

Impact of monsoon-induced discharge on phytoplankton community structure in the tropical Indian estuaries

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Abstract

To understand the influence of monsoon-induced river discharge and associated environmental changes on phytoplankton community structure in the Indian estuaries, physical and biogeochemical parameters were collected from 28 major and medium estuaries along the Indian coast during the peak discharge period. Relatively higher river discharge was recorded in the estuaries located in northern India associated with higher suspended particulate matter (SPM), which arrested light penetration, resulting in a decreased in phytoplankton abundance and biomass. In contrast, higher phytoplankton abundance and biomass were observed in the estuaries located in southern India due to lower discharge and SPM than northern India. Diatoms were the dominant phytoplankton group in the Indian estuaries, except in estuaries located in the southeast coast, where blue-green algae predominate due to the existence of brackish water and stagnant water conditions due to less discharge. Higher phytoplankton diversity was observed in the south Indian estuaries than north Indian estuaries due to the long water residence time in the former. A present study is revealing that the magnitude of river discharge and SPM load seems to be the primary factors controlling phytoplankton abundances and community composition in the Indian estuaries.

Keywords Estuary, River discharge, phytoplankton, diatoms, SPM.

1. Introduction

Phytoplankton contain essential biochemicals and it is a resource base supporting production at higher trophic levels in the aquatic ecosystem (Cloern et al., 2014). The species composition, biomass, relative abundance and their spatial and temporal distribution of this aquatic biota are an expression of the environmental health or biological integrity of a particular water body (Ekwu and Sikoki, 2006). Land driven nutrients support rich phytoplankton production in estuaries (Crouzet et al., 1999; Neill 2005). Excess nutrients through anthropogenic activities, such as extensive use of fertilizers in agricultural fields, plantation of leguminous plants, deposition of oxidized form of nitrogen (N), and domestic and industrial sewage significantly influences the riverine supply of nitrogen (N) and phosphorus (P) to rivers, subsequently to biota in the coastal systems. In addition to nutrients, river discharge events also change water residence time, flushing time and turbidity, which can have negative effects on phytoplankton productivity (Burford et al., 2012). This is most pronounced in the subtropics and tropics where the magnitude and duration of flow events are much higher, due to monsoonal weather pattern.

Estuaries in India are influenced by monsoonal rainfall, hence they are called monsoonal estuaries (Sarma et al., 2014). Seasonal runoff into these monsoonal estuaries far exceeds the total volume of the estuary during the times of peak discharges, and the entire estuary turns into river (Sarma et al., 2009). Flow events can have major impacts on biogeochemical processes and primary productivity. Although high nutrient concentrations are observed during peak discharge period, lower phytoplankton biomass is noticed in several Indian estuaries (Cochin estuary (Gupta et al., 2009), Godavari estuary (Sarma et al., 2009), and Mandovi-Zuari estuary (Pednekar et al., 2011) due to high turbidity that inhibits light penetration. On the other hand, enhanced phytoplankton biomass was noticed during the dry period associated with lower turbidity and nutrient concentrations than peak discharge period [Sarma et al., 2009; Pednekar et al., 2011], suggesting that the clarity of water is more important than nutrients in the Indian estuaries. Moreover, river discharge not only affect phytoplankton biomass but also functional groups of phytoplankton community due to changes in salinity, nutrients composition, turbidity and flow pattern. Many estuaries (Kaduviyar estuary- (Perumal et al., 2009); Mahanadi estuary (Naik et al., 2009) and Godavari estuary (Bharathi et al., 2018) dominated by diatoms during dry period, whereas it is replaced by green algae and blue-green algae during discharge period.

Moreover, State-wise fertilizer consumption is not the same across the Indian subcontinent, it is different from state to state with reference to the season, including vegetation type. Therefore, their

contribution to the nutrients carried by distinct rivers is anticipated to be different. In addition, precipitation pattern, discharge volume of fresh water, geochemistry and soil nature of the India differ from state to state (Sarma et al., 2014; Krishna et al., 2018). Hence, the characteristics of various rivers in the Indian subcontinent are expected to be different from estuary to estuary depending on size, tidal amplitude, discharge characteristics, SPM concentrations, and variable residence time of water. Though several studies have been carried out on phytoplankton distribution in some of the Indian estuaries, integrated studies combining physical, chemical and biological processes are rather scarce. Even if few studies are available, but these were mainly conducted in each estuary during different period (or year) in India (comparative studies among estuaries are limited). Thus, we have made an effort to study 28 Indian major and medium estuaries along the Indian coast to understand the variability in phytoplankton community structure with respect to variable river discharges and their associated changes.

2. Material and methods

2.1. Site description

India has extensive coastline of about 6100 km and it is mostly covered by a complex estuarine ecosystem (almost 14 major, 44 medium and 162 minor estuaries). Indian estuaries are different from other estuaries in the world with reference to timing and magnitude of discharge as they are characterized by seasonal discharge during monsoon period (July to October). The rainfall in India is broadly influenced by two monsoons *viz.*, Southwest monsoon (June – September) that influences mostly west coast, northern and northeastern India and Northeast monsoon (October – December), which impacts southeast coast of India (Perumal 1993) due to masking effect of Western Ghats (Deepthy and Balakrishnan 2005). India receives three quarters of the rainfall during southwest monsoon period. The precipitation pattern over the Indian subcontinent shows strong spatial variations, which are relatively higher in southwestern India (~3000 mm) followed by northeastern India (1000–2500 mm) and the least over southeast (300–500 mm) and northwestern India (200 – 500 mm) (Soman and Kumar 1990). The spatial variations in magnitude of discharge in the Indian rivers depend on the monsoonal precipitation pattern over the Indian subcontinent (Vijith et al., 2009; Sarma et al., 2014). About 78% of the Indian fertilizer consumption occurs in the states located along the Northern India through which major rivers are flown than Southern India (Ministry of Agriculture, Government of India, http://eands.dacnet.nic.in/latest_2006.htm).

2.2. Sampling strategy, data collection and analysis

In order to understand the variability in biogeochemical properties and phytoplankton community structure in the Indian estuaries, surface water samples were collected in 28 estuaries (Fig. 1) along the Indian coast during peak (July 28–August 18, 2011) discharge period using local mechanized boats. River discharge data were collected from Kumar et al., (2005) and also from the dam authorities wherever available (Table 1). Though discharge takes place only during 3 to 6 months in a year, the mean discharge during this period is represented as annual mean. Temperature, salinity, and depth were measured using a conductivity-temperature-depth profiler (Sea Bird Electronics, SBE 19 plus, USA). Nutrients (nitrite, nitrate, ammonium, phosphate and silicate) were measured using colorimetric method following Grashoff et al., (1992) using autoanalyzer. About 500 mL of sample was filtered through Glass Fiber (GF/F; 0.7 μm pore size; 47 mm diameter; Whatman) filter at gentle vacuum and Chlorophyll a (Chl a) retained on the filter was extracted to dimethylformamide and fluorescence of the extract was measured using Varian Eclipse fluorescence photometer (Varian Electronics, USA) following Suzuki and Ishimaru (1990). SPM was measured as weight difference of material retained on 0.2 μm polycarbonate filter (Millipore) after passing 200–500mL of water. One liter of surface water sample was collected for phytoplankton composition in a polyethylene bottle and fixed with 0.5% Lugols iodine solution (Thronsdon 1978). Before identification, water samples were allowed to settle for 24 hours and the supernatant was decanted and sample concentrated to 10 ml. About 100 μl of concentrated sample were taken in a common glass slide and observed under BX51 OLYMPUS microscope (Olympus, Japan). Phytoplankton cell counts (abundance) were observed under 400X magnification. Phytoplankton was identified following procedures given by earlier investigations (Santra 1993; Tomas 1996; Baker 2012). Diversity (Shannon Wiener Diversity Index) and dominance (Simpson's Dominance Index) is computed using Primer 5.2.8 software (Clarke and Warwick 1994). Spatial variations in phytoplankton were examined by hierarchical cluster analysis using the Bray-Curtis similarity index (~40% similarity cut off) as an estimate of similarity among stations using Primer 5.2.8 software. Correlation analysis (Spearman) and factor analysis has been performed with the help of Statistica software to know the relationship among physicochemical and biological parameters.

3. Results and Discussion

During Peak Discharge Period (PDP), Indian monsoonal estuaries display wide ranges of hydrological conditions, from low fresh water flow and longer residence time to high fresh water flow and short residence time. The mean annual discharge varied from ~28 to 3500 $\text{m}^3 \text{s}^{-1}$ relatively

higher discharge has been found in the estuaries situated in the northern than southern part of India (Table 1), because most of the major rivers are located in the northern India (north of 16°N) relative to south. The tidal amplitudes ranged between 1.3 and 10.9 m and higher tidal amplitudes (>2 m) were found in the estuaries located in the northern India whereas it is mostly <2 m in the south (Table 1). Number of dams is constructed on most of these rivers at various distances from mouth to control the flow of the freshwater. The water is stored in the dam reservoirs for over 6 months during the dry period for irrigation and domestic usage. This storage leads to the formation of stagnant conditions that favour microbial degradation of organic matter and release of nutrients (Sarma et al., 2011, 2012). Therefore, the storage capacity of dam reservoir, magnitude of discharge, precipitation pattern and amplitude of tides control the water column stability, residence time, salinity, SPM, and nutrient composition in the Indian estuaries during peak discharge period. These are the key factors for spatial variations in biogeochemical properties in the Indian estuaries.

3.1. Spatial variations in physico-chemical properties in the Indian estuaries during PDP

In Indian estuaries temperature varied between 25.5 and 33.2°C and relatively warmer temperatures were found in the estuaries located along the east coast of India (30.8 °C) than west coast of India (27.1°C) (Table. 1). During PDP, salinity mainly depends upon magnitude of discharge (Sarma et al., 2009; 2010). Salinity varied between ~0 and 28.9 PSU with mean values of 5.2 ± 7.8 in the Indian estuaries. Significant inverse relation was observed between discharge and salinity (Table 2 and Fig 2). Higher salinity values (>10) have been found in northeast estuaries (minor river estuaries) such as Rushikulya, Vamsadhara, Nagavali which receive less freshwater from the upstream, and southeast estuaries such as Penna, Vellar and Vaigai which receives negligible precipitation during PDP. Even though Cauvery is a major river, however, high salinity (~10) was observed due to construction of several dams and also this region receives less precipitation during PDP. Nearly freshwater was noticed in other estuaries except above-mentioned estuaries. SPM displayed large spatial variability and ranged between 6.5 and 918 mg l⁻¹. The higher SPM (>200 mg L⁻¹) was observed in Tapi, Narmada, Sabarmati, Haldi and Godavari estuaries and lower values (<100 mg L⁻¹) were found in other estuaries (Table 1). The concentrations of SPM in the estuaries were related to magnitude of discharge. Mostly higher SPM values were found in estuaries receiving >1000 m³ s⁻¹ of discharge than other estuaries. Insignificant relationship between SPM and river discharge was noticed (Table 2 and Fig 2), suggesting that the bed composition of the upstream river may be potential reason for its variability.

High concentrations of nutrients are reported to be associated with river discharge compared to non –monsoon period in Mandovi Zuari estuary (Ram et al., 2003), Cochin estuary (Gupta et al., 2009), Godavari estuary (Sarma et al., 2010) and Hoogly estuary (Mukhopadhyay et al., 2006). Monsoonal estuaries from India displayed a wide range of concentrations (Table 1) from 0.65–15.23, 0.1–11.1, 2.27–67.50, 0.7–38.6 and 13.4–270.0 μM for ammonium, nitrite, nitrate, phosphate, and silicate, respectively, during study period. The variability in nutrient concentrations in Indian estuaries was explained in detail in Sarma et al., (2014) and Krishna et al., (2016), however, it is explained in brief here. Dissolved inorganic nitrogen (DIN) (Ammonium + Nitrite + Nitrate) is relatively higher in the estuaries located along northern India than southern India (Table 1) due to high fertilizer consumption in the former region. Such high concentrations in the northern India again supported by nitrogen stable isotopic composition of particulate nitrogen (Sarma et al., 2014). Relatively higher concentrations were noticed in Narmada and Tapi where intense industrial activities can be noticed and their effluents into these estuaries enhance their concentrations. Concentrations of phosphate were tended to be higher in the southwest estuaries (mean 12.6 μM) than the other estuaries (mean 5.4 μM). The possible reason could be, apart from fertilizer consumption, the high elevation of catchment of the southwest rivers, which originates from the western Ghats. Higher silicate concentrations were observed in southeast coast estuaries (151.8 μM) than other (32.2 μM) estuaries (Table 1). The silicate concentrations are mainly related to weathering and dissolution of silicate rocks and such variability were caused due to variations in terrain characteristics. Soils in catchment areas of the southeast rivers are composed mainly of red sandy soils and alluvial soils both of which are rich in silicate (Krishna et al., 2016; 2018).

Changes in nutrient ratios have been reported in different estuaries and were attributed to variations in discharge and residence time (Van Den Brink et al., 1994; Walz and Welker 1998). N: P ratios were mostly below the Redfield ratio (16) in all Indian estuaries (except in Narmada and Tapi) indicating that excess phosphate inputs relative to nitrogen (Table 1). Such high phosphate could possibly due to input of sedimentary phosphate during resuspension of sediment during discharge. N:Si ratios are above the limiting conditions (>1) suggests that silicate never been a limiting nutrient in the Indian estuaries (except Northwest estuaries; Table 1). Nevertheless such variable nutrients ratios may have significant impact on the composition of phytoplankton in the Indian estuaries.

3.2. Spatial variability in phytoplankton community structure during PDP

The phytoplankton biomass (as chlorophyll-a) ranged between 0.01 and 160 mg m^{-3} in the Indian estuaries during PDP (Table 1). Comparatively, higher phytoplankton biomass was noticed in

estuaries along southern India than northern India. The carbon isotopic composition of particulate organic matter (POM) suggested that in situ production was a dominated source of organic matter in the southern estuaries, where as terrestrial sources (mainly detritus from C₃ plants) contributed to POM pool in the northern estuaries (Sarma et al., 2014). The high phytoplankton biomass values in the southern estuaries were supported by low river discharge and SPM concentrations. Hambright and Zohary (2000) stated that higher phytoplankton biomass was always associated with high nutrient concentrations, solar radiation, temperature and turbulence. The higher concentrations of phytoplankton biomass (>100 mg m⁻³) were found in Ponnayaar and Ambalayaar estuaries, which receives high amount of domestic and industrial pollutants (Rao and Sarma 2013). Similarly higher phytoplankton biomass (~20 mg m⁻³) was also noticed in Subarnarekha and Cauvery estuaries, which were also relatively polluted due to port activities and domestic sewage.

The distribution of phytoplankton abundance exhibited remarkable spatial variations due to variable hydrological (mainly river discharge) conditions and their influence on individual species. Relatively higher phytoplankton abundances were observed in estuaries situated along the east (0.4 x 10⁵- 78.2 x 10⁵ cells.L⁻¹) than west coast of India (0.9 x 10⁵- 5.9 x 10⁵ cells.L⁻¹) (Fig. 3a). The highest phytoplankton abundance was observed in the estuaries located in the Southeast coast (henceforth called as SEC) estuaries (1.4 x 10⁵ to 78.2 x 10⁵ cells.L⁻¹) and minor estuaries (Subarnarekha, Rushikulya) located in Northeast coast (henceforth called as NEC) region (10.2 x 10⁵-14.9 x 10⁵ cells.L⁻¹) (Fig. 3a). The discharge from these estuaries is significantly smaller compared to other estuaries (Table 1), hence the higher abundance is attributed to high residence time of water, brackish salinity and low suspended matter. On the other hand, moderate cell abundance was observed in estuaries located along the Southwest coast (henceforth called as SWC) region (1.3 x 10⁵-5.9 x 10⁵ cells.L⁻¹) where river discharge is relatively higher than estuaries located in the NEC region (Table 1 and Fig 3a). On the other hand, the lowest cell number has been observed in Northwest coast (henceforth called as NWC) region (0.9 x 10⁵-1.5 x 10⁵ cells.L⁻¹) where the highest turbidity and high discharge (Table 1) was found. It is well known that phytoplankton abundance is expected to be the lowest in fast flowing compared to slow flowing systems. Even though, concentrations of nutrients are high in NWC region, phytoplankton abundance did not coincided due to high turbidity and flushing. A number of studies revealed negative relationship between phytoplankton abundance and discharge rate (Schemel et al., 2004; Phlips et al., 2007; Strayer et al., 2008) and noticed that water residence time or flushing rates can control phytoplankton doubling rates in estuaries other than hydrology (such as nutrients, salinity, grazing and light) and generally phytoplankton biomass increases with water residence time (Paerl et al., 2006).

Of the identified 84 genera of phytoplankton, 34 belong to diatoms, 6 to dinoflagellates, 23 to green algae, 19 to blue-green algae, 1 belong to chrysophytes and 1 belong to cryptomonads (Table 3). Diatoms, dinoflagellates, green algae, blue-green algae and cryptomonads cell abundances were ranged from 0.2 to 14.5×10^5 ; 0 to 2.6×10^5 ; 0.0 to 6.0×10^5 ; 0.0 to 66.9×10^5 and 0.0 to 7.6×10^5 cells/L. respectively. Diatoms, green algae and blue green algae showed their high abundance in estuaries located along the east coast of India associated with longer residence time and low SPM. The relative abundance of diatoms, dinoflagellates, green algae and blue-green algae groups varied from 5.7 to 100%; 0.0 to 44.9%; 0.0 to 41.9%; 0.0 to 85.6% and 0.0 to 58.0% (Fig. 4) respectively during PDP. Diatoms dominated in the entire study region except in estuaries located in the southeast coast of India, where blue-green algae and green algae were abundant (Fig. 4). Higher water residence time, phosphate concentrations and lower nitrate concentrations favored blue green algae growth in SEC region. Low N:P ratios significantly correlated with abundance of blue-green algae ($r^2=0.7$; $n=7$; $p<0.05$) in SEC. The highest diatoms contribution was observed in SWC region (87.8%) than rest of the regions and lowest diatoms contribution was observed in SEC region (29.5%). Earlier investigators reported that diatoms were predominant in the estuaries located along the west coast of India during southwest monsoon period (Tiwari and Nair 1998; Ramaiah and Ramaiah 1998; Gowda et al., 2001). Low flow rate and longer residence times favors slow growing taxa such as blue-green algae and high flow rate (low horizontal stability) and less water residence time allow only fast growing taxa such as diatoms (Arhonditsis et al., 2007). From our research, also consistent with others with dominant diatoms in the SWC region due to high flow rate (comparatively SEC) and SEC is dominated by non-diatoms due to longer residence time. Moreover diatoms divide faster than other taxa, as they have high growth rates (Smayda 1997) under nutrient rich conditions (Dugdale and Wilkerson 1992).

3.3. Influence of physico-chemical properties on phytoplankton composition

Although, Blue-green algae dominated in SEC region and diatoms in other estuaries, different taxa were found in different estuaries due to variable environmental properties (Table 3; dominant species in each estuary were presented in supplementary figure 1). In order to understand the similarity among Indian estuaries in phytoplankton composition, dendrogram was made based on phytoplankton abundance using primer software (Fig. 5a). Dendrogram is divided into two major groups under ~40% similarity (Fig. 5a). cluster (1) contains two estuaries namely Ponnayaar and Ambalayaar, which are located in the SEC that receives low discharge ($28 \text{ m}^3/\text{s}$), nutrients (Table 4), salinity (2.2) and SPM (48.5 mg/l). The Ponnayaar and Ambalayaar estuaries are known to receive

nutrients from the local industries and therefore nutrients in the estuary were contributed by both discharge and local inputs (Rao and Sarma 2013). Hence, these estuaries exhibited the highest phytoplankton abundance (56.2×10^5 cells.L⁻¹) among other estuaries. Due to low discharge, high residence time of water, less SPM, and significant nutrients availability favours phytoplankton growth in these estuaries. In these estuaries, phytoplankton abundance was mainly contributed by blue-green algae (*Pseudanabaena* spp. and *Gomphosphaeria* sp.), and these species are known to grow in polluted waters (Pilar Mateo et al., 2015).

Cluster (2) divided into 2 groups namely A and B under 50% similarity level (Fig. 5). These groups were mainly formed due to the inconsistency in magnitude of discharge, salinity, concentration of suspended matter and nutrients in the estuary. The estuaries that fall under sub group A1 receive high discharge (1951 ± 1372 m³/s), high SPM (414 ± 436 mg/L) and low salinity (0.1), with the least phytoplankton abundance (0.6×10^5 cells.L⁻¹) (Table 4). The nutrients concentrations are significantly high in A1 estuaries due to high discharge. Such low phytoplankton abundance was resulted from high SPM and low flushing time leading to less light penetration and unstable water column. The phytoplankton composition in these estuaries indicates that major contribution from the benthic diatoms such as *Fragilaria* spp., *Thalassiosira* spp., *Navicula* spp., and *Amphora costata*. (Table 3&4). Such higher rates of discharge disturb upper few centimeters of the sediment leading to re-suspension of benthic dwelling organisms to the water column (Costa et al., 2009). The estuaries in sub group A2 receive moderate discharge (869 ± 938 m³/s), and moderate SPM (199 ± 196 mg/L) (Table 4). Due to decrease in discharge, phytoplankton abundance increased significantly (1.6×10^5 cells.L⁻¹) from that of high discharged estuaries (A1 estuaries). The major contributors of phytoplankton in these estuaries are both benthic and fresh water plankton such as *Oscillatoria* spp., *Fragilaria* spp., *Coscinodiscus granii*., *Navicula* spp. and *Melosira moniliformis*. (Table 3 and 4). Taxa such as *Navicula* spp. (benthic diatom) are good evidence of benthic resuspension in the water column (Muylaert 1994; CNEXO 1977). Nagavali and Vaigai estuaries also come under this group, which contained exceptionally low phosphate, nitrate concentrations and higher salinity compared to other estuaries in this group (Table 1). Such low concentrations of nutrients were due to low freshwater discharge, as indicated by high salinity. The estuaries in sub group A3 consists of minor estuaries, which received low discharge (215 ± 154 m³/s), and low SPM (23.3 ± 12.6 mg/L). Even though these estuaries received low discharge, salinity was also low (~2 psu) due to high precipitation. The phytoplankton abundance was higher than (3.3×10^5 cells.L⁻¹) that of sub groups A1 and A2, and contributed mainly by fresh water diatoms (centric diatoms) such as *Melosira moniliformis*. and *Thalassiosira eccentrica*. Centric diatoms are known to adapt in the

turbulent waters with high nutrient concentrations (Reynolds 1994). Baykal et al., (2009) noticed the presence of *Melosira* over a range of discharge rates.

Under the group B, Penna and Mandovi has formed separately with abundant cryptomonads and dinoflagellates. No significant differences were found compared to other estuaries in these two estuaries except higher phosphate concentration than nitrate. Penna estuary is having more favorable conditions such as low river flow, warmer temperatures, absence of turbulent mixing and presence of a salt wedge conditions for cryptomonads to grow in high abundance (Robertson and Stevens 2008). Cryptomonads are both heterotrophic as well as autotrophic nature and due to their small size, they can survive even in less nutrient conditions. On the other hand, comparatively other estuaries, high dinoflagellate (*Peridinium* spp.) contribution was observed in the Mandovi estuary, which contained relatively cooler temperatures and excess phosphate resulting low N:P ratio (0.5) might have supported to increase their dominance followed by diatoms. Pednekar et al. (2011) and Parab et al. (2013) also noticed dinoflagellates bloom followed by diatoms during late monsoon in Mandovi estuary.

Comparatively, low nutrients concentrations (nitrate and phosphate) were noticed in group B than group A due to high utilization of nutrients by phytoplankton in former region. Flynn et al., (2002) noticed that the competition for nutrients is depending upon physiological properties, storage capacity, growth rate and transportation rate. The estuaries under group B were divided into sub groups B1 and B2, which were located mainly in the east coast of India. The estuaries in sub group B1 received relatively lower discharge (minor/small estuaries with reference to length of the river) ($392 \text{ m}^3/\text{s}$) than B2 ($614 \pm 89.1 \text{ m}^3/\text{s}$), and both contained similar SPM ($\sim 34 \pm 20 \text{ mg/l}$). The salinity in the estuary was brackish (6-12 psu). However diatoms (*Skeletonema* spp. and *Thalassiosira* spp.) were dominant in group B1 whereas blue-green algae (*Pseudanabaena* spp. and *Merismopedia* spp.) and green algae (*Desmodesmus* spp.) in the B2 sub group. Such difference in phytoplankton abundance and their relative abundance in these two sub groups were mainly driven by phosphate concentrations which are significantly lower in the sub group B1 than that of B2. Some taxa or functional groups only can survive under limiting nutrient conditions because of either they have high ability to utilize or lowest requirement that will succeed in competition (Tilman 1977; 1982; Tilman et al., 1982). In the estuaries in group B1 *Skeletonema costatum* is the dominant genus, and requires optimum N:P ratio of 9:1 (Sakshaug and Olsen 1986; Gilpin et al., 2004). The N:P ratios in Subarnarekha and Rushikulya estuaries were close to that of Redfield N:P ratio (9 and 8 respectively). Huang et al., (2004) noticed that, *Skeletonema* sp. is a euryhaline and eurythermal

species and can grow very quickly under eutrophic conditions (Uttah et al., 2008). Stable water column, high phosphate and low nitrate conditions favors blue green algae in sub group B2 estuaries. Whereas, green algae are known to be the poorest competitors for nitrogen and good competitors for phosphate (Sommer 1999). Moderate to low flow waters are favorable conditions for *Merismopedia* spp. (in B2 sub group) to grow which are common blue-green algae forms in eutrophic and mesotrophic waters (Vincent 2009). Though blue-green algae can form nuisance algal blooms, no toxic blooms were found in any Indian estuaries.

Low contribution of diatoms in SEC might be due to low concentrations of nitrate. Though, high concentration of silicate is available, due to relative limitation of nitrate, diatom contribution significantly decreased in these estuaries. Gilpin et al., (2004) declared that lower N:Si ratios did not change the species composition of the diatom assemblage but did influence diatom metabolism with implications for biomass estimation and the potential to alter pelagic food web dynamics. Moreover, zooplankton grazing also controls phytoplankton abundance during low discharge period (Gosselain et al., 1998). Particularly, mesozooplankton prefers diatoms as the main food source (Fessenden and Cowles 1994; Calbet 2001). Present study shows high zooplankton abundance in east coast region (106 organisms/m³) than west coast region (70 organisms/m³) (Dr. V. Venkata Ramana personal communications). On the other hand a positive correlation was observed between diatom abundance and silicate concentrations along west coast estuaries ($r^2 = 0.8$; $n = 8$; $p < 0.001$). It was noticed that high phosphate, low nitrate and silicate in the estuaries located in the SWC region (A3 sub group) can lead to development of non diatoms phytoplankton such as blue-green algae (Egge and Aksnes 1992) but high flow rate is limiting the non diatom abundance in these estuaries.

Factor analysis was done to find out controlling factors on phytoplankton biomass and abundance (Table 5). Factor analysis gave three factors that explained 65% of the total variance of the dataset (PCA biplot for environmental variables and biological properties was made and presented in supplementary figure 2). Factors 1 and 2 explained 33% and 18% of the total variance, respectively, and indicated a strong positive loading of SPM and nutrient (nitrate), and a strong negative loading of phytoplankton biomass and abundance. This indicates that the phytoplankton growth declined because of the increase SPM load. Phytoplankton biomass and abundance showing strong positive loading with non diatom abundances (green algae, blue-green algae and cryptomonads) due to high phytoplankton abundances occurred in estuaries which is situated in SEC region. Hence, factor analysis confirmed that the SPM load is prime controlling on phytoplankton biomass and abundances along Indian estuaries.

Community response showed remarkable variations with respect to river discharge. Diversity index ranged between 0.5 and 1.3 during PDP with relatively high diversity index in estuaries located along the southern India (0.9) than northern India (0.7; except Vamsadhara) (Fig. 3b). Dominance was shown to be the higher (0.3) in estuaries located along Northern India (Fig. 3b), while other estuaries located along Southern India are showed lower dominance (0.2). Phytoplankton diversity mainly depended upon hydrology (along gradients of salinity and water flow velocity) as well as biotic factors (Scheffer 1998; Moss 1988). Lower biodiversity of estuarine organisms is commonly related to high environmental variability (Laprise and Dodson 1994; Elliott and McLusky 2002). High phytoplankton diversity was observed along southern estuaries than northern estuaries due to the longer water residence time in the former, which can favor the growth of different taxa of phytoplankton. In southern India, SEC region shows high diversity due to involving major algal categories such as diatoms and additional representation of green algae and blue-green algae.

4. Summary and conclusions

The summary of the physical and chemical conditions during different discharge volumes and biological responses were given in Fig. 6. The magnitude of discharge controlled the water column stability, residence time, salinity, SPM load, nutrient composition and their ratios in the Indian estuaries. Despite high nutrient levels in high discharge estuaries (mainly northern and major river estuaries), the highest phytoplankton biomass and abundance were noticed in moderate and low discharge estuaries due to longer residence time with brackish salinity conditions and low suspended matter in the latter estuaries. Correlation analysis and factor analysis are also revealing that irrespective of nutrients, high SPM load is predominantly controlling phytoplankton abundance in Indian estuaries. Present study proved that residence time of water column and nutrients composition considerably brought changes in phytoplankton abundance as well as relative abundance of their functional groups and species assemblages. Diatoms dominated in most of the Indian estuaries studied whereas blue-green and green algae predominant in the southeast estuaries due to brackish water and stagnant water conditions. Benthic and freshwater plankton, such as *Scenedesmus* spp., *Coscinodiscus* spp., contributed in the northern estuaries associated with high discharge, SPM load and low saline water. Centric diatoms such as *Melosira* spp. and *Thalassiosira* spp., were observed in the estuaries located in the southwest India as these group prefers turbulent conditions. High phytoplankton diversity was observed along southern estuaries than northern estuaries due to the longer water residence time in the former, which can favor the growth of different taxa of phytoplankton. This study suggests that magnitude of river discharge has significant impact on the

phytoplankton composition due to modifications in suspended load, nutrients composition and their ratios. The modifications in the river discharges, due to dam constructions or inter-linking rivers, may significantly modify phytoplankton composition and it may have significant impact on heterotrophs. Time-series observations are highly essential to understand possible modification in the future as inter-linking rivers are underway for Indian rivers and several dams are proposed to construct in the future.

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Table 1 Variations in physico-chemical and biological parameters in Indian estuaries during PDP.

River	Discharge (m ³ /s)	Amplitude (m)	Temperature (°C)	Salinity (PSU)	SPM (mg/l)	Nitrite (µM)	DIN (µM)	Phosphate (µM)	Silicate (µM)	N:P	N:Si	Chl a (mg/m ³)
Haldi	1600	7.01	30.6	0.8	267	1	17.3	30.5	15.7	0.6	0.064	5.2
Subarnarekha	392		32.2	4	50.8	0.6	7.1	0.8	28.2	8.9	0.021	18.0
Baitarani	903		32.4	0.1	149	3.4	10.1	2.4	34.8	4.2	0.098	4.0
Mahanadi	2121	2.82	29.8	0.1	40	0.5	8.6	4.6	54.6	1.9	0.009	3.5
Rushikulya			33.2	19.3	18.4	0.2	5.4	0.7	16.3	7.7	0.012	8.7
Nagavali		2.17	30.9	28.9	28	0.2	6.3	0.8	13.4	7.9	0.015	14.0
Vamsadhara			30.5	13.3	43.9	0.7	6.8	1.4	23.9	4.9	0.029	6.3
Godavari	3505	2.1	30.2	0.2	175	1.5	49.1	1.7	67	28.9	0.022	2.5
Krishna	551	1.98	29.3	5.3	15.8	0.5	9.5	9.8	185.7	1.0	0.003	7.5
Penna	200		30.2	9.3	26	0.9	4.4	5.8	204.9	0.8	0.004	6.3
Ponnayyar			29.2	0.3	29.5	0.3	6.8	3.3	270	2.1	0.001	97.2
Vellar		1.51	31.4	11.6	32	0.6	6.1	5	140.1	1.2	0.004	12.7
Cauvery	677		30.8	8.6	26	0.6	12.4	5.2	129.9	2.4	0.005	22.2
Kollidam			28.3	0.9	60	0.4	6.7	2.9	227	2.3	0.002	6.3
Ambalayaar	28		31.6	4.2	67.5	0.9	8.6	5.7	103.8	1.5	0.009	159.9
Vaigai	36		32	24.6	40.2	0.2	4.5	1.6	38.1	2.8	0.005	3.1
CBW	391	1.34	27.2	3.9	28	0.5	34	14.9	42.3	2.3	0.012	3.2
Chalakudi			28.5	0.1	17	0.4	20.9	6.6	45.4	3.2	0.009	0.9
Bharatapuzha			29.7	0.1	6.5	0.1	8.3	6.6	41.9	1.3	0.002	
Netravathi			25.5	0.1	128	2.1	49.5	4.5	28.4	11.0	0.074	0.0
Sharavathi			25.6	0.1	12	0.4	16.1	8	27.8	2.0	0.014	4.3
Kali	152		27.5	3.6	31	0.2	17.3	10	30.9	1.7	0.006	0.6
Zuari	103	2.7	27.9	6.4	25	0.3	27.2	11.9	26.3	2.3	0.011	3.5
Mandovi	105	2.7	26.6	0.4	32.5	0.2	19.5	38.6	31.7	0.5	0.006	0.8
Tapti	472		27.5	0.2	546	7.7	70.9	3.5	39.9	20.3	0.193	0.0
Narmada	1447	10.9	26.5	0	918	2.3	71.8	3.1	41.6	23.2	0.055	0.0
Sabarmati	120		26.5	0	346	11.1	70.1	5.1	20.6	13.7	0.539	0.0
Mahisagar		7.63	25.9	0.1	138	6.1	83.3	13.4	47.8	6.2	0.128	0.2

Table 2 Rank correlation matrix (Spearman's) of phytoplankton biomass and abundance with physical and chemical parameters. Numbers in bold are indicating significant correlation ($p < 0.05$)

	Discharge	Salinity	SPM	Nitrate	Phosphate	Silicate	N:P	Chlorophyll a	Abundance	Diversity
Discharge(m ³ /s)	1.0									
Salinity (PSU)	-0.5	1.0								
SPM (mg/L)	0.3	-0.4	1.0							
Nitrate (μM)	0.1	-0.7	0.5	1.0						
Phosphate (μM)	-0.3	-0.2	-0.2	0.4	1.0					
Silicate (μM)	0.2	0.0	-0.1	-0.2	0.1	1.0				
N:P	0.3	-0.2	0.5	0.4	-0.6	-0.2	1.0			
Chlorophyll a (mg/m ³)	0.0	0.6	-0.4	-0.8	-0.3	0.2	-0.4	1.0		
Abundance (Cells/L)	-0.5	0.4	-0.4	-0.4	0.1	0.4	-0.4	0.7	1.0	
Diversity	0.0	0.2	-0.2	-0.3	0.1	0.4	-0.4	0.2	0.1	1.0
Diatoms	-0.4	0.2	-0.5	-0.2	0.2	0.0	-0.3	0.4	0.8	0.1
Dinoflagellates	-0.5	0.2	0.0	-0.2	0.0	0.4	-0.3	0.2	0.3	0.0
Green algae	0.1	0.1	-0.1	-0.3	0.0	0.8	-0.2	0.5	0.6	0.3
Blue green algae	0.0	0.3	-0.2	-0.4	0.1	0.6	-0.4	0.7	0.7	0.4
Cryptophytes	-0.5	0.1	0.0	-0.2	0.2	0.4	-0.4	0.3	0.5	-0.1

Table 3 List of dominant phytoplankton species in Indian estuaries during PDP

List of phytoplankton			Estuary	Dominant taxa (70%)
Diatoms	<i>Pleurosigma</i> spp.	<i>Selenastrum</i> spp.	Haldi	<i>Coscinodiscus granii</i> , <i>Oscillatoria</i> spp., <i>Melosira moniliformis</i> , <i>Leptocylindrus danicus</i>
<i>Chaetoceros</i> spp.	<i>Surirella</i> spp.	<i>Sorastrum</i> sp.	Subarnarekha	<i>Skeletonema costatum</i>
<i>Coscinodiscus</i> spp.	<i>Synedra</i> spp.	<i>Sphaerocystis</i> spp.	Baitarani	<i>Fragilaria</i> spp., <i>Coscinodiscus granii</i> , <i>Amphora costata</i> , <i>Scenedesmus</i>
<i>Cyclotella</i> spp.	<i>Thalassionema</i> spp.	<i>Staurostrum</i> sp.	Mahanadi	<i>Melosira moniliformis</i> , <i>Fragilaria</i> spp., <i>Nitzschia longissima</i> , <i>Scenedesmus</i>
<i>Ditylum</i> spp.	<i>Thalassiothrix</i> spp.	<i>Tetraspora</i> sp.	Rushikulya	<i>Skeletonema costatum</i> , <i>Thalassiosira</i> spp., <i>Nitzschia closterium</i>
<i>Guinardia</i> spp.	Dinoflagellates	<i>Volvox</i> spp.	Vamsadhara	<i>Thalassiosira anguste-lineate</i> , <i>Navicula</i> spp., <i>skeletonema costatum</i> , <i>Melosira</i> spp., <i>Nitzschia</i> spp., <i>Anabaena</i> spp., <i>Pleurosigma elongatum</i> , <i>Asterionella</i> spp., <i>Merismopedia</i> spp.
<i>Hemiaulus</i> spp.	<i>Ceratium</i> spp.	Blue-green algae	Nagavali	<i>Leptocylindrus</i> spp.
<i>Leptocylindrus</i> spp.	<i>Dinophysis</i> spp.	<i>Anabaena</i> spp.	Godavari	<i>Oscillatoria</i> spp., <i>Scenedesmus</i> spp., <i>Fragilaria</i> spp., <i>Navicula</i> spp., <i>Coscinodiscus granii</i> , <i>Synedra</i> spp.
<i>Melosira</i> spp.	<i>Gymnodinium</i> spp.	<i>Aphanocapsa</i> spp.	Krishna	<i>Pseudanabaena</i> sp., <i>Nitzschia</i> spp., <i>Merismopedia</i> spp., <i>Amphora costata</i>
<i>Odontella</i> spp.	<i>Peridinium</i> spp.	<i>Aphanothece</i> sp.	Penna	<i>Cryptomonas</i> spp., <i>Merismopedia</i> spp., <i>Amphora</i> spp.
<i>Paralia</i> sp.	<i>Prorocentrum</i> spp.	<i>Chroococcus</i> sp.	Ponnayaar	<i>Pseudanabaena</i> sp.
<i>Pseudoguinaridia</i> spp.	<i>Scrippsiella</i> spp.	<i>Coelosphaerium</i> spp.	Vellar	<i>Merismopedia</i> sp., <i>Dictyosphaerium</i> sp., <i>Thalassiosira anguste-lineate</i> , <i>Coelastrum</i> sp.
<i>Rhizosolenia</i> spp.	Green algae	<i>Cyanosarcina</i> sp.	Kollidam	<i>Desmodesmus</i> spp., <i>Amphora costata</i> , <i>Thalassiosira eccentrica</i> , <i>Nitzschia</i> spp.
<i>Skeletonema</i> spp.	<i>Actinotaenium</i> spp.	<i>Cylindrospermopsis</i> spp.	Cauvery	<i>Selenastrum</i> spp., <i>Merismopedia</i> sp., <i>Thalassiosira</i> spp., <i>Navicula</i> spp., <i>Actinastrum</i> spp.
<i>Thalassiosira</i> spp.	<i>Actinastrum</i> spp.	<i>Eucapsis</i> spp.	Ambalayaar	<i>Cryptomonas</i> spp., <i>Gomphosphaeria</i> sp., <i>Coelosphaerium</i> spp., <i>Eucapsis</i> spp., <i>Thalassiosira</i> spp., <i>Nitzschia</i> spp., <i>Navicula</i> spp., <i>Scrippsiella</i> spp.
Unknown diatom	<i>Ankistrodesmus</i> spp.	<i>Gloeocapsa</i> spp.	Vaigai	<i>Thalassionema nitzschioides</i> , <i>Amphora</i> spp., <i>Rhizosolenia</i> spp.
<i>Achnanthes</i> spp.	<i>Chlorella</i> spp.	<i>Gloeotheca</i> spp.	CBW	<i>Paralia sulcata</i> , <i>skeletonema costatum</i> , <i>Navicula</i> spp.
<i>Amphiprora</i> spp.	<i>Chlorococcum</i> sp.	<i>Gomphosphaeria</i> sp.	Chalakudi	<i>Melosira moniliformis</i> , <i>Thalassiothrix</i> spp., <i>Navicula</i> spp., <i>Nitzschia longissima</i>
<i>Amphora</i> spp.	<i>Closterium</i> sp.	<i>Lynghya</i> spp.	Bharatapuzha	<i>Melosira moniliformis</i> , <i>Paralia sulcata</i> , <i>Chroococcus</i> spp., <i>Thalassiothrix</i> spp.
<i>Asterionella</i> spp.	<i>Coelastrum</i> sp.	<i>Merismopedia</i> spp.	Netravathi	<i>Navicula costata</i> , <i>Fragilaria</i> spp.
<i>Bacillaria</i> spp.	<i>Cosmarium</i> sp.	<i>Microcystis</i> spp.	Sharavathi	<i>Thalassiosira eccentrica</i> , <i>Navicula</i> spp., <i>Pleurosigma</i> sp., <i>Thalassionema</i> spp., <i>Amphora</i> spp.
<i>Campylodiscus</i> spp.	<i>Desmodesmus</i> spp.	<i>Nostoc</i> spp.	Kali	<i>Thalassiosira</i> spp., <i>Melosira moniliformis</i> , <i>Navicula</i> spp., <i>Coscinodiscus</i> sp.
<i>Cocconeis</i> spp.	<i>Dictyosphaerium</i> spp.	<i>Oscillatoria</i> spp.	Zuari	<i>Peridinium</i> sp., <i>Thalassiosira</i> sp., <i>Nitzschia longissima</i>
<i>Cymbella</i> spp.	<i>Echinospaerella</i> spp.	<i>Pseudanabaena</i> sp.	Mandovi	<i>Melosira</i> spp.
<i>Diploneis</i> sp.	<i>Eudorina</i> spp.	<i>Spirulina</i> spp.	Tapti	<i>Thalassionema</i> spp., <i>Cosmarium</i> spp.
<i>Fragilaria</i> spp.	<i>Franceia</i> spp.	<i>Trichodesmium</i> spp.	Narmada	<i>Ditylum</i> spp., <i>Melosira moniliformis</i> , <i>Peridinium</i> spp.
<i>Haslea</i> sp.	<i>kirchneriellalunaris</i> spp.	Chrysophytes	Sabarmati	<i>Hemiaulus</i> spp., <i>Melosira</i> spp.
<i>Navicula</i> spp.	<i>Monoraphidium</i> sp.	<i>Synura</i> spp.		
<i>Nitzschia</i> spp.	<i>Pediastrum</i> spp.	Cryptomonads		
<i>Pinnularia</i> spp.	<i>Scenedesmus</i> spp.	<i>Cryptomonas</i> spp.		

Table 4 Variations in hydrographic properties, environmental variables and phytoplankton composition in Indian estuaries. Groups (First column) are made from cluster analysis (figure 5).

Groups	Conditions	Salinity (PSU)	Mean discharge (m ³ /s)	SPM (mg/L)	Abundance (cells/L)	Abundant group	Genus example	N (μM)	P (μM)	N:P
1	Low discharge rate, Low nutrients	2.2	28	48.5± 26.8	56.2 x 10 ⁵	Blue-green algae Cryptophytes	<i>Pseudanabaena</i> <i>Cryptomonas</i> <i>Gomphosphaeria</i>	8.6	5.7	1.5
A1	High discharge rate, high SPM	0.1	1951±1372	414±436	0.6 x 10 ⁵	Micro phyto benthos	<i>Navicula</i> <i>Thalassiosira</i> <i>Oscillatoria</i> <i>Fragilaria</i> , <i>Amphora</i>	60.4	2.4	25.6
A2	Moderate discharge rate, Moderate SPM	0.2	869±937.7	199±196.3	1.6 x 10 ⁵	Benthic and pelagic fresh water diatoms	<i>Oscillatoria</i> <i>Fragilaria</i> , <i>Navicula</i> <i>Melosira</i> <i>Hemiaulus</i>	32.5	7.2	8.3
A3	Low discharge rate low SPM fresh water	2.4	215±154	23.3±12.6	3.3 x 10 ⁵	pelagic fresh water diatoms	<i>Melosira</i> <i>Thalassiosira</i> <i>Paralia</i>	18.7	8.5	2.5
B1	Low discharge rate Low SPM brackish water	11.6	392	34.6±22.9	8.7 x 10 ⁵	Pelagic diatoms	<i>Skeletonema</i> <i>Thalassiosira</i>	6.3	0.7	8.4
B2	Moderate discharge rate, Low SPM brackish water	6.6	614±89.1	33.3±18.9	12.6 x 10 ⁵	Blue-green algae Green algae	<i>Pseudanabaena</i> <i>Merismopedia</i> <i>Desmodesmus</i> <i>Selenastrum</i>	8.7	5.7	8.4

Table 5 Factor-loading matrix, eigenvalues and total and cumulative variance values

Parameters	Factor 1	Factor 2	Factor 3
Discharge(m ³ /s)	0.3	-0.1	-0.6
Salinity (PSU)	-0.4	0.5	-0.2
SPM (mg/L)	0.6	-0.6	-0.2
Nitrate (μM)	0.7	-0.6	-0.2
Phosphate (μM)	0.0	0.3	0.6
Silicate (μM)	-0.5	0.1	-0.5
N:P	0.6	-0.5	-0.4
Si:P	-0.3	0.2	-0.5
N:Si	0.7	-0.5	0.1
Chlorophyll a (mg/m ³)	-0.8	-0.6	0.1
Diatoms	-0.1	0.0	0.5
Dinoflagellates	-0.1	0.2	0.6
Green algae	-0.8	-0.5	-0.1
Blue-green algae	-0.8	-0.5	0.0
Cryptophytes	-0.8	-0.5	0.0
Abundance (Cells/L)	-0.8	-0.5	0.2
Diversity	-0.5	0.5	-0.4
Dominance	0.3	-0.3	0.4
Expl.Var	5.9	3.2	2.4
Prp.Totl	0.3	0.2	0.1
Eigenvalue	5.9	3.2	2.4
% Total	33.0	18.0	13.6
Cumulative	33.0	51.1	64.7

Figure Legends:

Fig. 1 Map showing estuaries sampled in this study. Map also showing northwest coast, southwest coast, southeast coast and northeast coast estuaries in different colour symbols.

Fig. 2 Correlation analysis for salinity and SPM with discharge, phytoplankton biomass and phytoplankton abundances

Fig. 3 Spatial variability in (a) phytoplankton abundance (Y axis in logarithmic base 10), (b) diversity and dominance

Fig. 4 Variability in phytoplankton groups composition in Indian estuaries

Fig. 5 Dendrogram is showing similarity of estuaries in terms of phytoplankton abundance

Fig. 6 Schematic diagrams showing different physical, chemical conditions and biological responses during different discharge patterns in Indian estuaries.

Figure 1.

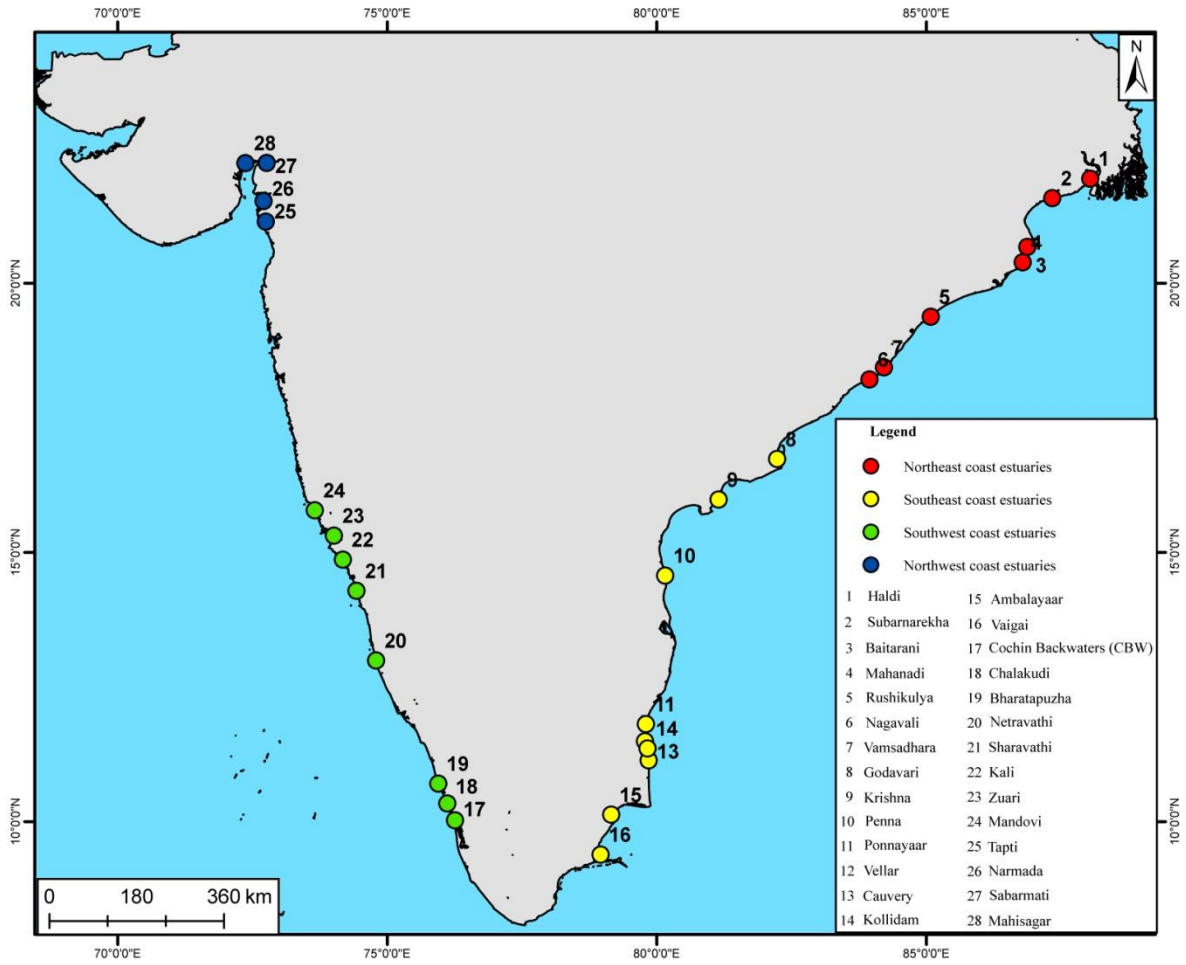


Figure 2.

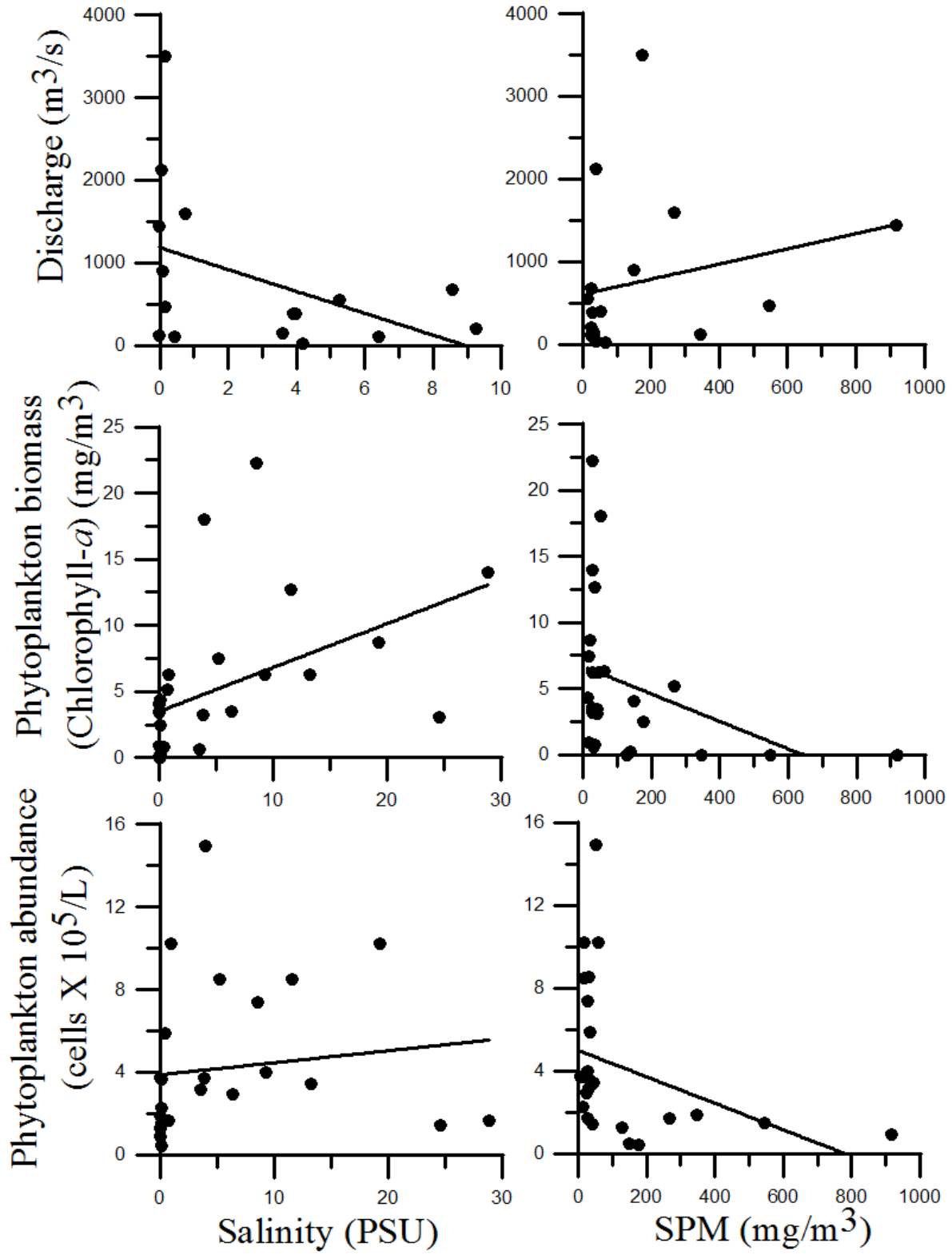


Figure 3.

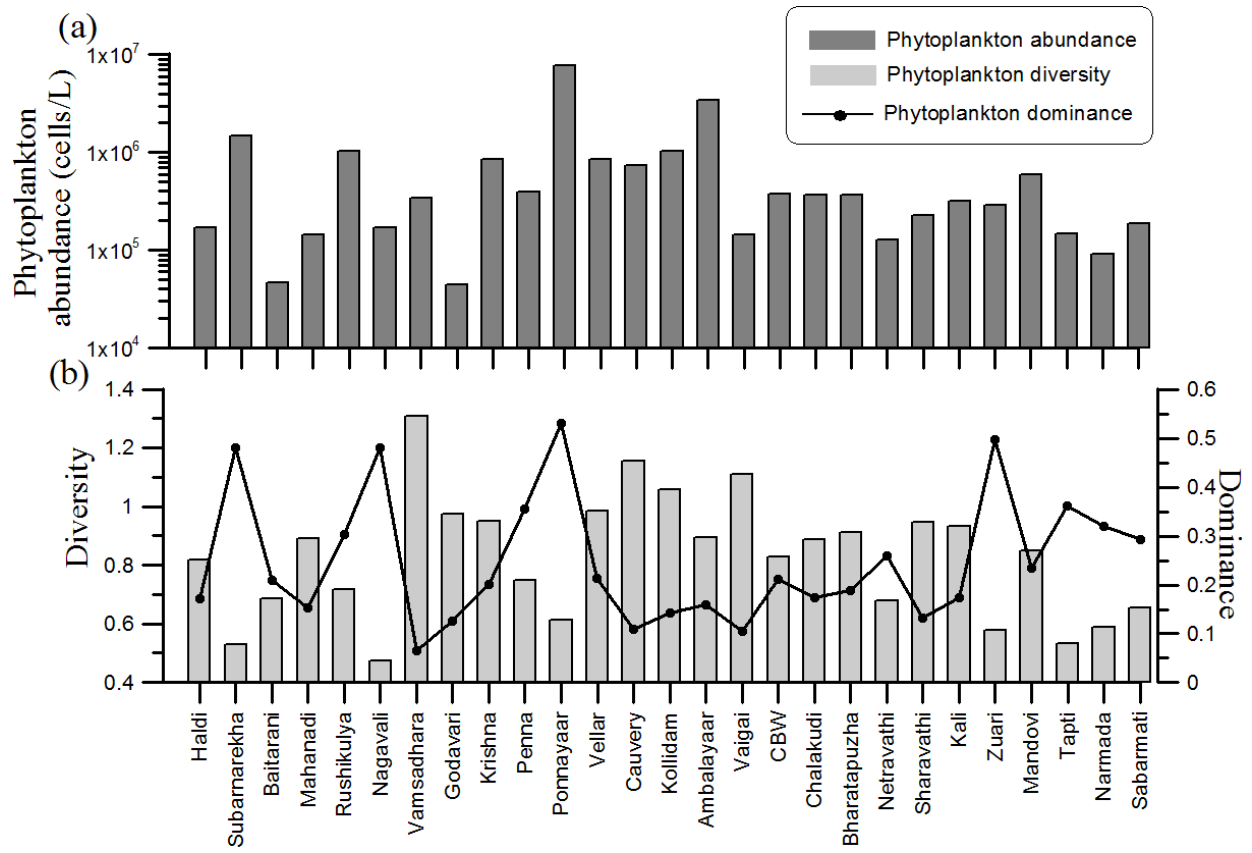


Figure 4.

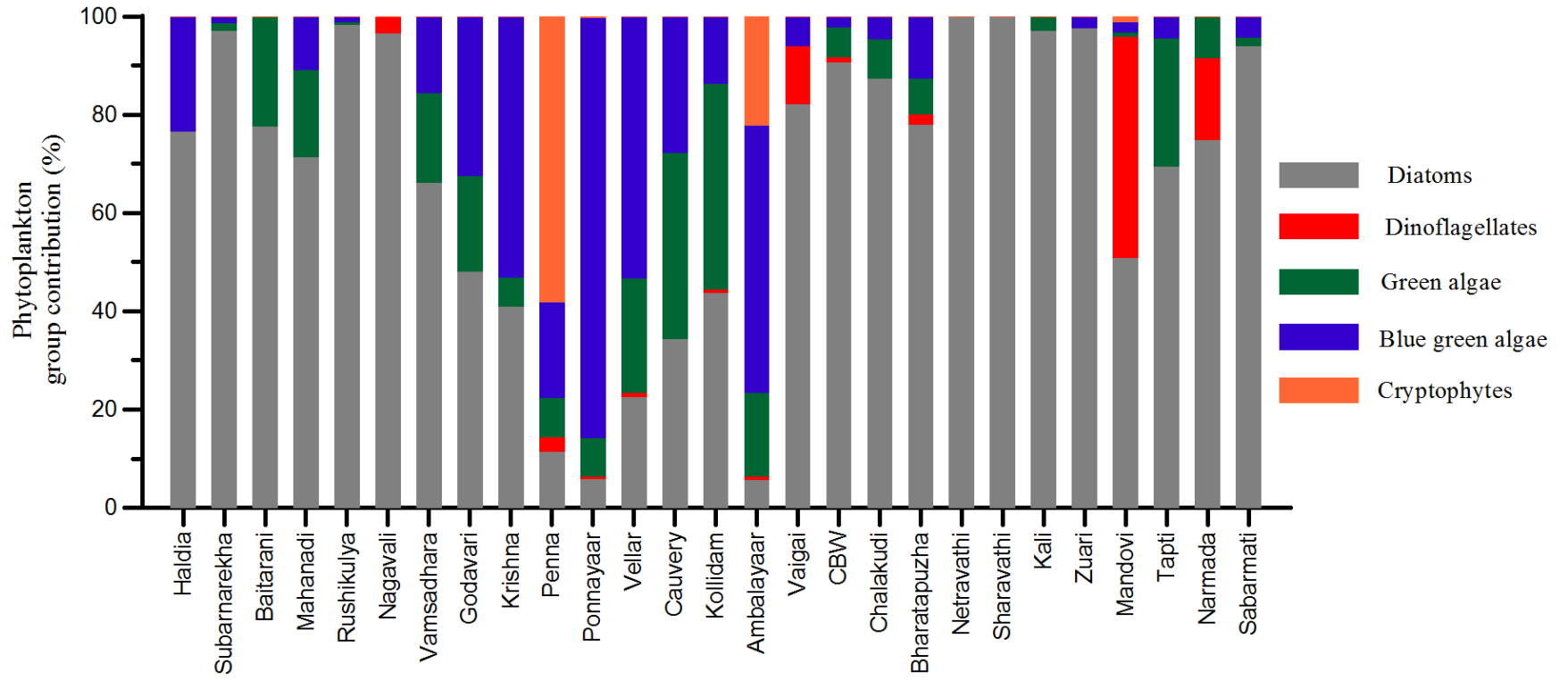


Figure 5.

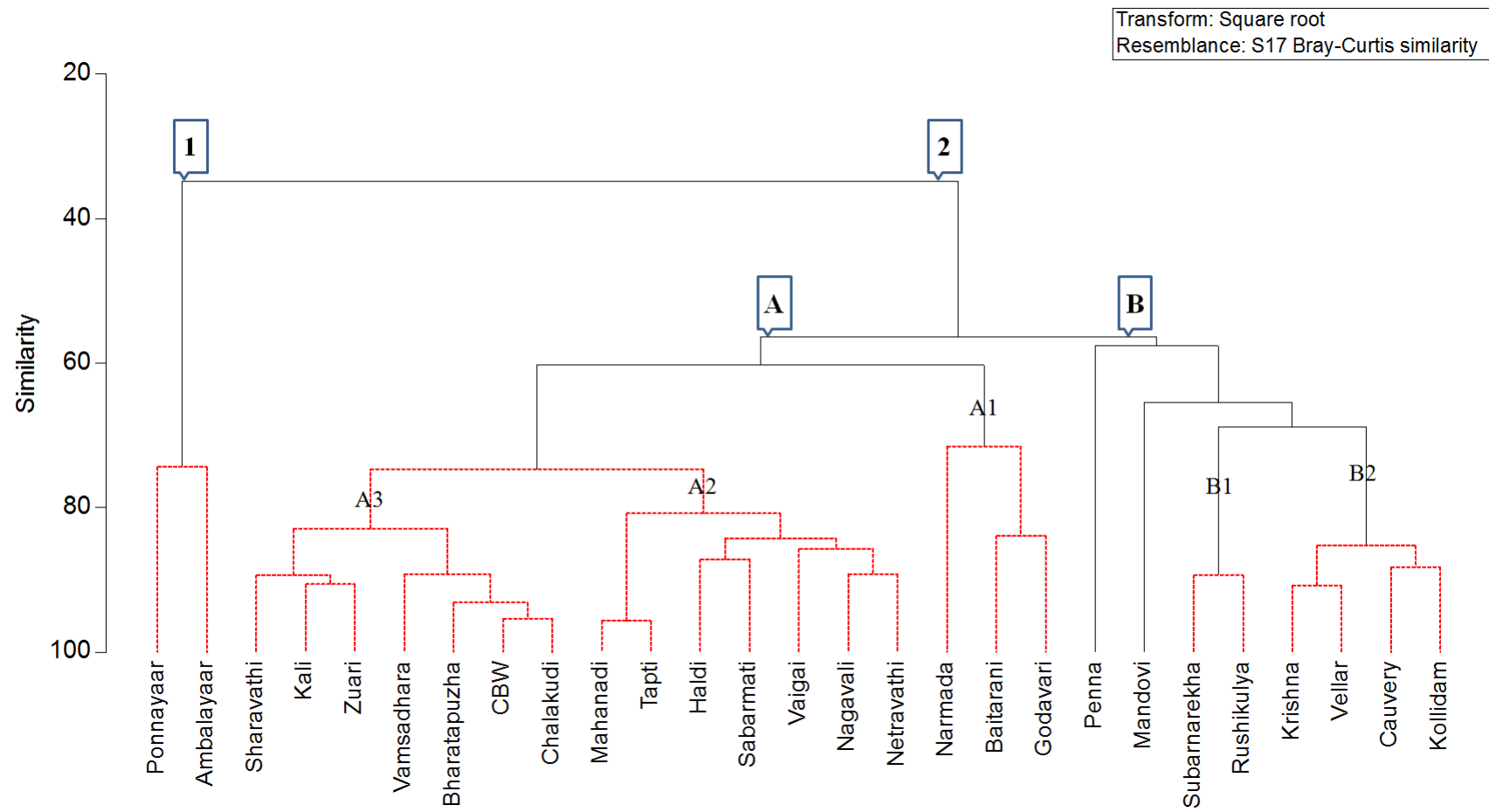


Figure 6.

