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Spatio-Temporal Pattern of Primary Production in a Tropical Coastal Wetland (Kodungallur-Azhikode Estuary), South West Coast of India

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Abstract

The Kodungallur-Azhikode Estuary (KAE) is part of the Vembanad wetland ecosystem in south-west coast of India that has recently been designated as the Ramsar site. Modern aquaculture, agriculture and other human activities in the catchment area export huge amounts of organic and inorganic wastes into the KAE. In this perspective, influences of anthropogenic activities on water quality and phytoplankton production in the KAE were studied at multiple sites from July 2009 to June 2010. The linear correlation with salinity (r^2=0.179, P<0.01), pH (r^2=0.195, P<0.01,) and redox potential (Eh) (r^2=0.188, P<0.01) was found to be significant with Chlorophyll-*a* (Chl-*a*) and negative correlation with turbidity (r^2=-0.212, P<0.01, N=168), nitrate (r^2=-0.297, P <0.01, N=168), and total dissolved solids (TDS) (r^2=-0.266, P<0.01, N=168). The present study showed annual average gross primary productivity (gross PP) of 1580 ± 388 mgC $m^{-3}d^{-1}$ and net primary productivity (net PP) 790 ± 472 mgC $m^{-3}d^{-1}$, with significant monthly variation. The mean Chl-*a* content in the estuary also showed moderately high values (6.42 ± 3.91 mg m^{-3}). In spatial scale, it varied from 5.07 ± 4.03 mg m^{-3} at Station II to 7.80 ± 6.07 mg m^{-3} at Station V. Primary productivity in the estuary was nitrogen limited during pre monsoon period, however average N: P ratio in the water column was well above the Redfield ratio during south west monsoon period (27.9 ± 14.2). Trophic Index (TRIX) analysis in the KAE also showed that estuary experiencing high productivity by the effect of eutrophication.

Keywords: Coastal wetlands; Primary productivity; Nutrients; Eutrophication; Estuaries; Kodungallur-Azhikode Estuary (KAE); Vembanad wetland; Kerala; India

Introduction

Estuaries are among the most important environments of the coastal wetlands, which constitutes transition zones or ecotones, where fresh water from land drainage mixes with seawater, creating some of the most biologically productive area on earth, yet threatened, contributing to a specialized trophic environment [1]. It acts as an indispensable habitat to a variety of biological and economically important resident and migratory aquatic fauna [2-4]. In addition, the estuarine systems act as sinks and sources for pollutants depending on the geographical sources of the contaminants, their biological and chemical nature and with temporal variations in tidal amplitude, river flow, seasons, winds, waves. They are considered as the kidneys of earth for cleaning function they perform through biogeochemical cycles [5]. Pronounced seasonal cycles often occur in temperature, light, waves, river flows, stratification, nutrients, oxygen and biotic communities and these seasonal cycles along with extreme episodic events may be extremely significant for estuarine ecology [6]. Coastal environments play an important role in the global biogeochemical cycles of carbon and macronutrients [7]. Longhurst and Daniel Pauly [8] reviewed the biological productivity of the tropical coastal ecosystems. Information on the rate of Primary Productivity (PP) and factors affecting it are essential for understanding the overall production potential in an estuarine ecosystem; because physico-chemical and biological conditions rapidly fluctuate in the spatio-temporal scale. Biological productivity in estuarine waters is influenced by a number of factors including season, temperature, turbidity, nutrient transport and recycling, tides, river discharge, salinity, grazing and geomorphology of water body. Upstream river influx affects the PP, salinity, nutrient transport, transparency, dissolved oxygen and stratification of estuarine waters [9,10]. Bioassays have indicated that PP is predominantly nitrogen-limited in estuarine systems [11]. PP of Indian estuaries have been studied [12-20]. The word 'eutrophication' has its root in two Greek words: 'eu' which means 'well' and 'trope' which means 'nourishment'. The modern use of the word eutrophication is related to inputs and effects of nutrients in aquatic systems. Andersen et al. [21] defines eutrophication as 'the enrichment of water by nutrients, especially nitrogen and/or phosphorus and organic matter, causing an increased growth of algae and higher forms of plant life to produce an unacceptable deviation in structure, function and stability of organisms present in the water and to the quality of water concerned, compared to reference conditions'. Despite a common understanding of its causes and effects, there is no agreed definition of coastal eutrophication. Over the past century, humans have more than doubled the rate of nutrient input into terrestrial ecosystems, mostly through fossil fuel combustion and increased use of agricultural fertilizers. Excess nutrient flows into streams and a river, where it contributes to eutrophication, is one of the leading causes of degraded water quality worldwide. If it is not removed by biotic uptake, nutrients are ultimately exported from rivers to estuaries and coastal seas; where, it can promote blooms of phytoplankton and other harmful microorganisms. It can generate an excessive biochemical oxygen demand, which will result in hypoxic condition [22,23]. A primary objective of environmental policy and management is to control the input of nutrient into watersheds and to maximize its removal. The importance of early detection of human induced alteration of estuarine environments cannot be overstated,

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because the success of coast effective remedial measures clearly depends on addressing the problem expeditiously before it becomes intractable. It is recommended that measurements of Primary Production (PP), being a sensitive and accurate indicator of eutrophication, should be mandatory when monitoring and assessing the ecological status of coastal waters. Comprehensive scientific information is lacking on the trophic status of Kodungallur-Azhikode Estuary (KAE) in relation to primary productivity and nutrient loading. It is significant examining these in detail in order to develop effective management strategies to mitigate its effect.

Materials and Methods

Study area

On the south west coast of India, there is an extensive system of wetlands. Among these, the International Convention of wetlands recently designed three wetland ecosystems (Vembanad, Ashtamudi and Shastamkotta) in Kerala as Ramsar sites for the conservation of biological diversity for sustaining human life through the ecological and hydrological functions they perform (Bijoy Nandan, 2008). Of these, Vembanad wetland ecosystem (09°00'-10°40'N and 76°00'-77°30'E) is the largest. It has a length of 80km covering an area of about 200sq. km and the width varies between 500 and 4000m. A channel, at Cochin (Cochin estuary) and another at Azhikode (Kodungallur-Azhikode estuary), make permanent connections with the Arabian Sea. The Kodungallur-Azhikode estuary (10°11'-10°12'N and 76°10'-76°13' E) is the northern extremity of Vembanad wetland ecosystem having an area of 700ha and about 20km length. The width of the estuary near barmouth is 750m. During the present study, influences of anthropogenic activities on water quality and phytoplankton production in the KAE (Figure 1) were deliberated at multiple sites (seven stations) from July 2009 to June 2010. Station I, is located at estuarine mouth region and experiences intense tidal influx from the adjoining sea; station II, is having intense fishing and sand mining activity and also Chinese dipnet fishing is common in this area; station III, is receives discharge from the Karuvannur and Chalakkudy river and water is turbid; station IV, is situated on the northern arm of the backwater having intense sand mining, dip net fishing and exploitation of clam fishery by traditional methods is seen; station V, is noted for cage culture of fin fishes, semi intensive fishponds and agriculture practices, and is the northern most sampling site; station VI, the southern arm of the estuary and a branch of Periyar river empties into this zone and station VII, is the southernmost sampling station in the estuary, the riverine zone, where the main arm of Periyar river empties in to the zone. Tides in the estuary are semidiurnal, with microtidal tidal range [1,24]; tidal effects extend to approximately 25km land ward of Azhikode and average annual rainfall in the area is 310cm [24,25]. Two rivers that flow into the Kodungallur-Azhikode Estuary (KAE) are the Karuvannur River and Chalakkudy River. Estuary receives considerable amount of nutrient rich fresh water from these two rivers mainly during south west monsoon. KAE is a positive type of estuary and fresh water input varied from 10 m^3s^{-1} to 21 m^3s^{-1}during pre-monsoon season and 123m^3s^{-1} to 387 m^3s^{-1} during south west monsoon season [24]. Human population density of the study area was approximately 1806 km^2 GOI [26] and nearby Island Vypeen is also known to be the island having highest density of human population in the world 2158km^2; GOI [26]. Upper part of the study area historically practiced salt resistant paddy (Pokkali) cum prawn farming method and eventually those infertile fields were reclaimed and used for single crop or semi intensive fish farming. Modern aquaculture, agriculture and other human activities in the area releases huge amount of organic and inorganic wastes into the catchment area of KAE.

Sampling method

The measurements of PP, Chl-*a*, nutrients and other hydrographic parameters were made once in a month at selected seven stations in the KAE from July 2009 to June 2010. The surface and bottom (3m depth) water samples were collected during morning hours using 2

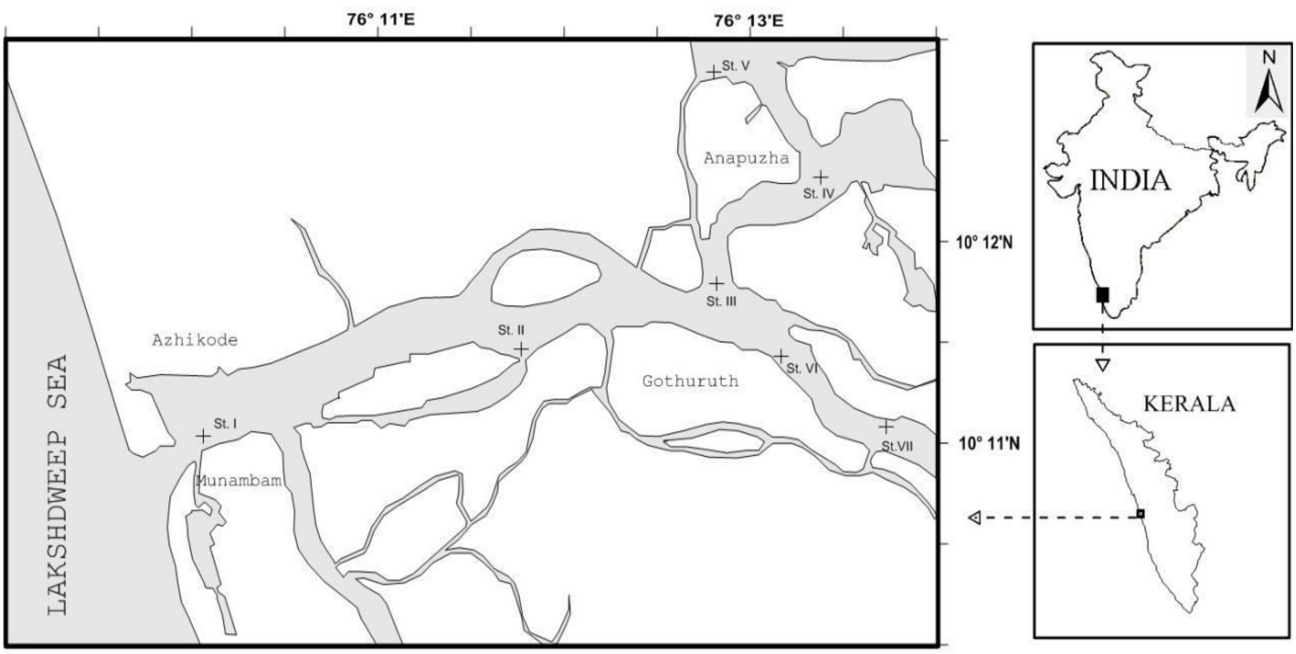

Figure 1: Location of the sampling sites in the Kodungallur-Azhikode estuary (KAE).

Parameters	Monsoon	Post monsoon	Pre monsoon
Water Temperature (°C)	27.5 ± 2.6	28.7 ± 1.3	30.4 ± 0.8
Transparency (m)	0.6± 0.3	1.3± 0.2	1.0± 0.2
Turbidity (NTU)	20.2 ± 15.8	2.3 ± 0.8	6.2 ± 2.1
Salinity (‰)	5.4 ± 5.8	21.6 ± 4.8	16.1 ± 3.6
pH	6.9 ± 0.2	7.7 ± 0.2	7.5 ± 0.1
Dissolved oxygen (mgL^{-1})	5.8 ± 0.5	5.0 ± 1.2	5.0 ± 0.9

Table 1: Seasonal variability of water quality parameters in the Kodugallur-Azhikode estuary during 2009-2010.

litter Niskin water sampler with the help of a motorized boat. The water transparency (Secchi disk transparency; SD) was measured by Secchi disk in the field. Dissolved Oxygen (DO) was estimated according to Winkler's method [27]. pH by Systronics pH meter (No. 335; accuracy ± 0.01). Samples for nutrients dissolved inorganic nitrogen (DIN; ammonium -nitrogen + nitrite-nitrogen + nitrate-nitrogen), DIP (dissolved inorganic phosphate) and DISi (dissolved inorganic silicate) were analyzed following the standard methods [27,28]. For the estimation of Chlorophyll-*a* (Chl-*a*), 500 ml of water sample was filtered through 47mm GF/F filters, extracted with 90% acetone for 24hrs, and kept in -20°C [29]. The extract was measured using a spectrophotometer (Systronics UV-VIS spectrophotometer, Model No. 117). Primary productivity was estimated by *in situ* incubation method using the light and dark bottle oxygen method [30]. Water samples for Primary productivity estimation were collected before sunrise, then immediately passed through a 200-μ sieve to remove large-sized zooplankton. The filtered water was transferred to 125ml capacity DO bottles (two light bottles and two dark bottles). The light and dark bottles were incubated for 3hrs and calculated hourly rate of primary production, then multiplied by the number of day light hours (~12). Temperature of water samples were measured with a centigrade thermometer, conductivity by Systronics digital potentiometer (No. 318), turbidity and total dissolved solids (TDS) by Systronics water analyser (Model No. 317) and salinity by Systronics water analyser (Model No. 317; accuracy ± 0.01) calibrated with standard seawater (APHA) [31]. Carbon dioxide, alkalinity, hardness and biological oxygen demand (BOD) was determined by standard procedures [31]. One-way analysis of variance (ANOVA) was used to calculate the monthly, seasonal and depth wise variation in different physico-chemical and biological parameters and the relationship between productivity parameters by multiple regression using the statistical software *SPSS v16*. Software pack *PRIMER v6* [32] was employed for Bray-Curtis similarity index analysis.

Indices and indicator used in the present study

Trophic Index TRIX formula is the following (Vollenweider et al.) [33] :

TRIX = (Log10 [Chl-a × aD%O × DIN× DIP] +k) / m

Each of the four components represents a trophic state variable, to say:

· Factors that are direct expression of productivity

Chlorophyll-*a*: [Chl-*a*: mg m^{-3}]

Oxygen as absolute (%) deviation from saturation: [abs | 100-%0 | = aD%O]

· Nutritional factors

Dissolved inorganic nitrogen as N-(NO_3- + NO_2- + NH_4+): [DIN = mineral N: mg m^{-3}]

Dissolved inorganic phosphorus as P-PO4: [DIP. PO4: mg m^{-3}]

The parameters *k*=1.5 and *m*=12/10=1.2, are scale coefficients, introduced to fix the lower limit value of the Index and the extension of the related Trophic Scale, from 0 to 10 TRIX units. TRIX point values assign an immediate measurement to the trophic level of coastal waters. Values exceeding 6 TRIX units are typical of highly productive coastal waters. Values lower than 4 TRIX units are instead associated to scarcely productive coastal waters, while values lower than 3 are usually found in the open sea.

Results

Physico-chemical parameters

The average depth of estuary was 3.6 ± 0.2 m with maximum at estuarine mouth (Station I; 4.3 ± 0.4 m). The water column remained relatively cool (Av. 28.9 ± 2°C) throughout the study period; comparatively low water temperature was observed during south west monsoon (Av. 27.5 ± 2.6°C) as compared to pre monsoon (30.4 ± 0.8°C) and post monsoon (Av. 28.7 ± 1.3°C) seasons, (Table 1). Transparency values were generally low in KAE especially during monsoon season (Av. 0.6 ± 0.3 m). On a spatial scale, it was lowest in Station V (Av. 0.8 ± 3 m) and highest in Station VI (1.1 ± 0.5 m). The turbidity values tended to show wide variations in the surface and bottom waters in KAE. Apparently high turbidity values were observed in the KAE waters with an average of 9.8 ± 11.8 NTU, whereas the peak concentration was recorded during monsoon season (Av. 20.2 ± 15.8 NTU). Highest mean turbidity value (Av. 13.1 ± 16.4 NTU) was observed at the estuarine mouth (Station I). The average Dissolved Oxygen (DO) concentration of 5.1 ± 1 mgL^{-1} was observed for the KAE; it ranged from 4.7 ± 1.3 mgL^{-1}in Station I to 5.9 ± 1.4 mgL^{-1} in Station IV. A discernible trend was observed in the DO regime, where the surface water (Av. 5.6 ± 1.1 mgL^{-1}) was higher than the bottom waters (Av. 4.7 ± 0.6 mgL^{-1}). The carbon dioxide (CO_2) values were high in post monsoon season (Av. 6.9 ± 1.8 mgL^{-1}) as compared to monsoon (Av. 6 ± 1.1 mgL^{-1}) and pre monsoon periods (Av. 6.3 ± 2.5 mgL^{-1}) in the KAE. Average BOD value during the present study was 2.6 ± 0.9 mgL^{-1}, whereas it was high in Station I (Av. 3.1 ± 1.5 mgL^{-1}). Distinct spatio-temporal variations were observed in the pH values (Table 1); it was generally on the alkaline side (Av. 7.4 ± 0.4) in most of the months. Alkalinity was comparatively high during pre-monsoon period (Av. 43.7 ± 20.4 mgL^{-1}) when compared to monsoon (Av. 24.4 ± 6 mgL^{-1}) and post monsoon (Av. 36.9 ± 20.9 mgL^{-1}) periods. The mean calcium hardness of the KAE was 750 ± 870.3 mgL^{-1} and it showed to increase from monsoon (Av. 490.2 ± 838.3 mgL^{-1}) to pre monsoon period (Av. 1294 ± 1070.9 mgL^{-1}). Salinity of the KAE was mixo-mesohaline in nature. A clear stratification was observed in the salinity values, whereas, the average bottom water salinity (Av. 16.9 ± 8.9%) was highest compared to the average surface water salinity (12.4 ± 7.4‰). The salinity values showed a definite trend, where it decreased from estuarine mouth to head (Figure 2e&f). The average nitrate-nitrogen (NO_3-N) of KAE water was 10.2 ± 12.8 μmol L^{-1}; values ranged from Av. 7.9 ± 9.9 μmol L^{-1} at Station II to Av. 13.6 ± 19.8 μmol L^{-1} at Station VII. Comparatively high NO_3-N was observed during monsoon period (Av. 19.1 ± 19.4 μmol L^{-1}) due to high allochthonous nutrient input, relatively low NO_3-N content observed in post monsoon (Av. 7.4 ± 3.6 μmol L^{-1}) and pre monsoon (Av. 3.8 ± 3.3 μmol L^{-1}) seasons. The

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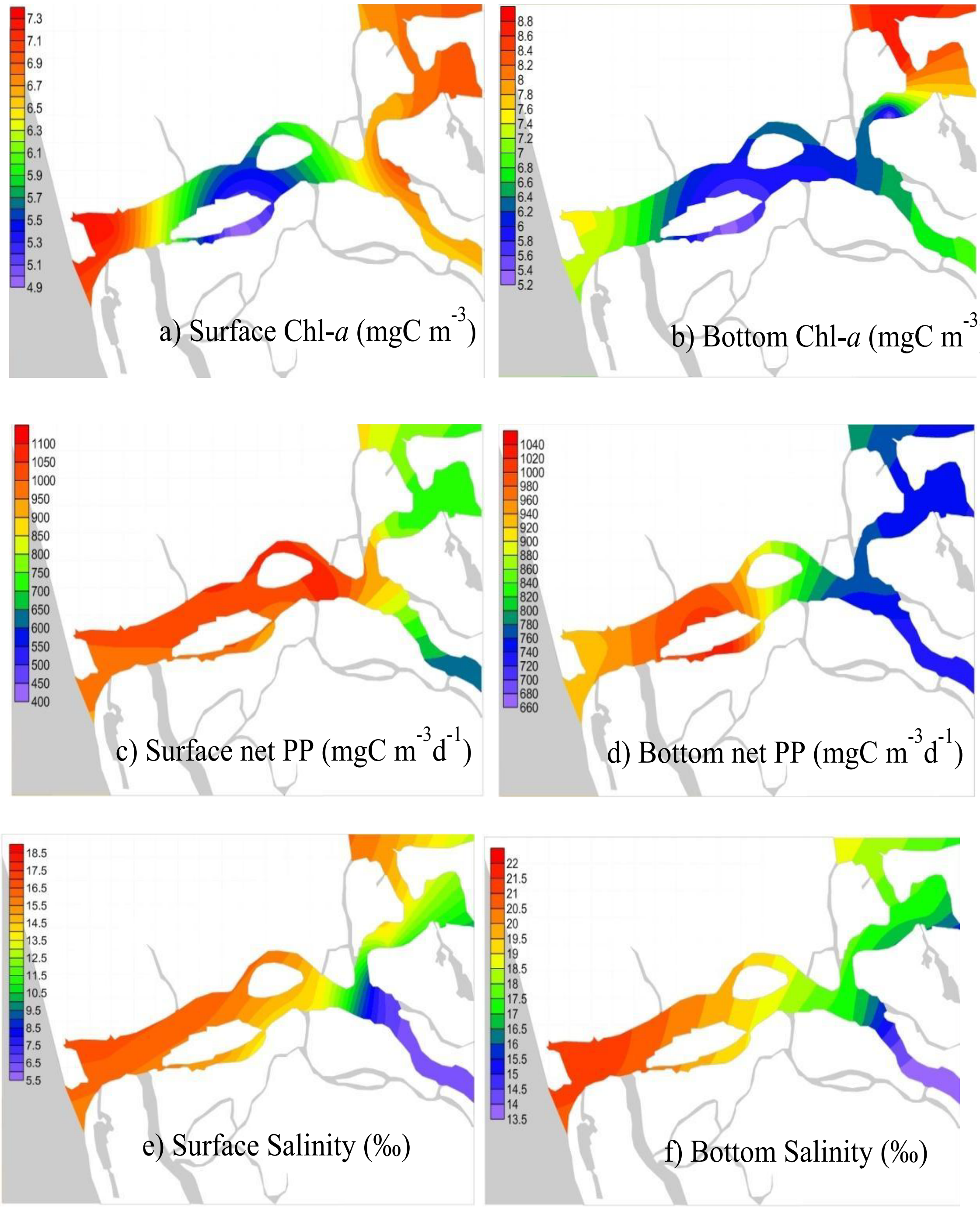

Figure 2: Mean spatial variation of surface and bottom Chlorophyll-*a* (mg m^{-3}), Net Primary. Productivity (mgC m^{-3}d^{-1}), Salinity (‰) in the Kodungallur-Azhikode estuary during 2009-2010.

average nitrite-nitrogen (NO_2-N) content of KAE waters was 0.3 ± 0.2 µmol L^{-1} and highest value was recorded during pre-monsoon period (0.4 ± 0.3 µmol L^{-1}). The mean ammonium-nitrogen (NH_4+-N) varied from 3 ± 2.8 µmol L^{-1} at Station VII to 5.6 ± 5.5 µmol L^{-1} at Station III. Ammonium-nitrogen value shows monthly average of 4.5 ± 2.9 µmol L^{-1} in the KAE. Dissolved inorganic nitrogen content (DIN) in water column showed an average of 15 ± 12.1µmol L^{-1} with highest peak observed during south west monsoon period (24.2 ± 17.7 µmol L-1; Figures 3a,b and 4f). DIP values gave an average of 1 ± 1.3 µmol L^{-1} in the seven stations (Figures 3c,d) with highest during the pre-monsoon (Figure 4e) season (Av. 2 ± 2.1 µmol L^{-1}). Comparatively high content of PO_4-P was observed in bottom waters (Av. 1.3 ± 1.7 µmol L^{-1}), when compared to surface waters (Av. 0.8 ± 0.8 µmol L^{-1}). DISi values displayed wide variations during the study period with average of 49.1 ± 28.7 µmol L^{-1} (Figure 3e and f). Considering the seasonal average (Table 2), slightly high DISi value was observed during post monsoon

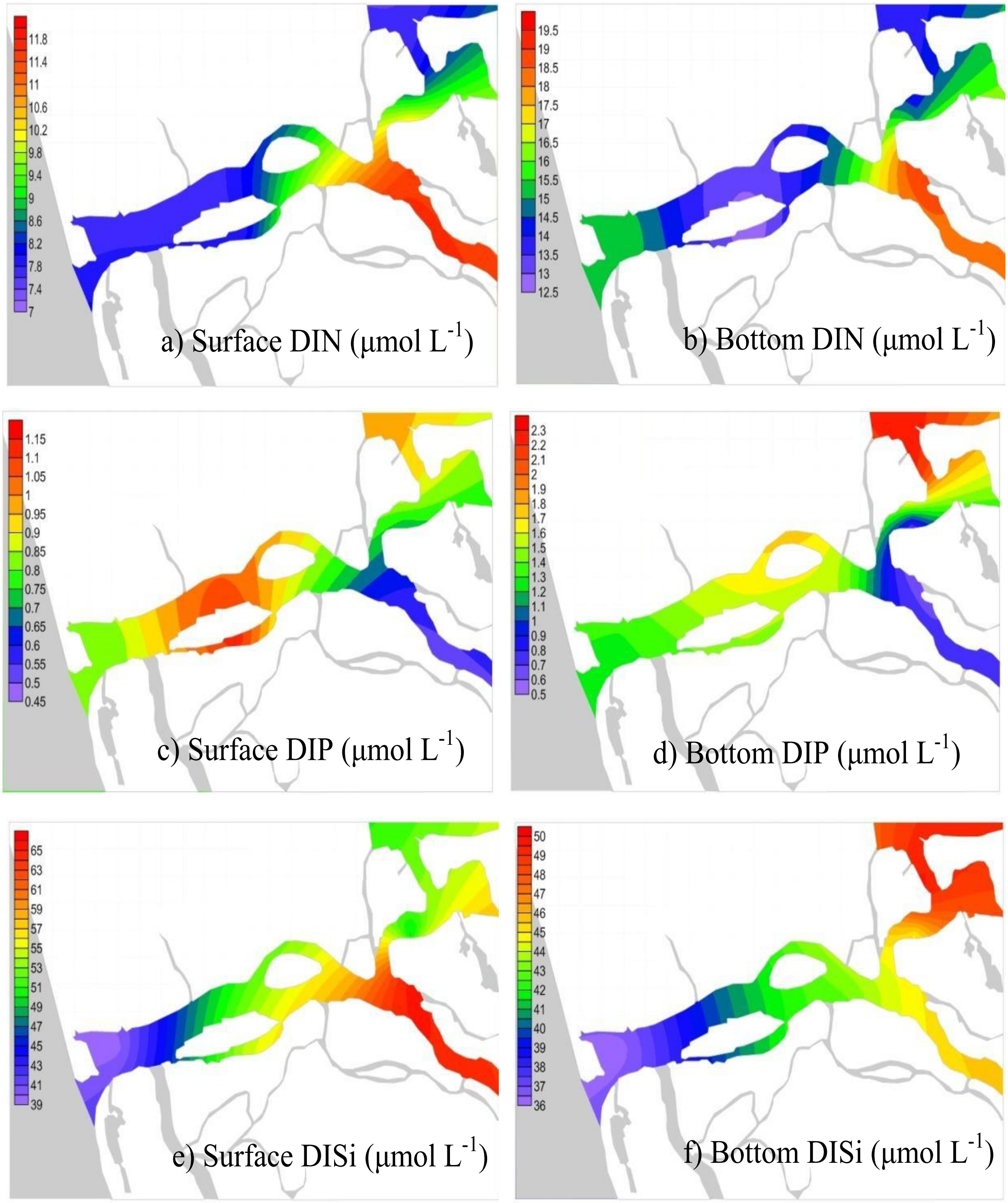

Figure 3: Mean spatial variation of surface and bottom Dissolved Inorganic Nitrogen (μmol L^{-1}), Dissolved Inorganic Phosphate (μmol L^{-1}), and Dissolved Inorganic Silicate (μmol L^{-1}) in theKodungallur-Azhikode estuary during 2009-2010.

period (56.4 ± 21.9 μmol L^{-1}) as compared to monsoon (52.7 ± 44.3 μmol L^{-1}; Figure 4f). The ANOVA showed significant seasonal variation in the dissolved inorganic nitrate-nitrogen (F=50.537, P<0.01), nitrite-nitrogen (F=9.357, P<0.01), ammonium-nitrogen (F=50.537, P<0.01), DISi (F=38.965, P<0.01) and DIP (F= 10.897, P<0.01) content in water column.

Chlorophyll-a

The average Chl-*a* for the seven stations of KAE was 6.42 ± 3.91 mg m^{-3}, however it varied from 5.07 ± 4.03 mg m^{-3} in Station II to 7.80 ± 6.07 mg m^{-3} in Station V (Figure 2a and b). Peak value of Chl-*a* were observed during pre-monsoon period (Av. 10.89 ± 3.29 mg m^{-3}) then it decreased to an average of 5.16 ± 2.10 mg m^{-3} during the monsoon season (Figure 4c). Slight variations was observed in vertical distribution of chl-*a* content in the KAE; high Chl-*a* content was noticed in the surface water (11.04 ± 3.07 mg m^{-3}) as compared to bottom (9.04

Parameters	Monsoon	Post monsoon	Pre monsoon
NO_2-N(µmol L^{-1})	0.3 ± 0.2	0.2 ± 0	0.4 ± 0.3
NO_3-N(µmol L^{-1})	19.1 ± 19.4	7.4 ± 3.6	3.8 ± 3.3
NH_4+(µmol L^{-1})	4.9 ± 3.6	3.0 ± 2	6.6 ± 2.4
N:P	27.9 ± 14.2	7.4 ± 3.4	4.2 ± 3.6
Si:N	3.1 ± 3.1	26.5 ± 9.6	11.4 ± 8.3
Si:P	83.2 ± 96.2	5.3 ± 1.7	4.5 ± 2.5

Table 2: Seasonal variability of DIN and the nutrient ratios in the Kodungallur-Azhikode estuary during 2009 – 2010.

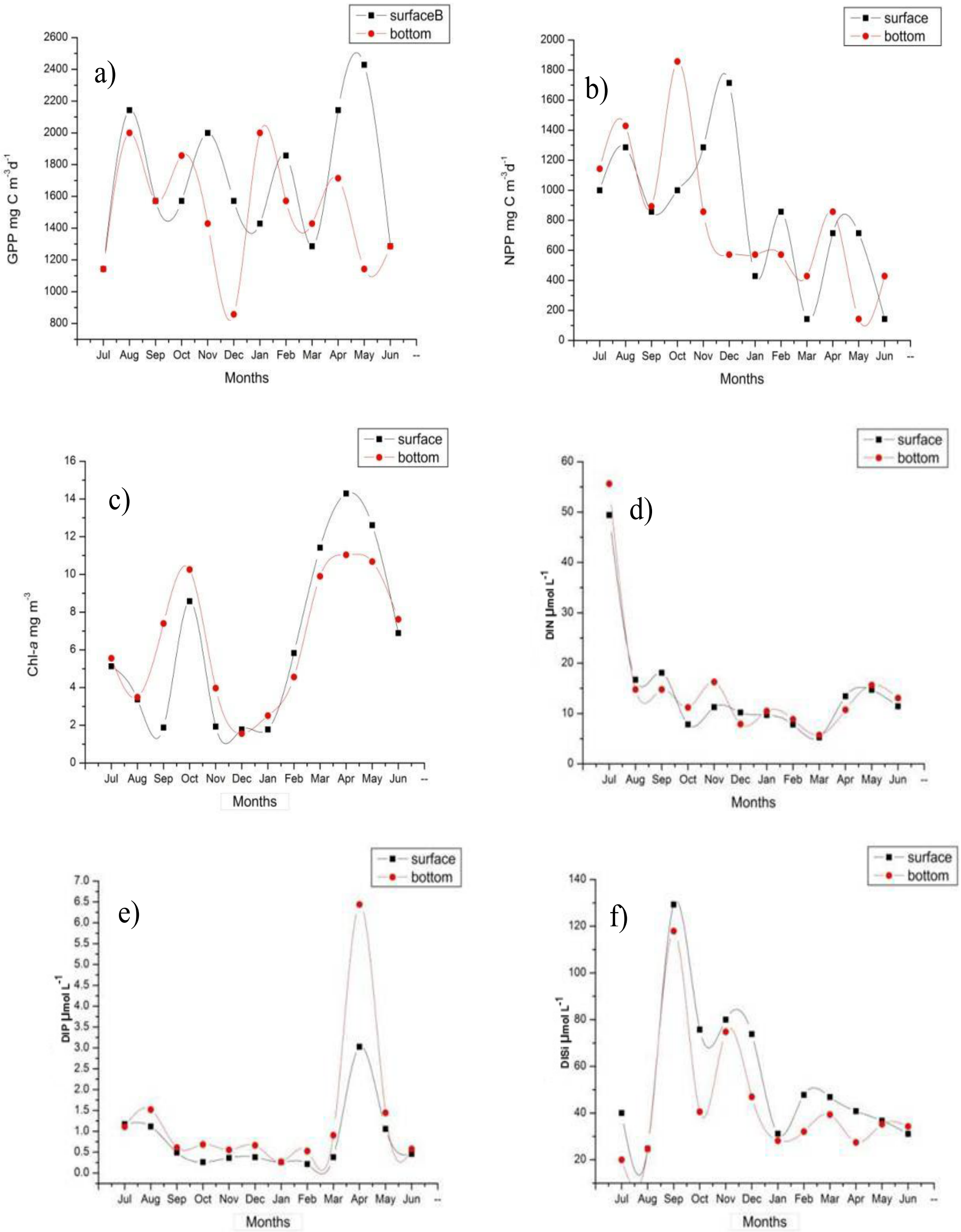

Figure 4: Distribution of gross PP (GPP), net PP, Chl-*a*, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorous (DIP), dissolved inorganic silicate (DISi) in the Kodungallur- Azhikode estuary during 2009-2010.

± 3.03mg m^{-3}) particularly during pre-monsoon period. Peak value of Chl-*a* was noticed during the month of April (Av. 11.65 ± 6.06 mg m^{-3}). An average of 0.04 ± 0.02 mg m^{-3}algal biomass and phytoplankton carbon of 5.2 ± 2.6 mgC m^{-3} was observed in KAE waters. The algal biomass as well as the phytoplankton carbon also showed a similar trend as that of the Chl-*a* in the KAE. The ANOVA of Chl-*a* showed that variation between months were significant at 1% level (F=14.295, *P*<0.01). Bray-Curtis similarity index of Chl-*a* value showed 90.6 % similarity between Station I and III in the surface water. The month wise highest similarity (91.6%) of Chl-*a* content in the surface waters was observed between months of post monsoon season (November 2009 and January 2010); whereas, bottom water displayed highest of 90.8% similarity between pre monsoon months (March 2010 and April 2010). Primary Productivity The gross PP showed an average of 1580 ± 388 mg C $m^{-3}d^{-1}$ in the estuary, whereas the net PP was 790 ± 472 mg C $m^{-3}d^{-1}$ during the study period. Highest gross PP was observed during pre-monsoon (Av. 1785 ± 434 mg C $m^{-3}d^{-1}$) followed by post monsoon (Av. 1589 ± 377 mg C $m^{-3}d^{-1}$) and monsoon (Av. 1517 ± 381 mg C $m^{-3}d^{-1}$) respectively (Figure 4a). A distinct variation in gross PP was observed in the water column, that was high in the surface waters (Av. 1702 ± 406 mg C m^{-3}d-1) when compared to bottom waters (Av. 1500 ± 357 mg C $m^{-3}d^{-1}$), whereas comparatively less variation was noticed during monsoon period due to well mixing of the water column. Generally, increased gross PP was noticed in the stations nearby estuarine mouth (Station I; Av.1625 ± 0.824 mg C $m^{-3}d^{-1}$, Station II; Av. 1750 ± 0.989 mg C $m^{-3}d^{-1}$and Station III, Av. 1750 ± 737 mg C $m^{-3}d^{-1}$). Highest net PP was observed during post monsoon (Av. 1035 ± 538 mg C $m^{-3}d^{-1}$) followed by monsoon (Av. 828 ± 473 mgC $m^{-3}d^{-1}$) and pre monsoon (Av. 585 ± 290 mgC $m^{-3}d^{-1}$) respectively (Figure 4b). Net PP was high in the surface waters (Av. 845 ± 465 mg C $m^{-3}d^{-1)}$ when compared to bottom waters (Av. 766 ± 495 mgC $m^{-3}d^{-1}$; Figure 2c and d). While, comparatively less variation was noticed during monsoon period due to well mixing of water column. Relatively high net PP values were observed in Station III (Av. 921 ± 875 mgC $m^{-3}d^{-1}$); however, Station VI showed comparatively low net PP values (Av. 588 ± 720 mgC $m^{-3}d^{-1}$).The ANOVA showed that monthly variations in gross PP was significant (F=1.581, *P*<0.05). Bray-Curtis similarity index of gross PP showed 91.8 % similarity between Stations IIand III in the surface water, whereas, bottom water showed 96.3% similarity between Station IV and VI. The month wise highest similarity of surface was 94.7% between July and January (2010). Bottom water showed highest similarity of 91.5 between April (2010) and July (2009).The ANOVA of net PP showed that variations between months were significant at 1% level (F=4.117, *P*<0.01). Bray-Curtis similarity index of net PP showed 90.1 % similarity between Stations I and VII in the surface water; however, bottom water showed 83.8% similarity between Stations I and II. Month wise Bray-Curtis similarity showed cent percent similarity between March (2010) and June (2010) in the surface water. Similarly, bottom water showed highest similarity (89.7 %) between February and April (2010).

Discussion

Primary production is the rate at which organic matter is synthesized from raw materials (carbondioxide, water, inorganic nutrients and light energy), and forms the base of the food web in most environments. In aquatic ecosystems, excessive primary production leads to eutrophication and taking the form of algal blooms has a host of undesirable effects, including bottom-water anoxia, loss of fish species and large-scale production of algal toxins [23,34]. Phytoplankton biomass and productivity in the aquatic environment are primarily regulated by abiotic and biotic interactions [35]. Among abiotic interactions, the freshwater flow and tidal activity play a crucial role in phytoplankton growth and abundance in an estuary. Estuarine circulation is important as it controls water residence and phytoplankton turnover time. In KAE, rainfall is seasonal and therefore definite seasonal patterns of estuarine phytoplankton production were noticed during the study. In some estuaries, rates of physical removal may dominate over rates of *in situ* production [36]. Water column stability in KAE during summer season promoted phytoplankton production by inhibiting vertical mixing and increased river flow is the reason for noticed reduction in their concentration by increasing dilution rate during monsoon. Water residence time is also important in terms of nutrient utilization. If retention time is short, then there is insufficient time for the phytoplankton nutrient uptake. Stable tidal conditions and nutrient allows the phytoplankton to bloom as the water was present for longer than the doubling time requirements to produce the bloom. Water residence times will depend on freshwater flow as well as tidal activity and the condition of the estuarine mouth [24]. One of the most obvious factors influencing primary productivity (PP) is the amount of solar energy reaching the surface of water body [13,17]. In the present study, Chl-*a* displayed a negative correlation with turbidity (r^2=-0.212, *P*<0.01, *N*=168) and TDS (r^2=-0.266, *P*<0.01, *N*=168) in the water column. Temperature also is an important factor controlling metabolic rates of phytoplankton population. Many attempts have been made by [37] to relate turbidity and rate of photosynthesis of phytoplankton populations. Depth of light penetration depends on the concentration of suspended particulate matter, both living and non-living. Generally, the concentrations of suspended particles in estuarine water are high and light is rapidly attenuated. River inflow affects estuarine turbidity either by bringing in suspended particulates or dissolved humics, or by modifying turbulence and thus altering the extent to which particulates are maintained in suspension mainly during monsoon season. Average transparency was lowest in all the stations during monsoon (Av: 0.6 ± 0.3m) synchronizing with high turbidity and river discharge, whereas, transparency was comparatively high during the post monsoon (Av. 1.3 ± 0.2 m) and pre monsoon (Av. 1.1 ± 0.2 m) periods. The heavy river discharge with allochthonous material flux, fishing boat movements, fish processing waste discharge, intense sand mining and clam mining activities could be the reason for comparatively high turbidity in the KAE. The most important elements for phytoplankton growth are the macronutrients such as nitrogen (N) and phosphorous (P) and that for diatoms, silica (Si). Generally phytoplankton cells uptake dissolved forms of C, N and P across their cell surfaces in an atomic ratio of106C:16N:1P. Sometimes the ratios of dissolved nutrients in the water column are different to those required for phytoplankton growth. This provides an indication of nutrient limited phytoplankton growth in the water column. N:P ratios that are much higher than16 imply that P limitation of algal growth is taking place, which means that the lack of P is preventing phytoplankton production. Alternatively, a ratio of less than 10 would imply N-limited growth of phytoplankton. However, under nutrient-depleted conditions, nano phytoplankton, small dinoflagellates and monads became dominated [38]. Previous studies indicated that PP strongly correlated with surface nitrate concentrations and negatively correlated with salinity [9]; besides, increased river flow associated with increased nitrate-nitrogen content and decreased salinity. The main cause of eutrophication in estuary is the input of phosphorus and nitrogen, which tend to be the limiting nutrients in that demand for them by phytoplankton often exceeds supply. Nutrient availability appears to be the major freshwater related factor controlling phytoplankton biomass, increased nutrient availability leading to increased biomass [39]. Increased nutrient availability in the KAE could be due to a number of processes, namely increased nutrient loading in the river water input, increased autochthonous nutrient regeneration, or increased river flow during monsoon period such as benthic regenerated nutrients are mixed into the water surface. Agricultural and aquaculture out flow into the KAE has increased the input rate of nutrients. Dissolved Inorganic Nitrogen (DIN) in the water column seems to be decreased during pre-monsoon. This could be due to comparatively less allochthonous nutrient input, decreased autothonous nutrient regeneration and continuous phytoplankton uptake. PP in the estuary was nitrogen limited during pre-monsoon period (4.2 ± 3.6); whereas, the average N: P ratio in the estuary was well above Redfield ratio during south west monsoon season (27.9 ± 14.2). Nitrogen addition frequently increases phytoplankton growth where total N: P is expected to be low, but P, Fe or Si augment phytoplankton growth in waters where total N: P is high. The inorganic nitrate-nitrogen contributed significant amount to total DIN (Av. 58%) content in the water column of KAE. Chl-*a* also showed negative correlation with NO_3-N (r^2=-0.297, P<0.01, N=168) in the water column. High rate of NO_3-N uptake for phytoplankton production has been observed as factors that decrease the nitrate content of water column during pre-monsoon period. Silicate-silicon is the second most abundant element of the lithosphere; it is a major product of weathering, making up a large portion of river loads, a key nutrient affecting food webs especially for diatom growth and elemental cycles of coastal ocean, and it comes almost exclusively from natural sources [40]. Slightly high DISi values with aid of high salinity in the KAE waters could be favourable for diatom growth. Primary production is a fundamental ecological indicator (variable), because it is a measure of the extent to which primary energy input (solar energy) to the aquatic environment is transformed into the biological/ecological sphere. It is defined as the flux of inorganic carbon into planktonic algae per unit time [21]. It has significant capability to indicate and characterize the status of a particular water body and is a widely used method when assessing eutrophication effects in coastal waters. According to Qasim [19], salinity has apparently no influence on primary productivity. KAE waters displayed a positive correlation between Chl-*a* and salinity (r^2=0.179, P<0.01), which could be due to dominance of marine phytoplankton species. Average Chl-*a* content in the KAE was high, compared to inshore waters of Indian coast. Chl-*a* displayed higher values than that of coastal waters of Cochin (Av. 5.3 ± 1.8 mg m^{-3}; Madhu et al. [41] and Arabian Sea (Av. 0.95-0.8 mg m^{-3}; [42]. The linear correlation between salinity (r^2=0.179), pH (r^2=0.195), Eh (r^2=0.188) was found to be significant with Chl-*a* at 1% level; whereas, Chl-*a* showed 5% significant correlation with water temperature (r^2=0.314) and CO_2 (r^2=0.283). The average gross primary productivity (gross PP) in the KAE was higher (1580 ± 388 mg C $m^{-3}d^{-1}$) than that presented in the reports from the same estuary (865 ± 134 mg C $m^{-3}d^{-1}$) by Anon. Similarly the net primary productivity (net PP) also increased from 525 ± 700 mg C $m^{-3}d^{-1}$ to 790 ± 472 mg C $m^{-3}d^{-1}$, possibly due to high nutrient enrichment in the estuary from various anthropogenic sources. From the multiple regression analysis of Chl-*a* and net PP, *p*-value of the F-test the overall model was statistically significant (P<0.01). The r^2 of Chl-*a* was 0.501, indicated that approximately 50.1 % of the variability was accounted for the variables in the model; similarly, the r^2 of net PP was 0.472. Nair et al. [43] reported an annual average rate of gross production ranging from 150 to 650 g C m^{-2} at different regions and a total annual gross PP of 10^{11} g C for the entire Vembanad Lake. In the present study, annual average gross PP in the KAE was 584 ± 141 g cm^{-3}; whereas, maximum net PP was noticed during pre-monsoon period (1035 ± 538 g C m^{-3}). This moderately high primary production generate huge amount of autochthonous organic matter which lead to extreme adverse conditions. Nair et al. [43] assessed the magnitude of primary, secondary and tertiary production in the Vembanad Lake from Alappuzha to Azhikode. They estimated Chl-*a* of the Cochin Backwaters with an overall range of 1.5 -18 mg m^{-3}. The findings of Joseph and Nair [44] indicate that maximum Chl-*a* concentration for pelagic flora occurs during monsoon. In this study two peak of Chl-*a* values were observed, a minor peak during fall of summer monsoon and a much considerable peak during pre-monsoon period. Chl-*a* content of KAE was moderately less when compared to Cochin backwater (Av. 13.7 ± 8 mg m^{-3}; and this could be due to less water residence time and high turbidity level in the KAE [41]. With respect to Smith et al. [45] classification of aquatic ecosystems; the KAE lies in the oligotrophic to hypertrophic range. When applying trophic index TRIX [33] to KAE, annual average TRIX unit exceeding six (6.91); it ranges from 6.93 (Station VI) to 7.37 (Station V) TRIX point values assign an immediate measurement to the trophic level of coastal waters. Referring to the various coastal waters, values exceeding 6 TRIX units are typical of highly productive coastal waters that show the effects of eutrophication [33]. Changes in delivery of river-borne nutrients such as dissolved phosphate, nitrate and silicate, owing to land-use changes and anthropogenic emissions, are known to result in eutrophication and controlling these nutrients in water column is a primary objective of most environmental policy. Increased loading of nutrients has supported consistently high primary production [25] and it may result in occurrence of harmful algal blooms [46]. However, nutrient loading and its residence time were important in controlling productivity and can be considered as useful indicators of trophic conditions within the ecosystem. Nutrient enrichment and water column stability could have resulted in a peak primary production during pre-monsoon season. Primary producers have a significant role in estuaries that form food for different trophic levels of organisms. On the other hand excessive carbon supply could have resulted in ecosystem stress. Therefore, quantity and quality of primary production and hydrography will be an important factor that controls the biotic potential of KAE.

Conclusion

Spatio-temporal variations in water quality play a crucial role on phytoplankton carbon fixation and trophic status of KAE. Annual nutrient and carbon supply in the KAE increased due to a range of impacts such as catchment degradation caused by intensive sand mining, aquaculture, pollution, fish processing wastes discharge, artificial breaching, urban encroachment and harbour development. Trophic index TRIX analysis in the KAE also showed that values are typical of highly productive coastal waters, where the effect of eutrophication is apparent. Implementation of effective management policies with the aid of public participation have been required to mitigate the effect of eutrophication in coastal environment. A growing body of recent research has also suggested that conservation of biodiversity might be a useful management tool for reducing the concentrations of nutrients in aquatic environment. Even though the Kodungallur-Azhikode estuary is part of the greater Ramsar site, the Vembanad wetland ecosystem, the problem of eutrophication is increasing due to various human interferences. It is over a decade that, the International Ramsar Convention has designated Vembanad and associated estuaries on the South West coast of the State for its wise use and long term conservation measures; however, follow up action has not been taken by the Government to ameliorate various ecological issues faced by these systems. So it is high time that such studies are brought to the notice of the policy makers to curb the menace of pollution and various other forms of impacts in the coastal systems of India.

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