

Reduced river discharge intensifies phytoplankton bloom in Godavari estuary, India

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ABSTRACT

Changes in river discharge alter material load and the consequent estuarine and coastal biogeochemical process. Evidence for biogeochemical response to variable rainfall over catchment area or changes in river discharges due to dam regulations is sparse. Inter-annual variability in monsoon rainfall and the consequent river discharges, either dam regulated or otherwise, in India are the best suited to test the influence of altered discharges on estuarine biogeochemistry. Our experiments in Godavari river estuary over three years revealed that a decrease in precipitation over the Indian subcontinent from 2007 to 2009 resulted in the lowering of mean annual discharge from $748.63 \text{ m}^3 \text{ s}^{-1}$ in 2007 to $218.40 \text{ m}^3 \text{ s}^{-1}$ in 2009. The reduced water discharge, during the peak discharge period, slowed the flushing of the estuary from 1.2 days to 6.3 days, respectively. The consequent increase in stability of water column and reduced suspended material load gave rise to intense phytoplankton blooms (Chl *a* $18 \mu\text{g l}^{-1}$ in 2007 to $28 \mu\text{g l}^{-1}$ in 2009). Resilience towards the unwanted phytoplankton bloom and overall health of the Indian estuaries is thus tuned by the variability in monsoon rainfall and dam regulated discharge.

Key words: Godavari estuary, river discharge, inter-annual variability, dam, phytoplankton bloom

1. Introduction

The health of estuaries and coastal oceans and their resilience towards extreme phytoplankton bloom varies considerably in different parts of the world (Clarke et al., 2006; Garnier et al., 2010; Seitzinger et al., 2010). Most estuaries in the United States and European Union are moderate to highly eutrophic (Bricker et al., 2008; Ferreira et al., 2007; Scavia and Bricker, 2006). In the estuaries of those regions it has been observed that fresh water discharge during the spring freshets enhances the nutrient load from the drainage basin and intensify the phytoplankton bloom (Admiraal et al., 1990; Van Bennekom and Salomons, 1981). However, the evidence of unnatural phytoplankton bloom has not been found in the estuaries of high discharge rivers such as Amazon with the highest discharge of $209000 \text{ m}^3 \text{ s}^{-1}$ and other major rivers such as, Congo, Brahmaputra, Ganges etc, where average discharge exceeds $20000 \text{ m}^3 \text{ s}^{-1}$ (Selman et al., 2008).

Indian subcontinent houses some of the worlds' largest estuaries at the mouth of mighty rivers such as the Ganges, Godavari, Krishna, Narmada etc. which are largely fed by Indian Summer Monsoon (ISM) rainfall (July-September). Most of these rivers are dammed at several locations along their course for crop irrigation and domestic as well as industrial consumptive usages. Availability of fresh water in the downstream rivers and estuaries are thus regulated by dam authorities who allow excess water to flow down by lifting the sluice gate when water holding capacity of dam reservoirs surpass. During the monsoon period huge volume of fresh water is discharged from the dam reservoir (at times greater than the entire volume of estuary) that flushes entire estuary less than a day (Vijith et al., 2009). In contrast, enhanced stratification sets in during the lean discharge period with longer flushing time. Alluvial plains along the Indian rivers and the coasts are rich cultivable land and application of fertilizers, such as urea, di-ammonium phosphate and potash (nitrogen-phosphorus-potassium), in agricultural fields is quite high; $\sim 24.34 \text{ kg hectare}^{-1}$ (Indian Agricultural department, <http://indiastat.com/agriculture/2/stats.aspx>). Cultivation of paddy, which is the major crop in India, is done during the ISM period when the rainfall is plentiful throughout the alluvial plain. Excess of the fertilizers that are applied in the field during this time is washed by the rainfall and ultimately make their entry in different water bodies including estuaries. Fresh water discharge into the monsoonal estuaries also peaks during the same time period making them prone towards intense and large scale phytoplankton bloom. Biogeochemical aspects of Indian estuaries have been mostly studied concerning nutrient dynamics (Mukhopadhyay et al., 2006; Sarma et al., 2010), inorganic and organic carbon biogeochemistry and trace gases (Bouillon et al., 2003; Bouillon et al., 2000; Sarma et al., 2009; Sarma et al., 2011), behaviour of different

elements (Sarma et al., 1993) and heavy metals (Somayajulu et al., 1993). Virtually no systematic studies have been undertaken so far in these estuaries focussing on spatial and-temporal variability of phytoplankton biomass. Likewise our understanding about the response of this sensitive ecosystem towards excessive nutrient load from the agricultural field is nil.

To address this knowledge gap, three year (2007-2009) extensive daily time series observation was carried out in the Godavari river estuary, a major river of Indian subcontinent, to examine how inter-annual variability in the monsoon driven rainfall and consequent discharge pattern regulates phytoplankton biomass.

Sarma et al. (2009) reported that Godavari estuary is net heterotrophic where water column respiration far exceeds over the mean photic zone productivity. As a result, a large portion of the carbon demand in Godavari estuary is met from the terrestrial organic carbon input. Resulting high heterotrophic activity, mostly triggered by the bacterial respiration makes Godavari as one of the highest CO₂ emitter estuaries in the world (Sarma et al., 2011). River discharge was identified as the major source of nutrients in Godavari estuary by Sarma et al. (2010). They observed that significant amount of nutrients (>80 µM of dissolved inorganic nitrogen (DIN) and >12 µM of dissolved inorganic phosphate (DIP)) were associated with peak discharge. However, during that time phytoplankton biomass remained low (<2 mg m⁻³) due to severe light limitation.

Present study focuses on the inter annual (2007-2009) variability of phytoplankton biomass in Godavari estuary with a major objective of finding the mechanistic link between the phytoplankton bloom and monsoon driven river discharge. Major emphasis has been given on year 2009 which was a drought-hit year with lowest recorded rainfall in last two decades.

2. Study region

Godavari is the largest among the Indian Peninsular rivers which are mostly rain fed and non-perennial (www.india.gov.in/knowindia_rivers.php). It originates in the western ghats and flows towards south east before opening into the Bay of Bengal, east coast of India. It contributes ~5% (Rao, 1975) of the riverine inputs into the Bay of Bengal. Its Deltaic plain is extensively cultivated and the fertilizer usage (~49.34 kg hectare⁻¹) is almost double to that of the national average. The river is dammed at four locations in upstream and one of the dams (Dowlaiswaram), that regulates fresh water flow into the estuary, is situated at approximately 60 km upstream of the mouth. The river bifurcates into two distributaries, Gouthami and Vasishta after emerging from the Dowlaiswaram dam. Our daily time series station was located at Gouthami branch as it carries the

majority (~70%) of flow. Lower 40 km stretch of Gouthami Godavari constitutes the estuary until where tidal effect is observed. Tide is semidiurnal in nature with the amplitude of 1.5 m and average current speed of 1-2 m s⁻¹. The average water column depth of the estuary is 7 m.

3. Material and methods

Daily observations were carried out at Yanam, situated in the middle of the Gautami branch of the Godavari estuary (Fig. 1) since September 2007 at fixed time (11:00 h). The time was fixed to avoid the associated diurnal changes in biogeochemical properties while comparing the daily data. Temperature, salinity and depth were measured using respective sensors attached to a CTD system (SBE 19 plus, Sea-Bird Electronics, USA). The precisions of temperature and salinity were found to be 0.001 °C and 0.004, respectively. Salinity values obtained from conductivity sensor of the CTD, particularly during peak monsoon period, were routinely checked against the results of Autosal (8400b) and argentimetric titrations as CTD sensors are less precise at low salinity ranges (accuracy between the two was found to be 0.02 RSD).

Flushing time (T_{FR}) is defined as the time required to renew existing volume (V_e) of water in an estuary at a volumetric flow rate of (Q) through the estuary due to river run off alone (Vijith et al., 2009) i.e.

$$T_{FR} = V_e / Q \quad (1)$$

Tide- driven flushing time (T_{FT}) during dry/zero discharge period was calculated by tidal prism method following (Dyer, 1991; Monsen et al., 2002).

$$T_{FT} = V_e T / (1-b) P \quad (2)$$

where, T is tidal period, P is the tidal prism and b is the return flow factor (Monsen et al., 2002). According to Vijith et al., (2009), b was assumed to be 0.5. A tide gauge was installed at Yanam which continuously logged data at 1 minute interval.

Daily discharge data, for Gautami Godavari, were obtained from the irrigation department of Dowleiswaram dam authorities. Nutrients for dissolved inorganic nitrogen (DIN), dissolved inorganic phosphate (DIP) and dissolved inorganic silicate (DSi) samples were collected in 50 ml polyethylene containers which were filled up to the brim. To stop the biological uptake of nutrients a few drops of saturated mercuric chloride solution was added into the bottles before they were air tightened by means of sticky plaster. Nutrient bottles were frozen in -20°C freezer until they were

analyzed using autoanalyzer as per the standard method (Grasshoff et al., 1992). The precisions of the DIN, DIP and DSi were ± 0.02 , 0.02 and 0.01 $\mu\text{mol l}^{-1}$, respectively. About 150 to 500 ml of a water sample was filtered, through preweighed 0.22 μm polycarbonate filters (Millipore), dried at 40° C and reweighed to quantify suspended particulate matter (SPM, g l^{-1}). Another 150 ml of water sample was filtered through GF/F filter (Whatman) and Chlorophyll-a (henceforth, Chl-a) on the filter was extracted with N,N, Dimethyl Formamide (DMF) at 4°C in dark for 24 h and was measured spectrofluorometrically (Cary Eclipse-Fluorescence Spectrophotometer, Varian Instruments, USA) following Suzuki and Ishimaru (1990). The analytical precision for Chl-a analysis was $\pm 4\%$. About 300-500 ml of samples were also filtered through GF/F filter and pigments in the filter were extracted into 90% acetone and measured using High Performance Liquid Chromatography (LC 1200 series, Agilent Technologies, USA). Method proposed by Van Heukelem and Thomas (2001) was adopted for pigment analysis during the study. Variation in diatom population in the present study was monitored using their class specific marker pigment fucoxanthin (Jeffrey et al., 1997; Mantoura and Llewellyn, 1983; Wright et al., 1991).

To confirm the influence of SPM and flushing time on phytoplankton bloom a laboratory-based incubation experiment was conducted. Surface water samples were collected in triplicates of 50 litre transparent polycarbonate bottles (Nalgene) from regular station location at Yanam (see Fig. 1) during the peak discharge period of August 2009. These sample bottles were incubated in chambers filled with estuarine surface water under sunlight for 6 days and was sampled every day at 1800 h for Chl-a, total organic carbon, pH and $\delta^{13}\text{C}_{\text{DIC}}$. At the beginning of the experiment nutrient concentrations in terms of nitrate, phosphate, ammonium and silicate were 40.2, 14.8, 22.1 and 83.2 $\mu\text{mol l}^{-1}$ respectively. Water was highly turbid with SPM concentration of 0.78 g l^{-1} and discharge on the day of sampling was 9200 $\text{m}^3 \text{s}^{-1}$ and photic depth was 0.02 m. During the incubation experiment bottles were gently mixed twice in a day at a fixed time to avoid settling of phytoplankton. The pH was measured by potentiometric titration (835- Titrand, Metrohm, Switzerland) and $\delta^{13}\text{C}_{\text{DIC}}$ was measured using Mass Spectrometer (Delta V Plus, Thermo Scientific, Germany) attached to Gas Bench (Finnigan, Gas Bench II, Thermo Scientific, Germany) with the precision of 0.002 and 0.2‰ respectively.

4. Results and Discussion

4.1. Intra- and inter-annual variations in river discharge into the Godavari estuary

The dam controlled freshwater discharge into the Godavari estuary begins by June and continues until mid-December with its maxima in August. In general there is virtually no discharge between January and May. We categorized fresh water discharge in Godavari estuary into (1) high discharge ($>2000 \text{ m}^3 \text{ s}^{-1}$), (2) moderate discharge ($>0-2000 \text{ m}^3 \text{ s}^{-1}$) and (3) zero discharge ($0 \text{ m}^3 \text{ s}^{-1}$). Usually high discharge period spans from June to September, moderate discharge from October to December and zero discharge from January to May when upstream river water is locked in the dam reservoir until the next monsoon. However, this ideal state gets altered depending on the variability of south-west monsoon rainfall. The mean annual river discharge decreased significantly (Fig. 3a) from 2007 ($748.63 \text{ m}^3 \text{ s}^{-1}$) to 2009 ($218.40 \text{ m}^3 \text{ s}^{-1}$) and this pattern was consistent with the precipitation over the Indian continent (Dr. A.S. Rao, Indian Institute of Tropical Meteorology, Pune, India, personal communication, 2010). Fig. 2b reveals that the high discharge period ($>2000 \text{ m}^3 \text{ s}^{-1}$) was longer during 2007 (53 days) that decreased in the following years; 2008 (30 days) and 2009 (13 days). Year 2009 received about 22% less rainfall from that of long term means averaged all over India (Fig. 2c) which was highest recorded negative rainfall departure since last 20 years (<http://www.imd.gov.in/section/nhac/dynamic/endseasonreport09.pdf>). IMD (Indian Meteorological Department) recognized year 2009 as a drought-hit year which recorded “highest mean annual temperature averaged over the country since 1901” (<http://www.imd.gov.in/doc/warm2009.pdf>). Consistent with meagre rainfall pattern, the length of zero discharge periods of year 2009 (193 days) in Godavari river estuary was far above than 2008 (119 days) and 2007 (118 days) (Fig. 2b). In addition to this, the mean annual average discharge of Godavari estuary in 2009 was the lowest ($218.40 \text{ m}^3 \text{ s}^{-1}$) since last 22 years and was about one fourth of the long term average ($939.7 \text{ m}^3 \text{ s}^{-1}$) (Fig. 2a).

Monsoon fed Godavari estuary turns into a river (Fig. 3a) during high discharge period ($>2000 \text{ m}^3 \text{ s}^{-1}$). Bottom salinity which was near zero during that time gradually increased to >28 when the discharge started to become moderate ($0-2000 \text{ m}^3 \text{ s}^{-1}$) followed by zero ($0 \text{ m}^3 \text{ s}^{-1}$) with the commencement of dry period (Fig. 3b). Stratification gradually developed when the fresh water discharge in to the Godavari estuary started to reduce (the increased salinity difference between surface and bottom as in Fig. 3b is indicative of intensity of stratification) which is a typical feature of Indian monsoon driven estuaries (see, Vijith et al., 2009). Such a pattern is contrary to most

American and European estuaries where stratification is formed followed by high fresh water discharge during spring freshets (Christopher et al., 2002; Moore et al., 1997).

As the number of high discharge days that resulted in near zero salinity (Fig. 2b) were more in 2007 compared to 2008 and 2009, the length of well mixed conditions (i.e. homogenised water column with near zero salinity) occurred for longer duration in 2007 (40 days) than in 2008 (25 days) and 2009 (4 days). The entire estuarine water was replaced rapidly with considerable low flushing time of few hours during high discharge period but was slow (>30 days) during zero discharge periods (Fig. 3c). Mean flushing time during peak discharge period was the fastest during 2007 (1.2 days) followed by 2008 (2.1 days) and 2009 (6.3 days). This suggests that the decrease in river discharge in Godavari estuary facilitates stratification and enhances the stability of water column. It is important to note that when there is complete cessation of discharge, the flushing time in Godavari estuary is solely governed by tides and was ranged between 14 to 27 days using tidal prism method. It must be kept in mind that the tidal prism method estimates based on salinity introduced by gravitational circulation. Hence this method estimates the shortest possible time to flush the estuary and these values may be underestimated (Monsen et al., 2002).

4.2. *Impact of variations in magnitude of river discharge on phytoplankton blooms.*

The SPM in the Godavari estuary ranged between 0.01 and 0.75 g l^{-1} (Fig. 3d) and displayed positive relationship with river discharge ($r^2=0.48$; $n=584$; $p<0.001$) as the latter brings higher input of sediments from the watershed and resuspend particles from river and estuarine bed (Howarth et al., 2000). Freshwater discharge is the major source of nutrients to the estuary. An increase in nutrients ($\sim 18 \mu\text{mol l}^{-1}$ of DIP in association with $\sim 80 \mu\text{mol l}^{-1}$ of DIN) were found to have occurred during the high discharge period while $< 1 \mu\text{mol l}^{-1}$ of DIP was found (Sarma et al., 2010) during zero discharge period (Fig. 3e). Despite high nutrient levels, phytoplankton did not proliferate during peak discharge period due to high SPM load that led to shallowing of photic depth to as low as <0.01 m (Sarma et al., 2009). Besides the SPM limited photic depth, low flushing time and decreased water column stability did not favour phytoplankton growth during high discharge period. In contrary reduced fresh water discharge and enhanced tidal influence facilitated stratification during moderate and zero discharge period which in turn led to longer flushing time (> 20 days) (Fig. 3b & 3c). Photic depth was also deepened to more than 3m due to periodic tidal mixing and reduced land drainage (Sarma et al., 2009). The stable and clearer water column favoured phytoplankton cells to grow and to uptake the available dissolved nutrients (see the inverse relationship between DIP and Chl *a* in Fig. 3e & 3f) and multiplied up to bloom proportions (see the shaded rectangle of Fig. 3f). The

highest Chl-*a* concentration found was $\sim 18 \mu\text{g l}^{-1}$ in 2007 that increased to 22 and $\sim 28 \mu\text{g l}^{-1}$ in 2008 and 2009, respectively (Fig. 3f).

Several authors investigated the relationship between phytoplankton growth and estuarine water column stability. Howarth et al. (2000) showed in Hudson river estuary, USA that vigorous mixing of water column during high discharge periods carry phytoplankton cells into deeper and darker water where they cannot photosynthesize. Increased stratification (typical two layered estuarine structure with saline bottom and fresher surface water) and stability keeps phytoplankton cells floating in the photic layer thereby raising their mean exposure to sunlight for photosynthesis. Jassby (2005) computed a power relation $Q \propto B^{-0.76}$ between discharge (*Q*) and Chl *a* (*B*) in San Joaquin River estuary, USA where he showed that net increase in phytoplankton biomass takes place when flushing time of estuary exceeds the phytoplankton population doubling time. Higher stability and stratification in estuary also helps in the proliferation of phytoplankton biomass by decoupling them from potential benthic grazers as evidenced by the work of Cloern (1991) in South San Francisco Bay Estuary, USA.

The mean annual Chl-*a* concentration computed over 2007 -2009 was $4.17 \pm 0.43 \mu\text{g l}^{-1}$. Using this value, we identified the period October and November as bloom months as about 45% of the days recorded Chl-*a* $> 4 \text{ mg m}^{-3}$. Our observation also indicated that the magnitude of discharge influenced the phytoplankton composition during bloom period (October-November).

4.3. *Impact of decrease in river discharge on intensification of phytoplankton blooms*

Figure 4 shows distribution of discharge, salinity, SPM, Chl-*a* and marker pigments for diatoms (fucoxanthin) plotted for October-November bloom period of 2007, 2008 and 2009. Progressive reduction in discharge resulted in increased salinity and decreased SPM from 2007-2009 (Fig. 4b and 4c). The mean Chl-*a* in 2009 was higher ($14.1 \mu\text{g l}^{-1}$) than in 2008 ($10.2 \mu\text{g l}^{-1}$) and 2007 ($6 \mu\text{g l}^{-1}$) (Fig. 4e). The increase in bloom intensity from 2007 to 2009 were likely favoured by the progressively decreased average SPM during the same period ($0.56 \pm 0.03 \text{ g l}^{-1}$ in 2007, $0.16 \pm 0.01 \text{ g l}^{-1}$ in 2008 and $0.05 \pm 0.04 \text{ g l}^{-1}$ in 2009 (Fig. 4c) along with longer flushing times (2.4 days in 2007, 15.5 days in 2008 to 28 days in 2009, (Fig. 3e)). This suggests that lower turbidity and higher stability of the water column facilitated the formation of phytoplankton blooms, which in turn were governed by the amount of freshwater discharge in to the estuary.

Figure 4d and 4e shows that fucoxanthin, the marker pigment of diatoms, closely followed the temporal variability of Chl *a* during October- November. The average concentration of

fucoxanthin in 2009 ($5.7 \mu\text{g l}^{-1}$) was comparatively higher than in 2008 ($3.3 \mu\text{g l}^{-1}$) and 2007 ($0.6 \mu\text{g l}^{-1}$) (Fig. 4d). We also found progressive increase in the average fucoxanthin: Chl *a* ratio from 2007 (0.03) to 2009 (0.4) indicating that diatoms responded quite well in the clearer and more stable water column. Similar observation was also made by Bode and Fernandez (1992) who showed that higher stability and water column clarity favoured blooming of diatoms. This strongly suggests that stability of water column driven by low discharge not only regulated phytoplankton biomass but also their community composition by favouring diatoms proliferation.

4.4. Laboratory experiment

In order to further confirm the role of water column stability and SPM controlled phytoplankton bloom during October- November an *in vitro* laboratory experiment was conducted. In the incubation bottles Chl-*a* concentration exponentially increased from $1.8 \mu\text{g l}^{-1}$ on the day of incubation to $38.7 \mu\text{g l}^{-1}$ on day 4 with a growth rate of $65.8\% \text{ day}^{-1}$ (Fig. 5a). Chl-*a* value decreased to 34.14 and $26.73 \mu\text{g l}^{-1}$ and on day 5 and day 6 respectively, possibly due to the increased zooplankton grazing pressure (Fig. 5a). Phytoplankton cell count (number of cells l^{-1}) increased from 381000 to 952000 on day 6 registering a growth rate of 149.87%. About 68.5% of the phytoplankton community on day 6 was contributed by diatoms dominated by *Melosira sp.*, *Fragellaria sp.*, *Navicula sp.*, *Amphiprora sp.*, *Synedra sp.*, *Amprora sp.*, *Pinnularia sp.*, *Thalassionema sp.*, *Coscinodiscus sp.*, and *Nitzschia sp.* pH of the water increased from 7.82 at the beginning of the experiment to 8.89 on day 5 (Fig. 5b). The $\delta^{13}\text{C}_{\text{DIC}}$ was enriched by ~ 5 per mil clearly indicating that CO_2 was consumed during primary production that enhanced phytoplankton biomass (Fig. 5c). The enhanced primary production was also confirmed by increase in total organic carbon (TOC) concentration by $371.17 \mu\text{mol l}^{-1}$ in 6 days of incubation (Fig. 5d). Exponential growth rate of phytoplankton ($65.8\% \text{ day}^{-1}$) in the bottle experiment during August, 2009 was in accordance to the growth rate in the bloom period of October, 2009 ($44.7\% \text{ day}^{-1}$; $R^2 = 0.96$) in the field. Also the highest Chl-*a* concentration attained in the experiment ($38.7 \mu\text{g l}^{-1}$) was analogous to the highest Chl-*a* concentration recorded during daily time series observation on October 12, 2009 ($27.55 \mu\text{g l}^{-1}$).

Therefore it is apparent that August water samples (representative of high discharge period enriched with dissolved inorganic nutrients and SPM) if allowed to gravitationally settle may demonstrate comparable phytoplankton growth rate and Chl-*a* maxima to that of the bloom month of October. This experiment clearly shows that stability and clarity of the water column are two most important factors in Godavari estuary for the development and intensification of phytoplankton bloom mostly constituted by diatoms.

5. Summary and conclusions

Our present high resolution inter annual observation suggest the strong possibility of bloom intensification in the monsoonal estuaries (Godavari in our case) with reduction in river discharge, due either to reduction in rainfall or regulated discharges from the dam. Conducive environment for the intense phytoplankton bloom in Godavari estuary is formed by the decrease in river discharge which helps in stabilising water column (longer flushing time) and enhancing light penetration through decreased SPM.

Present study also confirms that high SPM and low flushing time in Indian estuaries act as a shield against the phytoplankton bloom. Therefore, these estuaries which are otherwise resistant towards unprecedented phytoplankton bloom may turn eutrophic in the scenario of reduced water availability in the estuary. Such a condition is likely by the build up of more dams and other large scale climate driven features.

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Figure captions:

Figure 1: Map showing the study area and locations of daily sampling station (Yanam) and dam (Dowleiswaram). In set shows the entire course of the river Godavari along Indian sub continent.

Figure 2:a) average annual discharge data of last 22 years in Godavari estuary where 2009 had the lowest mean annual discharge b) categorical frequency distribution of discharge pattern (2007, 2008 and 2009) where $0 \text{ m}^3 \text{ s}^{-1}$ shown in white bar, $> 0 - 2000 \text{ m}^3 \text{ s}^{-1}$ (moderate discharge) in light gray bar and $> 2000 \text{ m}^3 \text{ s}^{-1}$ (high discharge) in dark bar. c) Percent of departure in rainfall (mm) from the long term mean (1990-2009) in India

Figure 3: Time series variations in a) river discharge, b) salinity at surface (black line) and bottom (red line) c) Suspended Particulate Matter (SPM), d) Dissolved Inorganic phosphate (DIP), e) Flushing time and f) Chl *a* at station location Yanam. Solid lines represent three points running average whereas individual data points have been shown for Chl *a* and flushing time. Shaded rectangles show major bloom periods for the years 2007, 2008 and 2009.

Figure 4: Variations in a) river discharge, b) salinity, c) SPM and d) fucoxanthin and e) Chl-a, during October-November 2007 (violet line), 2008 (green line) and 2009 (red line) in the Godavari estuary at Yanam. Individual lines represent three points running average of the data points.

Figure 5: Changes in a) Chlorophyll-a, b) pH c) $\delta^{13}\text{C}_{\text{DIC}}$ and d) TOC during the incubation experiment at Yanam in August, 2009 (high discharge period). Error bars represent $\pm 1\sigma$ in the incubation replicates.

Figure 1:

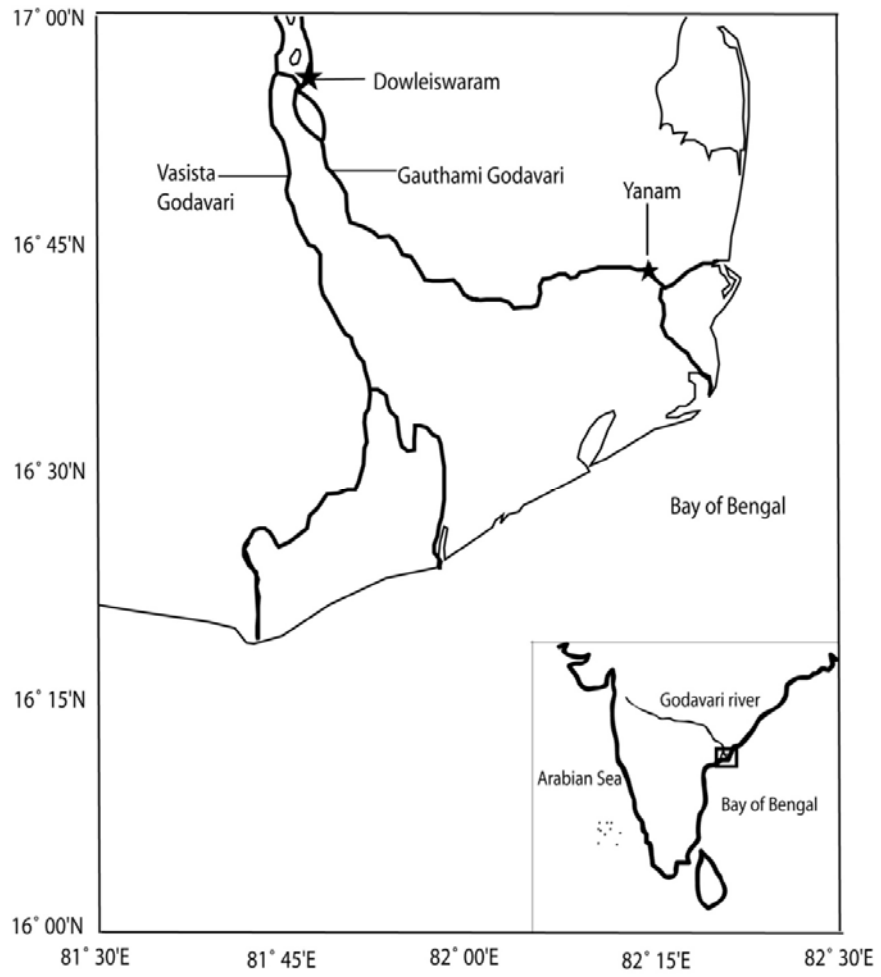


Figure 2

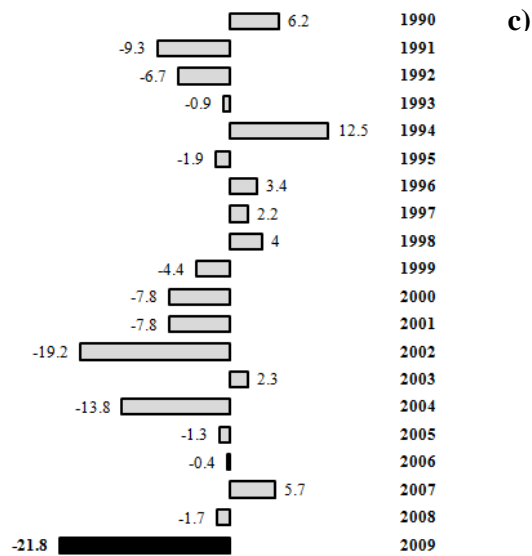
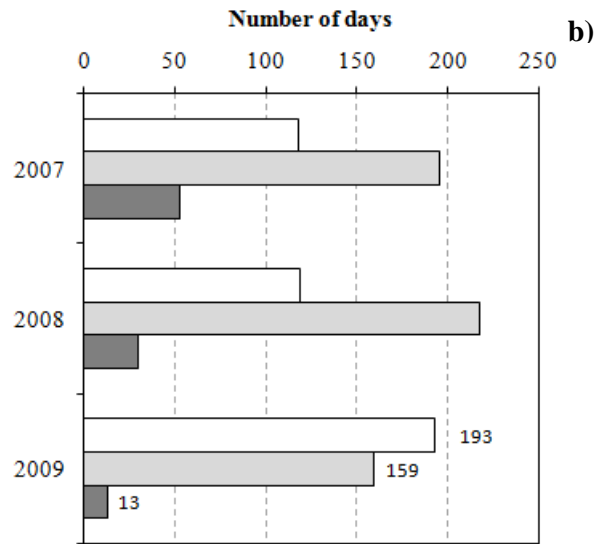
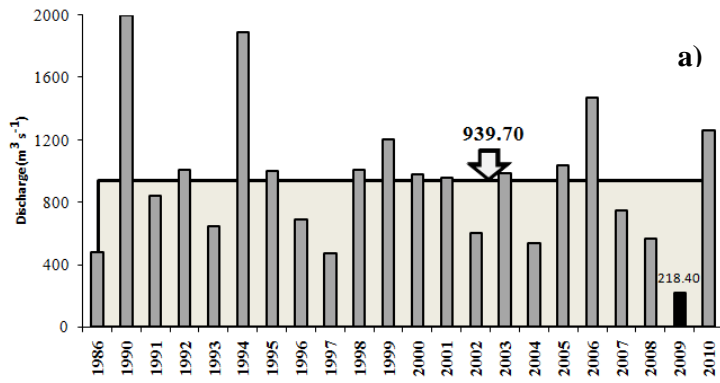


Figure 3:

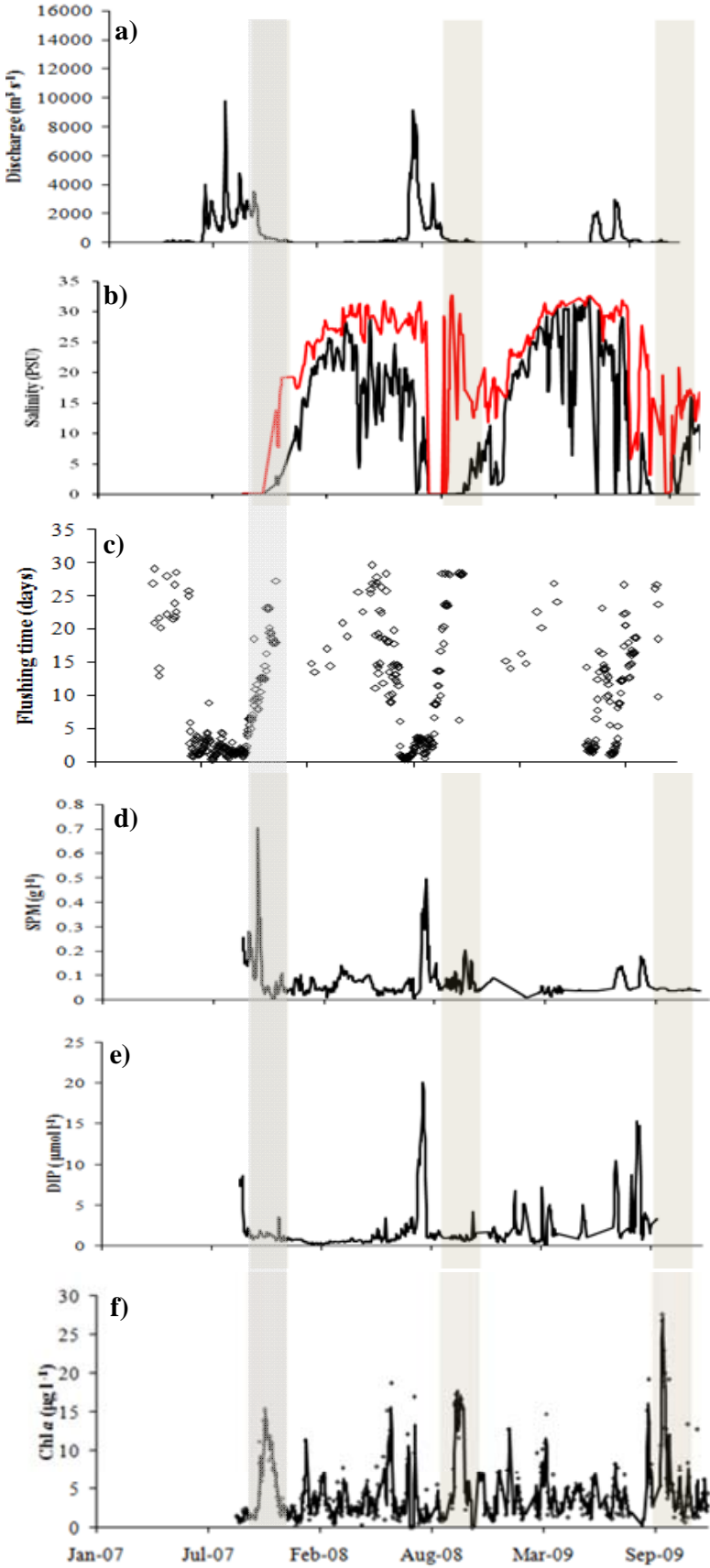


Figure 4

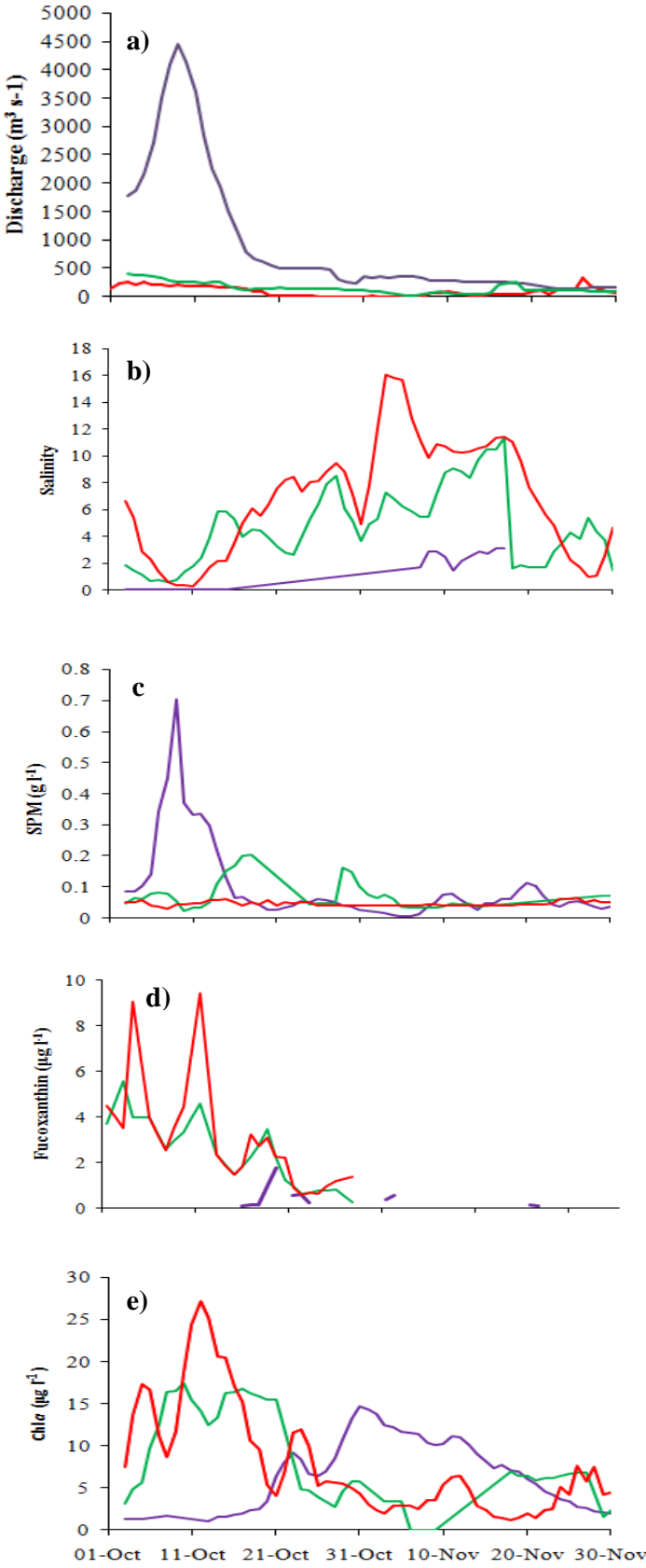


Figure 5:

