. disculoides Hustedt	+	+	+
C. pseudomarginata Gregory	+	-	-
Tropidonies lepidoptera Cleve	-	-	+
Family Bacillariaceae			
Bacillaria paxillifer (O.F.Muller) T.Marsson	+	+	+
**Cylindrotheca closterium* (Ehrenberg) Smith	+	+	+
Nitzschia acuminata (W.Smith) Grunow	+	+	+
N. angularis W.Smith	+	+	+
N. frigida Grunow	-	-	+
N. levidensis(W.Smith) Grunow	+	+	+
N. longissima (Brébisson) Ralfs	+	+	+
N. navicularis (Brébisson) Grunow	+	+	+
N. plana W.Smith	-	+	+
N. sigma (Kützing) W.Smith	-	-	+
Nitzschia sp.	+	+	+
**Pseudo-nitzschia multiseriata* Takano	+	+	+
**P. pungens* (Grunow ex Cleve) G.R.Hasle	+	+	+
**P. seriata* (Cleve) H.Peragallo	+	+	+
Family Climacospheniaceae			
Climacosphenia elongata Mereschkowsky	+	+	+
C. moniligera Ehrenberg	+	+	+
Family Cymbellaceae			
Amphora graeffei Cleve	+	+	+
Amphora hyalina Kützing	-	+	-
Amphora ostrearia Cleve	-	-	+
Amphora ventricosa W.Gregory	-	+	+
Amphora sp.	-	+	-
Family Fragilariaceae			
Asterionella japonica Cleve	+	+	+
Fragilaria cylindrus Grunow	+	-	-
F. oceanica Cleve	+	+	+
Fragilariopsis kerguelensis (O'Meara) Hustedt	-	-	+
Family Naviculaceae			
Amphiprora alata (Ehrenberg) Kuetz	-	-	+
A. surirelloides Hendey	+	+	+
Caloneis brevis (Gregory) Cleve	+	-	-
Caloneis liber (W.Smith) Cleve	-	-	+
C. linearis (Grunow) Boyer	+	+	+
C. subsalina (Donkin)Hendey	+	-	-
C. westii (W.Smith) Hendey	+	+	+

Table 2. (Continued).

C. rectangulata	-	-	+
Diploneis crabro (Ehrenberg) Ehrenberg	+	+	+
D. notabilis (Greville) Cleve	-	-	+
D. robustus R.Subrahmanyan	-	+	+
Gyrosigma balticum (Ehrenberg) Rabenh	+	+	+
G. fasciola Ehrenberg	+	+	+
G. hippocampus (Ehrenberg) Hassall	+	+	-
G. littorale (W.Smith) Griffith & Henfrey	+	+	+
G. wansbeckii (Donkin) Cleve	+	+	+
Navicula calida Hendey	+	+	+
N. clavata Gregory	+	-	-
N. cruciculoides C.Brokmann	-	-	+
N. directa (W.Smith) Ralf	+	+	+
N. dissipata Hustedt	-	+	-
N. distans (W.Smith) Ralf	+	-	-
N. elegans W.Smith	+	+	+
N. granulata de Brébisson	+	-	-
N. hyalina Donkin	+	+	-
N. hennedyii var. *manca* A.Schmidt	-	-	+
N. florinae Mørller	+	+	+
N. iyra Gregory	-	-	+
N. maculosa Donkin	+	+	+
N. membrancea C.Agardh	+	+	+
N. palperbralis Brébisson ex W.Smith	-	+	+
N. scopulorum de Brébisson ex Kützing	-	+	+
Navicula sp.1	-	-	+
Navicula sp.2	-	-	+
Navicula sp.3	-	-	+
Navicula sp.	-	+	+
Pleurosigma aestuarii (Brébisson ex Kützing) W.Smith	+	+	+
Okedenia inflexa (de Brébisson ex Kützing) De Toni	-	+	-
P. angulatum (Queckett)W.Smith	+	+	+
P. cuspidatum (Cleve) H.Peragallo	+	+	+
P. elongatum W.Smith	+	+	+
P. marinum Donkin	+	+	-
P. vanheurckii	-	-	+
Family Pinnulariaceae			
Pinnularia ambigua Cleve	+	+	+
P. angulatum (Quekett) W.Smith	+	-	+
P. rectangulata (Gregory) Rabenhorst	+	+	+

Table 2. (Continued).

Family Pleurosigmataceae			
Donkinia recta (Donkin) Grunow	-	-	+
Family Rhaphoneidaceae			
Rhaphoneis amphiceros (Ehrenberg) Ehrenberg	-	+	+
Family Striatellaceae			
Grammatophora undulate Ehrenberg	-	+	+
Family Stauroneidaceae			
Stauroneis amphioxys Gregory	+	+	+
Family Surirellaceae			
Campylodiscus fastuosus Ehrenberg	-	-	+
C. echeneis Ehrenberg ex Kützing	-	-	+
Surirella comis A.Schmidt	-	+	-
S. gemma Ehrenberg	-	+	+
S. ovate Kützing	+	+	+
S. ovalis Brébisson	+	+	+
S. striatula Turpin	-	+	-
Family Thalassionemataceae			
Thalassiothrix frauenfeldii (Grunow) Grunow	+	+	+
T. longissima Cleve & Grunow	+	+	+
Division Dinophyta			
Family Amphidomataceae			
Amphidoma nanum	-	+	+
Family Ceratiaceae			
Neoceratium breve (Ostenfeld & Schmidt)	+	-	-
**N. furca* (Ehrenberg) Gómez, Moreira & Lopez-Garcia	+	+	+
N. lineatum (Ehrenberg) Gómez, Moreira & Lopez-Garcia	+	+	-
N. symmetricum Pavillard	+	-	-
N. longirostrum Gourret	-	+	+
N. vultur Cleve	+	-	-
Family Dinophyceae incertae sedis			
Berghiella josephinae F.J.R.Taylor	-	-	+
Family Dinophysaceae			
Dinophysis bastata	+	-	+
D. brevisulcus Tai & Skogsberg	+	-	-
**D. caudata* Saville-Kent	+	-	-
**D. exigua* Kofoid & Skogsberg	+	-	-
D. infundibula J.Schiller	+	+	+
Family Goniodomataceae			
Alexandrium acatenella (Whedon & Kofoid) Balech	+	-	-
**A. ostenfeldii* (Paulsen) Balech & Tangen	+	+	+

Table 2. (Continued).

Pyrodinium scibilleri Smith	-	-	+
Pyrodinium sp.	+	-	-
Family Gonyaulacaceae			
Gonyaulax brevisulcatum P.Dangeard	+	-	-
G. diegensis Kofoid	-	-	+
G. kofoidii Pavillard	+	+	+
G. pavillardi Jörgensen	+	-	+
G. pacifica Kofoid	-	+	-
G. polyedra F.Stein	+	-	-
**G. polygramma* Stein	-	+	+
G. milneri (Murray & Whitting) Kofoid	-	+	-
Gonyaulax sp.	-	-	-
Amylax triacantha (Jorgensen) Sournia	+	+	+
Family Gymnodiniaceae			
**Gymnodinium breve* C.C.Davis	+	-	+
G. gracile Bergh	+	+	+
**G. splendens* Lebour	+	+	+
Family Gyrodiniaceae			
**Gyrodinium spirale* (Bergh) Kofoid & Swezy	+	+	+
Family Heterodiniaceae			
Heterodinium milneri (Murray & Whitting) Kofoid	-	+	-
Family Oxytoxaceae			
Oxytoxum scolopax Stein	+	-	+
Family Peridiniaceae			
Protoperidinium abei	+	-	-
Protoperidinium achromaticum (Levander) Balech	+	+	+
**P. conicum* (Gran) Balech	-	+	-
P. depressum (Bailey) Balech	+	+	+
P. divergens (Ehrenberg) Balech	-	-	+
P. inflatum (Okamura) Balech	+	-	-
P. inermis	+	-	-
P. longicollum Pavillard	-	-	+
P. paradoxum (F.J.R.Taylor) Balech	-	-	+
P. persicum Schiller	-	+	-
P. subinermis (Paulsen) Loeblich III	+	-	-
P. tristylum (Stein) Balech	+	+	+
Protoperdinium sp.	+	-	-
Family Prorocentraceae			
**P. gracile* Schutt	+	+	+
**P. lima* (Ehrenberg) F.Stein	+	-	-
**P. micans* Ehrenberg	+	+	+
**P. minimum* (Pavillard) J.Schiller	+	+	-

Table 2. (Continued).

Family Pyrocystaceae			
Pyrocystis noctiluca Murray ex Haeckel	+	+	+
Family Protoperidiniaceae			
Podolampus palmipes Stein	-	+	-
Family Pyrophacaceae			
Pyrophacus horologium Stein	+	+	+
Family Calciodinellaceae			
**Scrippsiella trochoidea*(Stein) Loeblich III	+	+	+
Division Haptophyta			
Family Prymnesiaceae			
Corymbellus sp.	+	-	+
Division Chlorophyta			
Family Scenedesmaceae			
Scenedesmus sp.	+	+	+
Division Chrysophyta			
Family Dinobryaceae			
Dinobryon balticum (Schütt) Lemmermann	+	-	+
D. porrectum Schiller	+	-	+
Family Dictyochaceae			
**Distephenus speculum* (Ehrenberg) Haeckel	+	+	+
**Dictyocha fibula* Ehrenberg	+	+	+
Division Cyanophyta			
Family Oscillatoriaceae			
**Trichodesmium erythraeum* Ehrenberg	+	+	+
**T. thibautii* Gomont	+	+	+

(0.5%; 1 species, 1 genus), Cyanophyta (1%; 2 species, 1 genus), Haptophyta (0.5%; 1 species, 1 genus), Chromophyta (1%; 2 species, 2 genera), and Chrysophyta (1%; 2 species, 1 genus) (Figure 5A). Division-wise percentage distributions at the 3 stations are given in Figures 5B–5E. Bacillariophyta genera formed the highest proportion of species numbers (66%–82%) at the upper, middle, and lower stations during the monsoon and nonmonsoon seasons. Dinophyta did not show much variation in the percentage distribution of genera and species along the 3 sections. Only during the monsoon period were the percentages of genera and species >20% in the lower section. During the nonmonsoon period, the percentages of genera were >20% at all 3 sections, while species percentage was >20% only at the lower section.

Members of the division Haptophyta were present only at the lower section, with 2% of the genera and 1% of the species during the monsoon; they were absent during the nonmonsoon period. Chromophyta were present at all stations during the monsoon and nonmonsoon periods, with 2%–3% of the genera and 1%–2% of the species. Chrysophyta were present only at the lower section during both seasons, with 2% of the genera and 2% of the species. Chlorophyta and Cyanophyta (including *Trichodesmium* Ehrenberg) were present at all 3 stations during the monsoon, while division Chlorophyta was absent at the middle and upper sections during the nonmonsoon period.

The Bacillariophyta consisted of 60 Centrales and 88 Pennales (Table 2). From this total composition, only the families having more genera and species are considered. In the case of Centrales, 4 main families were found: Chaetocerotaceae (13 species, 2 genera), Coscinodiscaceae (8 species, 1 genus), Thalassiosiraceae (6 species, 4 genera), and Rhizosolenia (6 species, 1 genus). The

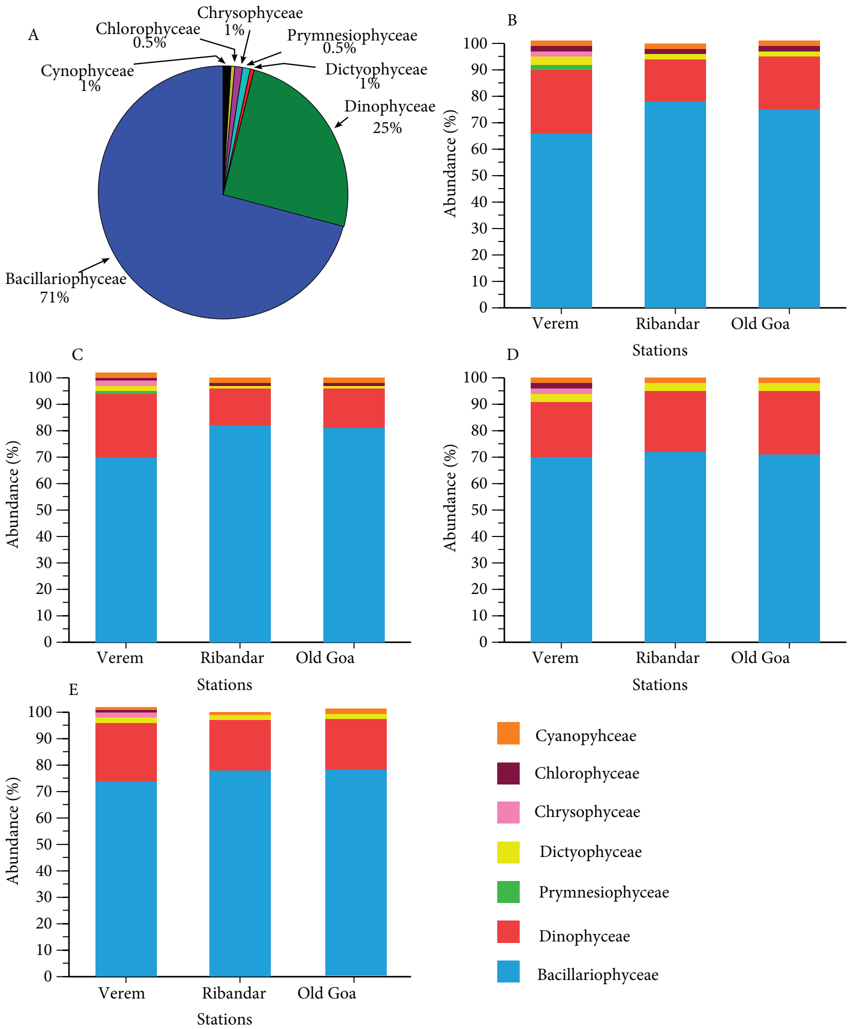

Figure 5. Percentage distribution of different phytoplankton divisions in the Mandovi estuary during June 2007–May 2008. A- Total species distribution in the Mandovi estuary, B- total genera distribution of phytoplankton at 3 different stations during monsoon season, C- total species distribution of phytoplankton at 3 different stations during monsoon season, D- total genera distribution of phytoplankton at 3 different stations during nonmonsoon season, E- total species distribution of phytoplankton at 3 different stations during nonmonsoon season.

Pennales included Achnanthaceae (5 species, 3 genera), Cymbellaceae (5 species, 1 genus), Naviculaceae (41 species, 6 genera), Bacillariophyceae (14 species, 4 genera), and Surirellaceae (7 species, 2 genera). In general, the centric diatoms decreased from the lower section (Verem) to the upper section (Old Goa), whereas the pennate diatoms followed the opposite trend (Figure 6).

3.2.1. Species composition, abundance along a transect

The lower section (Verem) station was dominated by 26 species of phytoplankton consisting of 22 species of Bacillariophyta and 4 species of Dinophyta, with cell counts of >1000 cells L^{-1}. At the middle section (Ribandar) station, 24 species of phytoplankton dominated, including

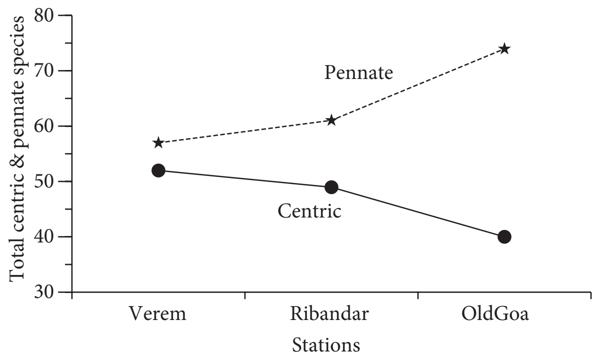

Figure 6. Variations in centric and pennate forms at 3 different stations in the Mandovi estuary.

22 species of Bacillariophyta and 2 species of Dinophyta. The upper section (Old Goa) station consisted of 20 species of Bacillariophyta and 4 species of Dinophyta. The Centrales included *Actinocyclus octonarius*, *Odontella sinensis*, *Chaetoceros curvisetus*, *Chaetoceros laciniosus*, *Chaetoceros lorenzianus*, *Skeletonema costatum*, and *Streptotheca thamensis*. Four Pennales were commonly distributed at all 3 stations: *Cylindrotheca closterium*, *Pseudo-nitzschia seriata*, *Stauroneis amphioxys*, and *Thalassiothrix frauenfeldii* (Figures 7A–7C).

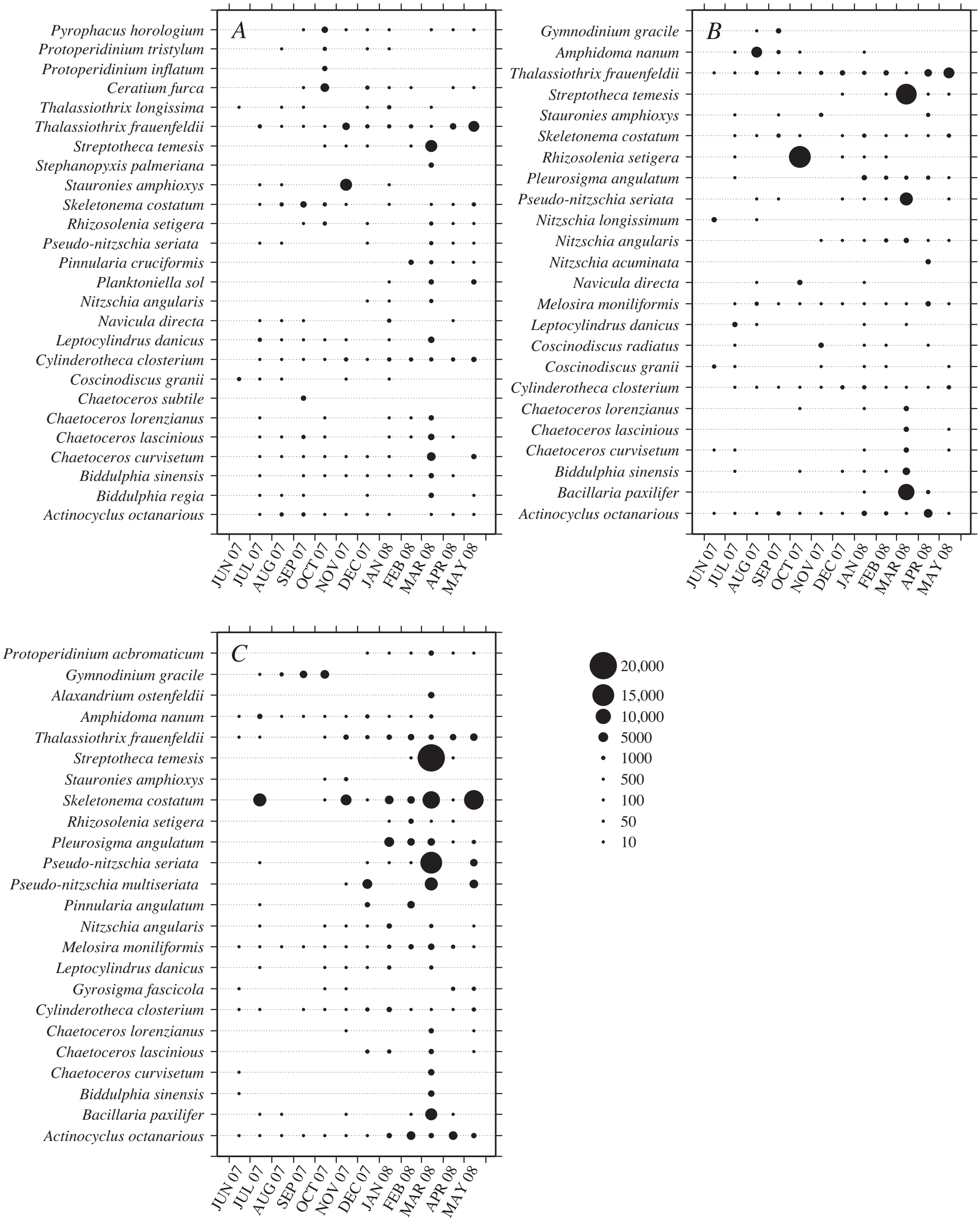

Figure 7. Seasonal dynamics of dominant phytoplankton species in the Mandovi estuary. A- Verem, B- Ribandar, C- Old Goa.

An oligohaline type of phytoplankton grew at salinities of 0–15 psu during June–September. *Chaetoceros subtilis* (1584 cells L^{-1}) was found in September only at the lower section. *Coscinodiscus granii* (1280 cells L^{-1}) was found in June and *C. radiatus* (1474 cells L^{-1}) was found in November, both at the middle section. *Nitzschia longissima* (1450 cells L^{-1}) was only at the middle section during the monsoon phase. Oligohaline dinoflagellates, e.g., *Amphidoma nanum* (5904 cells L^{-1}), were at the middle section in August.

Mesohaline species grew at 15–25 psu salinity from October to November, towards the end of the monsoon period. They included most of the dinoflagellates *Protoperidinium inflatum* (1640 cells L^{-1}), *Protoperidinium tristylum* (900 cells L^{-1}), and *Pyrophacus horologium* (2580 cells L^{-1}) and were present only at the lower section. *Gymnodinium gracile* (4920 cells L^{-1}) was found in October at the upper section and *Neoceratium furca* (4460 cells L^{-1}) was only at the lower section. Pennate diatoms, e.g., *Stauroneis amphioxys* (7264 cells L^{-1}), were at the lower section, while the pennate *Navicula directa* (2060 cells L^{-1}) and the centric *Rhizosolenia setigera* (15,080 cells L^{-1}) were at the middle section.

The third type includes most of the phytoplankton species growing during the nonmonsoon period, at a higher salinity range of 25–35 psu. These species were prominent during the December–May period and included the diatoms *Bacillaria paxillifer* (10,730 cells L^{-1}) in March at the middle section, with *Odontella sinensis*, *Chaetoceros curvisetus*, *Chaetoceros lorenzianus*, *Gyrosigma fasciola*, *Melosira moniliformis*, *Nitzschia acuminata*, *Nitzschia angularis*, *Pinnularia angulatum*, *Pseudo-nitzschia seriata* (15,320 cells L^{-1}), *Pseudo-nitzschia multiseriata* (8320 cells L^{-1}), and *Planktoniella sol* (1539 cells L^{-1}) found only at the lower section. *Pinnularia cruciformis*, *Pleurosigma angulatum*, and *Stephanopyxis palmeriana* were found at the lower section and *Streptotheca thamensis* (19,212 cells L^{-1}), *Thalassiothrix longissima*, and *Protoperidinium acbromaticum* were present at the upper section. *Alexandrium ostenfeldii*, which was reported only at the upper section, was reported here for the first time, with cell counts of 3104 cells L^{-1} in March.

The fourth type includes euryhaline species that grow in a wide range of salinity, 15–35 psu, and were present throughout the study period. These include the diatoms *Actinocyclus octonarius*, *Cylindrotheca closterium*, *Leptocylindrus danicus*, *Chaetoceros laciniosus*, *Skeletonema costatum* (13,535 cells L^{-1}), and *Thalassiothrix frauenfeldii* at the upper section.

4. Discussion

Several ecological factors are known to regulate the dynamics of phytoplankton in response to changing estuarine gradients (Underwood et al., 1998; Leland et al., 2001; Martin et al., 2007; Quinlan and Philips, 2007). The Mandovi estuary is governed by the monsoon regime. Breaks in the monsoon and daily tidal variations create changing nutrient and salinity zones, which are instrumental in affecting the adaptability of phytoplankton population composition (Qasim et al., 1972; Devassy and Goes, 1988; Matos et al., 2011). During the monsoon season, the Mandovi estuary gets flushed by fresh water entering upstream, which leads to an extreme drop in salinity conditions (Shetye et al., 2007). The salinity of the upper section was found to be in the range of 0–23 psu. Remnants of fresh water brought in by monsoonal runoff are moved downstream and mixed with the saline water at the lower section (Shetye et al., 2007). This results in variations in salinity, ranging from 3 to 32 psu at the middle section. At the lower section towards the mouth of the estuary, salinity varies from 4 to 36 psu.

The distribution of nutrients in the Mandovi estuary is greatly influenced by land runoff during the monsoon season, leading to flushing of nutrients into the estuary, with additions from anthropogenic activities and sediment resuspension (DeSousa, 1983; Martin et al., 2007). Nitrate was found to be higher (18.76 µM) at the lower section during the monsoon period. Nitrite and phosphate followed a similar pattern. However, changes in the silicate concentration are influenced by the tides. A significantly high silicate concentration (129.7 µM) was reported at the upper section.

The highest phytoplankton cell density (5.17×10^4 cells L^{-1}) and biomass (7.68 mg Chl *a* m^{-3}) were reported during the nonmonsoon period at the upper section, where the cell density was dominated by diatoms, whereas the phytoplankton diversity was greater during the monsoon season (3.46) compared to the nonmonsoon season (3.21). This may be attributed to changes in species composition reflecting the species' preference for different salinity ranges and also in part by phytoplankton from fresh water source (Qasim et al., 1972; Devassy and Goes, 1988; Krishna Kumari et al., 2002). The results of the present study showed more than twice as many species of phytoplankton, i.e. 209 species, including 148 diatoms, 53 dinoflagellates, and 8 other algae. This is basically due to the difference in the sampling strategy. An earlier study by Devassy and Goes (1988) recorded 82 species of phytoplankton from the Mandovi and Zuari estuarine complex from 1979 to 1980. Another study (Krishna Kumari et al., 2002) reported a still lower number of 49 species. At the adjacent Zuari estuary, 136 species (83 diatoms, 44 dinoflagellates, and 9 other algae) were reported (Patil and Anil, 2011) which is still lower compared to our study.

Bacillariophyta was the dominant group in the Mandovi estuary, with 71% of the total phytoplankton abundance. This was followed by Dinophyta, Dictyophyta, Chrysophyta, and Cyanophyta, each with 25% or less of the total abundance. Similar observations were recorded in previous studies, where diatoms and dinoflagellates were the most abundant groups of marine phytoplankton (Patil and Anil, 2011; Pednekar et al., 2011; Latif et. al., 2013). The high species abundance of Bacillariophyta reported from the middle and upper sections during the monsoon period could be related to the high concentration of silicate and nitrate that is flushed out from the mangrove swamps towards the upper section of the estuary, which then eventually leads to diatom growth (Underwood et al., 1998; Tanaka and Choo, 2000). Moreover, uptake by the diatoms during the monsoon period could then result in the observed decrease in nutrient concentration during the nonmonsoon period. Bacillariophyta species were dominated by Pennales over Centrales in the entire Mandovi estuary. Many pennate diatoms are regarded as benthic and are often dominant in shallow and turbulent waters (Sahu et al., 2012; Shams et al., 2012). Within the estuary, pennate diatoms increased from the lower to the upper sections while a reverse trend was observed for the centric forms.

Dinophyta showed little difference in the distribution along all 3 sections and seasons. This may be attributed to the dinoflagellates' multiple adaptive strategies to different environments. During the monsoon season, estuaries are rich in phosphate and nitrate, originating from land runoff and sediment resuspension in the numerous tributaries (DeSousa, 1983; Martin et al., 2007; Maya et al., 2011). This is correlated with the highest cell density of dinoflagellates (0.15×10^4 cells L^{-1}) reported during the monsoon period towards the upper section of the Mandovi estuary.

Species composition and distribution are dependent on many environmental factors. In this study, we found 26 dominant species at the lower section and 24 at both the middle and upper sections with cell densities of >1000 cells L^{-1}. The monsoon period supported the growth of oligohaline (0–15 psu) phytoplankton communities, which included centric diatom species *Chaetoceros subtilis*, *Coscinodiscus granii*, and *C. radiatus*, along with the pennate diatom *Nitzschia longissima* and the dinoflagellate *Amphidoma nanum*, with cell counts of >1000 cells L^{-1} only during the monsoon period towards the lower and middle sections of the estuary. This indicates the role of increased concentrations of nutrients in the water column, originating in part from the resuspension of sediments during the rains. However, Huang et al. (2004) reported high counts of *Nitzschia longissima* during the dry season in the Pearl River estuary. Patil and Anil (2008) also reported *Nitzschia longissima* in surface waters of the adjacent Zuari estuary during the monsoon period. *Nitzschia* has a growth advantage in low-saline waters (Matondkar et al., 2007).

Dinoflagellates were especially abundant at the upper section during the nonmonsoon period. The autotrophic marine dinoflagellate *Gymnodinium gracile* was detected only during the monsoon period and was found to grow in mesohaline conditions with low salinity (15–25 psu) and high levels of phosphate and humic acids in the present study. The genus *Gymnodinium* has been reported to grow in both fresh and marine waters, and especially in estuarine conditions (Reñe et. al., 2010). The other species of dinoflagellates included *Protoperidinium inflatum*, *Protoperidinium tristylum*, *Pyrophacus horologium,* and *Neoceratium furca*, which were present only at the lower section during October and November. *Neoceratium furca* in particular is tolerant to marine and brackish waters where nitrogen, rather than phosphorus, is the growth-limiting nutrient. *Neoceratium furca* is nontoxic but massive blooms are capable of killing aquatic biota through gill-clogging (Glibert, 2007; Ajuzie and Houvenaghel, 2009). A bloom of *Protoperidinium* was first reported by Sanilkumar et al. (2009) in October along the west coast of India where nutrients were abundant. The pennate diatoms *Stauroneis amphioxys* and *Rhizosolenia setigera* are marine and tend to grow in the presence of high concentrations of nutrients, especially nitrate and silicate (Pednekar et al., 2012), towards the lower and middle sections of the Mandovi estuary during the monsoon period.

Centric diatoms like *Chaetoceros curvisetus*, *Chaetoceros laciniosus*, and *Streptotheca thamensis* and pennate diatoms *Bacillaria paxillifer*, *Pseudo-nitzschia seriata*, and *Pseudo-nitzschia multiseriata* were reported only during nonmonsoon period, from December to May, where salinity ranged from 25–35 psu. These diatoms in particular showed a strong positive relation with salinity and a negative correlation with nutrients. This is supported by the study of Sahu et al. (2012), showing that high salinity supported high diatom diversity. Admiraal et al. (1990), Polat and Işık (2002), and Alp and Sen (2010), on the other hand, showed a negative relation between diatom abundance and nutrients. They represent the K-type growth strategy, able to grow in stressful conditions and develop the ability to harvest more light (Saunders, 2011; Smayda and Reynolds, 2001). *Nitzschia angularis*, *Pleurosigma angulatum*, *Streptotheca thamensis*, and *Pseudo-nitzschia seriata* are examples of large cells capable of exploiting low nutrient concentrations, e.g., by storing nutrients (Quinlan and Philips, 2007). The diatom *Pseudo-nitzschia seriata* was reported during the nonmonsoon period at the upper section of the Mandovi estuary, when nutrients and salinity were elevated. This species was also found in the adjacent Zuari estuary (Pednekar et al., 2012) during the nonmonsoon period. Its presence is of concern, because it produces the neurotoxin domoic acid (Fehling et al., 2004; Lelong et al., 2012). We also found the potentially toxic *Pseudo-nitzschia pungens* at the middle section in March, when the salinity was 25–30 psu, and nitrate, nitrite, and phosphate were >0.5 µM and silicate was approximately 10.8 µM. This species was also previously reported (Alkawri and Ramaiah, 2011) as being preponderant along the coast of Goa during the nonmonsoon season, characterized by a high-salinity and low-nutrient environment. The centric diatom *Streptotheca thamensis* showed very high cell density in March at all the stations, when total phytoplankton cell density and biomass were also elevated, and its presence is an indication of organic pollution (Naik et al., 2009; Sahu et al., 2012).

The potentially toxic dinoflagellate *Alexandrium ostenfeldii* was reported at the upper section during the nonmonsoon period. It may have been supported by the estuary's high humic acid content and originated from cysts or resting cells in the sediments (Cembella et al., 2000; D'Costa et al., 2008; Hakanen et al., 2012). This is the first report of this species along the west coast of India. This species is known to cause paralytic shellfish poisoning and produce spirolide toxins (Hu et al., 2001; Munday et al., 2012) that can harm humans. In the present study, we have reported very high counts of *Protoperidinium acbromaticum* in the month of March towards the upper section for the first time. Their growth is known to be favored in environments that are rich in humic and fulvic acids and other dissolved organic compounds, which constitute the bulk of the estuarine colored dissolved organic matter pool (Hair and Bassett, 1973; Goni et al., 2003; Suzumura et al., 2004).

Highly diverse species of centric diatoms, including *Skeletonema costatum*, *Actinocyclus octonarius*, *Chaetoceros lorenzianus*, and 2 pennate diatoms, *Cylindrotheca closterium* and *Thalassiothrix frauenfeldii*, are euryhaline and eurythermal species that proliferate rapidly in estuarine conditions. Large centric diatoms, like *Skeletonema costatum*, *Actinocyclus octonarius*, and *Chaetoceros lorenzianus*, have a low surface-to-volume ratio and begin multiplying during the monsoon period when the nutrient concentration is high, an environment conducive for their growth. *Cylindrotheca closterium* and *Thalassiothrix frauenfeldii* were present in high numbers during the nonmonsoon period, perhaps due to their high surface-to-volume ratio and thus their ability to absorb nutrients rapidly when nutrient concentrations are low and the salinity is optimum (Achary et al., 2010; Shams et al., 2012; Kükrer and Büyükışık, 2013). Diatom genera like *Skeletonema*, *Thalassiothrix*, and *Chaetoceros* are known to produce resting cells and spores under both silicate and nitrate limitations. These end up in the surface sediments, where they can eventually grow into vegetative cells under nutrient-rich, illuminated conditions (Çetin and Şen, 2004; Chen et al., 2009; Koçer and Şen, 2012), leading to their growth during both seasons.

In conclusion, phytoplankton communities in the present study were influenced by the annual riverine runoff and the associated changes in the physicochemical variables. The phytoplankton community showed gradual spatiotemporal shifts along the salinity and nutrients gradients, i.e. oligohaline species during the low salinity monsoon period, mesohaline species (15–25 psu), and euryhaline species, which are present throughout the study period. Bacillariophyta dominated the phytoplankton population with ≥70% of the total number of genera and species at the middle and upper sections. Dinophyta did not show much variation in the distribution along all 3 sections and seasons. An important output is that during the present study, the species richness reported was high compared to previous studies. An increase in the number of harmful algal bloom-forming species was reported. Twenty-five harmful and 11 toxic or potentially toxic species of diatoms, dinoflagellates, and cyanobacteria (including *Trichodesmium*) were observed during the study. Toxic bloom-forming phytoplankton species that have not been encountered here earlier, like *Alexandrium ostenfeldii*, *Pseudo-nitzschia pungens*, and *Gymnodinium breve*, were observed during the present study. The presence of certain species like *Streptotheca thamensis* is proposed to be used as an indicator of the water quality of the Mandovi estuary.

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