Phytoplankton community structure of the Gangetic (Hooghly-Matla) estuary: Status and ecological implications in relation to eco-climatic variability

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Review

Phytoplankton community structure of the Gangetic (Hooghly-Matla) estuary: Status and ecological implications in relation to eco-climatic variability

C.M. Roshith*, D.K. Meena*, R.K. Manna, A.K. Sahoo, H.S. Swain, R.K. Raman, A. Sengupta, B.K. Das

Central Inland Fisheries Research Institute, Barrackpore, West Bengal, 700120, India

A R T I C L E   I N F O

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A B S T R A C T

This study consolidated our understanding on community structure of phytoplankton of the Gangetic estuary (Hooghly-Matla) based on both bibliographic sources and field studies. A total of 378 species of phytoplankton taxa belonging to 196 genera and 109 families were reported from the Hooghly-Matla estuarine system which is among the major biodiversity hotspots of the world and plays a pivotal role as nursery ground for fish and shell species. Being an estuarine system its working as a sink for abatement of the pollutants and plays an important role in mitigating flood and other catastrophic changes mediated due to climatic invariability. About 97% of these phytoplankton taxa (365 species) are distributed across four major groups; the diatoms constitute 52% of the phytoplankton diversity with 195 species, followed by the green algae (82 species), blue-green algae (59 species) and dinoflagellates (29 species). Moreover, there are four minor groups that constitute the remaining 3% of phytoplankton taxa with 13 species. Our survey on the phytoplankton communities of the tidal freshwater zone recorded 91 species of phytoplankton, with dominance of green algae (41 species) followed by diatoms (34 species). Our own studies also revealed ecological indicator groups, with diatoms being dominant in open estuarine waters, whereas the estuarine wetlands were mainly inhabited by blue-green algae. A literature review revealed indicator plankton species for issues of global climate change and sea level rise in India and its neighbouring countries. Due to immense ecological variability, a shift in phytoplankton community structure was revealed in available literature. This article illustrates status of phytoplankton communities and their population dynamics along the entire estuarine system, providing a sound base for assessing impact studies and solving transboundary issues between India and adjoining countries.

1. Introduction

Phytoplankton populations indicate the biological wealth of a water body, constituting a vital link in the food chain (Boyd, 1973). They represent a wide assemblage of photo-autotrophic microorganisms which are essential components for maintaining the ecosystem balance and integrity of any aquatic systems as primary producers. About 90% of the total production in marine ecosystem is contributed by the phytoplankters that support commercial fisheries (Kartik et al., 2012). Besides their role as primary producers, phytoplankters are also good indicators of trophic status (Manna et al., 2010) and environmental stresses. Phytoplankton contributes to more than 40% of the global carbon fixed (Reynolds, 1984). Estuaries are the cradle grounds for phytoplankton because they receive constant supply of nutrients from rivers and other land based discharges (Ketchum, 1967).

In India, the various estuarine systems spreading over 300,000 ha form an important component of the inland capture fisheries resources (Sugunan and Sinha, 2001). Among the Indian estuaries, Hooghly is unique in being the largest, and as the mainstay of inland capture fisheries production of the country. This estuary, along with the Matla estuarine system on its east, forms one of the largest estuarine systems of the world. The Hooghly-Matla estuarine complex is unique due to presence of extensive mangrove forests in the Sundarbans, and other types of habitats such as the extensive tidal freshwater marshes in the upper reaches of Hooghly, inter-tidal mudflats, brackish water wetlands (locally known as 'bheries' and covers an area about 33000 ha) and vast expanses of shallow estuarine coastal waters off the lowest land fringe of the Hooghly estuary.

Phytoplankton communities of Hooghly-Matla system have been studied since 1940s, thereby providing a wealth of information

* Corresponding authors.
E-mail addresses: Rosith.M@icar.gov.in (C.M. Roshith), dkmeena@icar.gov.in (D.K. Meena).

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regarding diversity, community composition and seasonal dynamics. The tidal freshwater stretch has been completely neglected in these studies, despite being the major part of the Hooghly estuary (covering about 75% of the estuarine length),owing to the altered hydro-ecological conditions of freshwater influx from the Farakka barrage (commissioned in 1975). Moreover, the lower deltaic zone, *i.e*, the Sundarbans is highly dynamic and vulnerable to anthropogenic pressures coupled with the climate change related threat of sea level rise (SLR) that has changed the structure of biotic communities including phytoplankton. The Hoogly-Matla system is an important biodiversity hotspot. This article is an attempt to consolidate our understanding on the phytoplankton communities of Hooghly-Matla summarizing the information gathered from past 65 years of research and available literature. Thus, this database will provide the base line information on phytoplankton communities of Hooghly-Matla which will give a foundation for future cutting edge studies such as correlation between climate change and biotic communities status, habitat survey, establishing the different diversity indices by integrating all biotic and abiotic components of the estuarine system so that management plans may be formulated for sustainable management of the system. It will also be helpful in fortifying the existing knowledge on phytoplankton communities of Hooghly-Matla to academicians and researcher for further exploration.

2. Methodology

2.1. Study area

The Hooghly-Matla estuary (300 km North to South extent and 150 km East to West) forms the major part of the Gangetic delta (Sinha et al., 1996) and is associated with the extensive and largest single chunk of mangrove forest in the world, the Sundarbans. This massive estuarine system is a complex network of interconnecting channels, canals and creeks which are being associated with seven principal estuaries, *viz*., Hooghly, Saptamukhi, Thakuran, Matla, Harinbhanga, Raimangal and Bidya (Fig. 1) Of these, the Hooghly and Raimangal estuaries form the western and eastern boundaries of Indian Sundarbans respectively.

Hooghly estuary refers to that part of the Bhagirathi River (lower stretch of the Ganges in India) which is subjected to tidal action and covers about 14.1% of the total length of the river Ganges in India. The tidal influence extends up to Nabadwip; while the tributaries such as Damodar, Rupnarayan and Haldi join Hooghly in its lower course. The estuary bifurcates before its confluence with the Bay of Bengal, at Sagar Island into the Hooghly main channel and Muriganga estuary which is connected to the Saptamukhi through the Hatania-Duania channel (Fig. 1). Being the largest estuary with continuous freshwater influx (from the Ganges), Hooghly estuary can be devided into three distinct zones such as the tidal freshwater zone (subjected to tidal fluctuations without the influence of salinity), the gradient zone (true estuarine zone) and the marine zone (high saline zone with greater marine influence).

The huge spatial extent with a wide range of habitats (mangroves, intertidal mudflats, tidal freshwater marshes, estuarine wetlands, etc.) remained the major constrain that limited previous researchers in carrying out comprehensive studies on phytoplankton communities of the Hooghly-Matla estuarine system. Most of the rivers in the Matla system (except Raimangal) lost their permanent river connection and thereafter transformed into tidal creeks. Saptamukhi receives freshwater from the Hooghly through Hatania-Duania canal. The Raimangal is an off shoots of the river Padma (lower stretch of the Ganges in Bangladesh), and forms the international boundary between India and Bangladesh.

The entire estuarine system is under tidal influence with strong, variable, semidiurnal tides of meso-macrotidal amplitude (about 5–7 m) during summer (pre-monsoon) and relatively weaker tides in winter. The region experiences tropical climate with reversal of winds during summer (South-West) and winter (North-East) monsoons. The yearly weather conditions of the region can be categorized into three distinct seasons, viz., the summer (February–May) characterised by little or no rainfall and prevalence of high temperatures, the monsoon (June to September) with heavy precipitation and relatively lower temperatures compared to summer and the winter (October–January) season when there is occasional rainfall and prevalence of lower temperatures. The wind pattern is more or less similar to the general wind pattern of the Indian sub continent. Prevailing winds are from the north and north-east during October to mid-March, although calm weather prevails in January–February. The lower part of the estuarine system (the Sundarbans) frequently experiences rough weather conditions, especially during summer; characterized by violent thunderstorms (called as ‘norwesters’ or ‘kalbaishakhi’) or even more devastating cyclones.

2.2. Data sources and analysis

The present work is based on bibliographic sources related to phytoplankton population of the Hooghly-Matla estuarine system. The literature was searched by referring to the library of ICAR-CIFRI, Kolkata, India, and online available research in similar area by various authors. The earliest source dates back to Datta et al. (1954), the first comprehensive study on the phytoplankton of Hooghly estuary. Thus, it is evident that these biotic communities have been studied by researchers over a time scale of more than 65 years and there has been no lack of information. One of the major constraints in compilation of species checklist from previous studies is the taxonomic impediment resulting from adoption of varied classification schemes and discrepancies in the categorization of phytoplankton groups. Recently, phytoplankton systematics have undergone numerous changes that include the transfer as well as renaming of various taxa to other existing, or new genera, with even broader taxonomic modifications proposed for some taxa. For compilation of the phytoplankton species checklist we adhered to the classification system and updated scientific names as per AlgaeBase (Guiry and Guiry, 2014), the internationally accepted database on algae hosted by National University of Ireland.

A major deficit observed in phytoplankton studies of the Hooghly-Matla system is that most of the taxa are defined only upto genus level. This can lead to misinterpretation of data in highly speciose genera (*Nitzschia*, *Chaetoceros*, *Rhizosolenia*, *Oscillatoria*, *Closterium*, etc.) containing large numbers of species with varied habitat preferences (freshwater, brackish, marine or euryhaline). In order to solve this problem, only those fully defined species were considered for taxa where information regarding species is available. However, those taxa without a species identification had been listed in the check list (Appendix A in Supplementary material) up to genus level, and were considered as a single species. For assigning habitat preferences, we adhered to Pham et al. (2011) and AlgaeBase (Guiry and Guiry, 2014).

Although numerous bibliographic sources have been available for the estuarine (gradient) and marine zone of Hooghly estuary, no comprehensive studies on phytoplankton communities have been carried along the tidal freshwater zone, which covers about 3/4th of estuarine length due to greater influx of freshwater from the Ganges since the establishment of the Farakka barrage. The authors carried out intensive studies (2010–2012) on the phytoplankton population of the tidal freshwater zone of Hooghly estuary along the 168.9 km long stretch from Nabadwip to Godakhali (S1–S7), visiting seven sampling stations (Fig. 1) at different time periods in a year corresponding to three seasons, viz., pre-monsoon/summer (March-June), monsoon (July-October) and post-monsoon/winter (November-February). At each sampling station, the phytoplankton samples were collected by filtering 100 L of water through a tow phytoplankton net made of bolting silk No. 20 and preserved in neutralized formalin (4% final concentration). Counting of phytoplankton was performed using a Sedgwick-Rafter

Fig. 1. Google earth image of lower stretch of Hooghly along with the Matla estuarine system.

counting cell, and a Zeiss research microscope to determine the number of cells per litre of sample. Taxonomic identification was carried out with the help of standard references, viz., Prescott (1954), Desikachary (1959) and Santra et al. (1988). The identified taxa were classified and assigned to updated scientific names as per AlgaeBase (Guiry and Guiry, 2014).

Phytoplankton communities are sensitive to changes in their environment; therefore, many phytoplankton species as well as the phytoplankton biomass are used as indicators of water quality. In our study, Canonical Correspondence Analysis (CCA) was performed using the Canoco 4.5 program to establish a correlation between phytoplankton groups and physicochemical parameters of tidal freshwater zone of Hooghly estuary (Fig. 5).

3. Results and discussions

3.1. Phytoplankton diversity

The massive expanse of open estuarine waters and their associated brackish water wetlands provide ideal habitats for diverse groups of phytoplankton (Fig. 2). Even though the phytoplankton communities along the Gangetic delta have been a subject of intensive scientific studies, the majority of them mainly deal with the lower most part of the delta, *i.e.*, the Sundarbans. The first comprehensive work on the plankton communities of the Hooghly estuary was conducted by Datta et al. (1954), and addressed the diversity and seasonal dynamics of plankton communities of the Hooghly estuary in a 100 km stretch from Palta to Diamond Harbour from 1949 to 1951. The study listed 105 phytoplankton species which comprised 72 species of diatoms 18 species of green algae (Chlorophyceae), 9 species of blue-green algae (Cyanophyceae), 3 species of dinoflagellates (Dinophyceae) and 3 euglenoid species. Phytoplankton ecology of river Hooghly at Palta, West Bengal was studied by Roy (1955). Shetty et al. (1961) presented a detailed study of the plankton population of the Hooghly-Matla estuarine system (1956–1958) covering the entire stretch of Hooghly from Nabadwip to estuarine mouth, the Rupnarain and the Matla regions, and provided a detailed account of the distribution of plankton species in different zones. They list 106 phytoplankton species during the study period comprising of 50 species of diatoms, 30 species of green algae, 18 species of blue-green algae and 8 taxa belonging to flagellates. These works are supplemented by Gopalakrishnan (1971) in his studies on the biology of the Hooghly-Matla estuarine system which list 57 phytoplankton taxa (Table 1). Later, Sinha et al. (1996) highlight the shift in plankton community distribution in Hooghly estuary due to altered ecological conditions owing to the freshwater release from Farakka Barrage.

All the later studies (Dey et al., 1991, 1994; Santra et al., 1991; Banerjee and Santra, 2001; Mukhopadhyay and Pal, 2002; Sarkar and Naskar, 2002; Biswas et al., 2004, 2009; Choudhury and Pal, 2008, 2010, 2012; Manna et al., 2010; Akhand et al., 2012) either rely on the phytoplankton dynamics in relation to environmental variables or deal with the phytoplankton species encountered in the lower most part of Hooghly system, especially the Sundarbans. The most updated assessment on the algal biodiversity of Sundarbans is carried out by Sarkar (2011), based on previous literature and field observations; which listed 166 species of phytoplankton from the estuarine system and their associated brackish water wetlands. Almost all the above mentioned studies dealt with those phytoplankton taxa belonging to four major groups such as diatoms, dinoflagellates, green algae and cyanobacteria while groups such as Chrysophyceae and others were almost excluded in these studies despite their ecological significance as bio-indicators of water quality. The Chrysophyceae and related taxa of Hooghly-Matla estuarine system were exclusively studied by Roy and Jha (2004), where 9 species have been listed from the system of which 7 are planktonic forms. In the recent survey conducted on phytoplankton communities along the tidal freshwater stretch of Hooghly estuary, the

Fig. 2. Google earth image of Hooghly estuarine system with the various sampling locations.

Table 1
Categorization of phytoplankton taxa recorded from Hooghly-Matla system.

Phylum	Class	Numbers recorded			
		Order	Family	Genus	Species
HETEROKONTOPHYTA	Coscinodiscophyceae	14	21	39	108
	Bacillariophyceae	11	21	37	70
	Fragilariophyceae	8	8	15	17
	Xanthophyceae	2	2	2	2
	Chrysophyceae	1	1	1	1
	Synurophyceae	1	1	1	2
	Phaeothamniophyceae	1	1	1	1
DINOPHYTA	Dinophyceae	8	11	12	29
EUGLENOPHYTA	Euglenophyceae	1	2	4	5
HAPTOPHYTA	Coccolithophyceae	1	1	1	1
CRYPTOPHYTA	Cryptophyceae	1	1	1	1
CYANOBACTERIA	Cyanophyceae	5	14	30	59
CHLOROPHYTA	Chlorophyceae	5	15	29	32
	Trebouxiophyceae	2	3	8	11
	Prasinophyceae	1	1	1	1
CHAROPHYTA	Conjugatophyceae	2	4	12	33
	Ulvophyceae	2	2	2	5
Total numbers recorded in each category		66	109	196	378

[The classification scheme adopted in the table is based on AlgaeBase (2014)].

authors recorded 96 species of phytoplankton along a 168.9 km stretch from Nabadwip to Godakhali.

The combined estimate from both bibliographic sources and field studies based on the revised as well as updated algal systematics from AlgaeBase (Guiry and Guiry, 2014) revealed that a total of 378 species of phytoplankton belonging to 196 genera, 109 families and 66 orders have been reported from this estuarine system, including its adjacent wetlands (Appendix A in Supplementary material). The open estuarine waters alone harbour 349 species, whereas 77 phytoplankton species were reported from the estuarine wetlands.

3.2. Community structure

It is a well established fact that the phytoplankton community of estuaries and coastal waters is dominated by diatoms. This holds true for the Hooghly-Matla estuarine complex as well (open estuarine waters and estuarine wetlands), where diatoms make up 51.6% of the total phytoplankton taxa with 195 species, followed by the green algae (82 species), Cyanophyceae (59 species), dinoflagellates (29 species) and other minor groups with 13 defined species (Table 1). The vast areas of open estuarine waters provide ideal habitats for the diatoms and dinoflagellates whose distribution and abundance are greatly determined by the tidal cycle. The phytoplankton communities along estuarine waters were dominated by diatoms which constitute 55.9% of the defined phytoplankton taxa with 195 species, while the remaining 44.1% has been distributed among groups which include green algae (69 species), blue-green algae (43 species), dinoflagellates (29 species) and other minor groups (13 species). The situation was, however, different for estuarine wetlands (bheries) where relatively stagnant water conditions favour the growth of several planktonic, periphytic and epiphytic algal forms dominated by the members of Cyanophyceae and Chlorophyceae (Sarkar, 2011). Phytoplankton communities of the estuarine wetlands comprises cyanobacteria (38 species), green algae (28 species) and diatoms (11 species). Thus, it is evident that the open estuarine waters represented a diatom-dominated phytoplankton assemblage, whereas the estuarine wetlands were inhabited by communities dominated by Cyanophyceae and green algae (Fig. 2). Moreover, 29 species of phytoplankton have been recorded only from estuarine wetlands, which included 16 species of Cyanophyceans and 13 species of green algae (De Clerck et al., 2013; Guiry and Guiry, 2014; site.iugaza.edu.ps/elnabris/files/2015; Ruggiero et al., 2015; Appendix A in Supplementary material).

Following the modern classification scheme in algal taxonomy, the phytoplankton taxa of Hooghly-Matla system can be categorized into 17 classes under eight major phyla (Table 2). The diatoms, which constitute the major component of phytoplankton communities, have been grouped under three different classes − Coscinodiscophyceae, Bacillariophyceae and Fragilariophyceae. Coscinodiscophyceae refer to centric diatoms with the highest diversity among all the phytoplankton classes from this estuary with 108 species. This group contains some of the most speciose genera such as *Chaetoceros* (22 species) and *Coscinodiscus* (10 species), with the former being the dominant phytoplankton genera having the highest number of recorded species. The classes Bacillariophyceae (pennate diatoms with true raphae) and Fragilariophyceae (pennate diatoms without true raphae) are being represented by 70 and 17 species respectively. (Table 2). The pennate diatom *Nitzschia* forms the second largest phytoplankton genus with 14 recorded species. The other speciose genera include the green algae, *Spirogyra* (10 species), followed by the *Ceratium* (a dinoflagellate) with 9 species.

During our studies on phytoplankton diversity and seasonal dynamics along the tidal freshwater zone of Hooghly estuary, a total of 91 species of phytoplankton taxa (Appendix A in Supplementary material) were recorded along a stretch extending from Nabadwip to Godakhali (Fig. 3). Unlike other ecological zones of the Hooghly-Matla system, phytoplankton assemblages of the tidal freshwater zone represented a greater dominance of green algae with 41 species, followed by diatoms (34 species) and cyanophyceans (16 species). Phytoplankton communities along the freshwater tidal zone of Hooghly estuary during pre-Farakka period (Shetty et al., 1961; Gopalakrishnan, 1971) were dominated by diatoms due to ingression of many euryhaline and brackish water species with the tidal flow. The increased discharge of riverine waters from the Farakka barrage since 1975 resulted in alteration of hydro-ecological conditions of Hooghly and increased the available habitat for freshwater phytoplankton species; while many brackish water diatoms either disappeared from the system or shifted their distributional range to more favourable aquatic environments in the lower stretch. However, the increased availability of freshwater habitat allowed many pure freshwater phytoplankton species (green algae, blue-green algae and a few riverine diatoms) to enter the tidal freshwater zone through riverine discharge. This is shown by the high diversity of Chlorophyceae (41 species) of which the majority are purely freshwater forms (25 species) of riverine origin. Among the 91 phytoplankton taxa recorded during our study, 51 species were purely freshwater forms that had been previously reported along riverine stretches of the Ganges-Bhagirathi system by many researchers. Thus, it can be inferred that the majority of the phytoplankton species recorded from this zone have their origin in the Ganges river system.

As the estuarine complex is a tidal system characterized by tides of meso-macro amplitude, it is not surprising that the phytoplankton assemblage is dominated by 144 species, which were recorded to be of marine origin. The increased run-off from catchment areas due to monsoonal flooding introduces several lentic water species into the estuary. Thus, freshwater forms constitute the second major component with 108 species. The brackish water component is represented by 48 species, whereas 23 species of the recorded phytoplankton taxa are capable of tolerating extreme variations in salinity (euryhaline) ranging from freshwater to marine conditions.

Table 2
Seasonality of phytoplankton assemblages in tidal freshwater zone of Hooghly estuary.

Phytoplankton taxa	Group	Phytoplankton density (numbers/litre)		
		Pre-monsoon	Monsoon	Post-monsoon
Microcystis aeruginosa	BGA	4026 (7.26)		
Merismopedia tenuissima	BGA	3382 (6.10)	2071 (5.30)	
Oscillatoria spp.	BGA	3224 (5.82)	5082 (12.98)	
Spirulina major	BGA	2558 (4.62)		
Ankistrodesmus falcatus	GA			4032 (6.73)
Closterium	GA			2040 (3.40)
Oedogonium undulatum	GA		1430 (3.65)	
Pediastrum	GA	2187 (3.95)		2184 (3.64)
Scenedesmus	GA		1451 (3.70)	3088 (5.15)
Spirogyra spp.	GA	6770 (12.22)	4195 (10.71)	3010 (5.02)
Ulothrix zonata	GA			2144 (3.58)
Volvox globator	GA		2456 (6.27)	
Aulacoseira granulata	DIA	14603 (26.36)	5766 (14.72)	11710 (19.53)
Coscinodiscus	DIA	1980 (3.57)		
Cyclotella glomerata	DIA			3825 (6.38)
Cymbella cistula	DIA		2828 (7.22)	
Fragilaria vaucheriae	DIA		4424 (11.30)	8616 (14.37)
Gomphonema sphaerophorum	DIA			5878 (9.80)
Navicula radiosa	DIA	4474 (8.08)	2338 (5.97)	
Nitzschia amphibia	DIA	3261 (5.88)	2315 (5.91)	3040 (5.07)
Pinnularia	DIA	1610 (2.91)		
Synedra ulna	DIA		1528 (3.90)	2026 (3.38)
Surirella elegans	DIA	1420 (2.56)		

(BGA − blue-green algae, DIA − diatoms and GA − green algae. The percentage values provided under each season refers only to the twelve most abundant species/genera and does not represent the complete phytoplankton species composition).

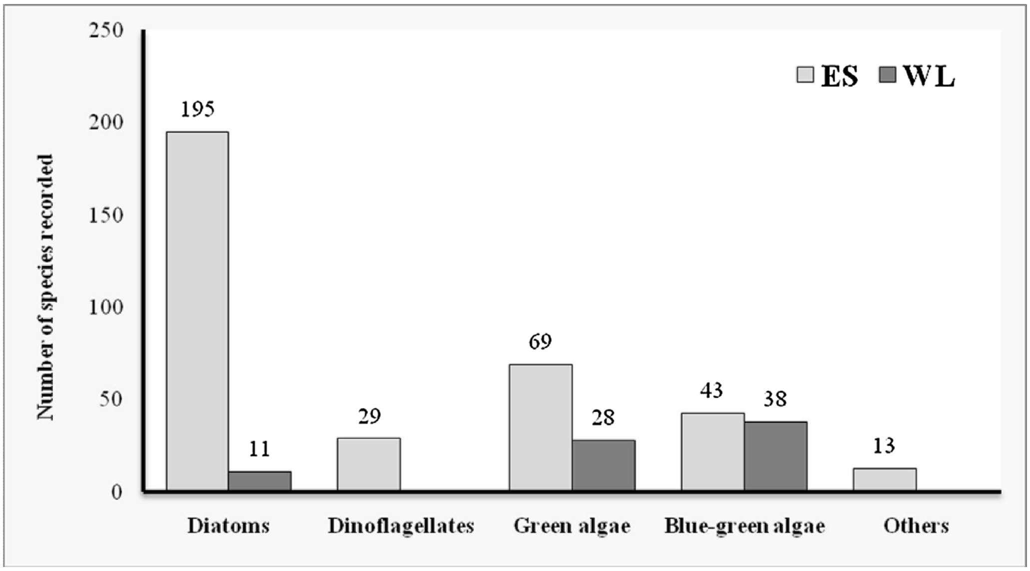

Fig. 3. Comparison of estuarine waters and wetlands with respect to phytoplankton assemblages.

4. Seasonal dynamics in phytoplankton assemblages

4.1. Hooghly estuary

The phytoplankton also exhibit marked variations in density and community structure within an estuarine system, as clearly depicted in the Hooghly estuary where the phytoplankton communities shows variations with respect to different zones (tidal freshwater, gradient and marine) as well as seasons. Moreover, the Hooghly estuary has undergone alterations in hydro-ecological conditions since 1975, owing to the building of Farakka barrage on the Bhagirathi River, the first offshoot of the Ganges in West Bengal, India.

The tidal freshwater zone, which encompasses about 74% (220 km) of the total length of Hooghly, is a unique biotope that experiences tidal fluctuations and retains freshwater conditions throughout the year (Roshith et al., 2013). Our study on phytoplankton communities of the tidal freshwater zone recorded 91 species, with higher dominance of green algae (45 species). The plankton communities showed seasonality, both in density (expressed as numbers/litre) and species composition. Although diatoms were numerically dominant throughout the year, there were marked seasonal variations in relative abundance of blue-green algae and green algae. In case of diatoms, the seasonality in relative abundance (expressed as% of the total phytoplankton density) was not much significant, with values of 56.7, 54.9 and 62.3% for summer, monsoon and winter respectively. The average total phytoplankton density (cells/litre) was higher during summer (55398 cells/litre), lowest in monsoon (39167/L) and attained its peak (59953/L) in winter season. The riverine diatom, *Aulacoseira granulata* dominated the phytoplankton population in summer and winter with relative abundance of 26.4% (14603 cells/L) and 19.5% (11710 cells/l) respectively (Table 2). Diversity of diatoms was highest during summer (24 species), while density was highest in winter due to four dominant species such as *A. granulata* (19.5% of total density), *Fragilaria vaucheriae* (14.4%), *Gomphonema sphaerophorum* (9.8%) *and Cyclotella glomerata* (6.4%). The Chlorophyceans showed a steady increase in relative abundance from summer to winter, while cyanophyceans showed a decline (Fig. 4). The genus *Spirogyra* formed the dominant green algal taxa in all seasons, except in winter when *Ankistrodesmus falcatus* dominated the green algal community (6.7% of total phytoplankton density). The colonial green algae, *Volvox globator* formed a significant component of phytoplankton population during monsoon (6.3%) along with the filamentous forms, *i.e. Spirogyra* (10.7%) and *Oedogonium undulatum* (3.7%). The dominant members of Cyanophyceae include *Oscillatoria* spp., *Microcystis aeruginosa*, *Merismopedia tenuissima* and *Spirulina major*; among which only *Oscillatoria* spp. have been observed in all seasons in fairly good numbers.

The gradient zone of Hooghly is a true estuarine stretch since this zone experiences wide fluctuations in salinity, ranging from near freshwater conditions in peak monsoon (September–October) when salinity reaches 0.08 ppt (parts per thousand) to a maximum value of about 4 ppt in peak summer (May–June). Phytoplankton communities along this zone have been studied in detail by Choudhury and Pal (2010), who revealed a unique pattern of species succession at Diamond Harbour (Fig. 3 & Table 3). It has been observed that most of the abundant phytoplankton taxa have specific seasons of maximum flourishing, representing different patterns of species succession. The diatom, *Leptocylindrus danicus* which dominated the phytoplankton community in June–July (2005) continued to be the dominant taxon during June–July (2006) and June (2007). This has been clearly demonstrated with respect to dominant phytoplankton species of other months also (Table 3). A total of 58 phytoplankton taxa have been recorded by Choudhury and Pal (2010), of which 53.7% were diatoms (Bacillariophyta) followed by Chlorophyta (28.57%) and Cyanophyta (17.9%). This study showed a specific succession patterns of species or species groups entering into the system and flourish. Blue-green algae appeared in summer and flourished in monsoon, while green algae appeared in the transition period between winter and summer. The winter community represented a diatom-dominated population, with the most abundant species being *Nitzschia delicatissima* (295 cells/ml). The other abundant diatom species (more than 200 cells/ml) include *Thalassionema nitzschioides*, *Gyrosigma beaufortianum*, *Pleurosigma salinarum*, *Odontella aurita*, *Paralia sulcata* and *Bacillaria paxillifer*.

The lower stretch (marine zone) of Hooghly forms the western margin of Indian Sundarbans and is the most ecologically disturbed zone (due to anthropogenic interferences and pollution), of the entire Hooghly-Matla system. Its proximity to the coastal waters makes it vulnerable to tropical cyclones of the Bay of Bengal. This marine influx (both tidal and from tropical storms), along with the riverine freshwater discharge from the Ganges create very complex hydro-ecological conditions along the lower stretches of Hooghly. According to a comparative analysis on the phytoplankton composition over two-decades (Biswas et al., 2009), the dominant phytoplankton taxa in the lower zone included *Asterionellopsis glacialis* (23.5%), followed by *Skeletonema costatum* (18.95%), *Bellerochea malleus* (9.75%), *Thalassiosira decipiens* (5.76%) and *Thalassiothrix* sp. (5.5%) during 2007 (Table 4). That study reported phytoplankton blooms during the winter period

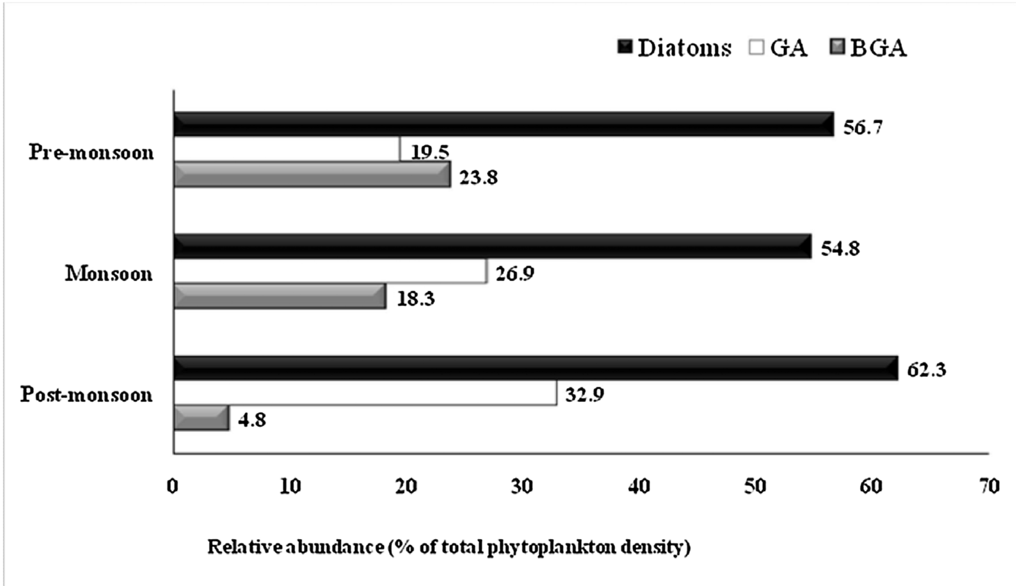

Fig. 4. Seasonality in abundance of phytoplankton groups (tidal freshwater zone).

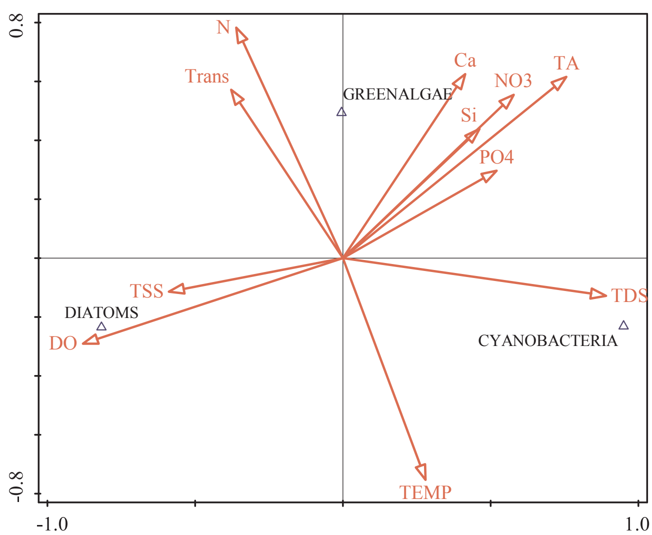

Fig. 5. CCA ordination diagram showing the correlation between phytoplanktonic species and physicochemical parameters of water.

Table 3
Species succession patterns in some phytoplankton taxa at Diamond Harbour (gradient zone).
Source: Modified from Choudhury and Pal (2010).

Dominant phytoplankton species	Time period		
	2005	2006	2007
Leptocylindrus danicus	June, July	June, July	June
Thalassiothrix frauenfeldii	August	August	
Merismopedia minima	September	September	
Microcystis aeruginosa	October, November	October, November	
Nitzschia delicatissima	December	December	
Pleurosigma salinarum		January	January
Coscinodiscus eccentricus		February	February
Pediastrum tetras		March	March, April
Scenedesmus dimorphus		April	
Pediastrum duplex		May	May

Table 4
Major bloom-forming phytoplankton taxa in the Hooghly-Matla estuary.
Source: Biswas et al., 2009.

Species	Relative Abundance (% of total density)	Bloom forming months
Asterionellopsis glacialis	23.5	January
Skeletonema costatum	18.95	January
Coscinodiscus excentricus	4.59	December
Thalassiosira hyalina	2.73	January
Pinnularia sp.	2.37	January
Pleurosigma elongatum	2.02	January
Coscinodiscus radiatus	1.69	January, March

(November–February), with all the blooms involving diatoms. The majority of blooms involved large-celled species, such as *Coscinodiscus eccentricus* and *Ditylum brightwelli*. The smallest bloom forming species included *Navicula rhombica*, *Leptocylindrus* sp., *Nitzschia seriata*, *N. sigma*, *Thalassiosira decipiens* and *Skeletonema costatum*. Winter blooms of *Coscinodiscus eccentricus* was also reported by Choudhury and Pal (2008) at Gangasagar/Sagar Island (Fig. 3), a station located within the marine zone. The other diatoms such as *Coscinodiscus granii*, *C. radiatus* and *Gyrosigma scalproides* were also abundant in winter (10000 cells/litre); while the summer phytoplankton blooms at Gangasagar involved *Biddulphia rhombus* and *Thalassiothrix frauenfeldii* (Choudhury and Pal, 2008).

4.2. Matla estuarine system

The hydro-ecological profile of Matla estuarine system is distinct from Hooghly, owing to the lack of perennial riverine freshwater sources due to heavy siltation and consequent drying up of the Bidyadhari Channel (the channel was a branch of Bhagirathi River during 15th and 16th centuries). Being deprived of a permanent riverine connection along with the tidal ingression of marine waters resulted in steady rise in salinity of Matla estuary and favoured the intrusion of stenohaline marine species of phytoplankton. Manna et al. (2010) recorded 46 species of phytoplankton from Jharkhali area (Fig. 1), situated in the Matla estuarine zone with densities (cells/litre) ranging from a higher value of 2.52×10^6 during winter to 9.93×10^5 in summer. Phytoplankton species richness was highest in summer (March), whereas higher phytoplankton densities had been recorded during winter months. Diatoms were the most dominant group (both

Table 5
Dominant phytoplankton taxa of the Matla estuarine system.
Data modified from Manna et al. (2010).

Phytoplankton group	Season	Species	Density (cells/ml)
DIATOMS	Winter	*Coscinodiscus radiatus*	19
		Triceratium sp.	20
		Bacteriastrum hyalinum	17
		Chaetoceros curvisetus	17
		Thalassiosira punctigera	17
		Chaetoceros convolutus	16
	Summer	*Thalassionema nitzschioides*	11
		Nitzschia sp.	10
		Diatoma sp.	10
		Climacosphenia sp.	9
DINOFLAGELLATES	Winter	*Protoperidinium pellucidum*	15
	Summer	*Polykrikos schwartzil*	14
GREEN ALGAE	Summer	*Dunaliella salina*	17
		Chlorella salina	9
		C. marina	8
BLUE GREEN ALGAE	Summer	*Trichodesmium* sp.	4

diversity and abundance) in both seasons, of which, the centric diatoms showed peak abundance during winter while pennate forms peaked in summer. The winter diatom assemblage was dominated by the centric diatom *Triceratium* sp. (20 cells/ml), whereas the pennate diatom *Thalassionema nitzschioides* formed a key component in summer with a density of 11 cells/ml (Table 5). Among dinoflagellates, *Protoperidinium pellucidum* was the major component in summer (15 cells/ml) while *Polykrikos schwartzii* dominated in winter (14 cells/ml). The overall density of dinoflagellates was higher in summer with 99×10^3 cells/litre (Manna et al., 2010) and slightly lower in winter (59×10^3 cells/litre). During peak summer when salinity values increased above 21 ppt, a new set of marine euryhaline species (resilient to higher salinities) dominated the phytoplankton community. This group comprised the blue-green algae, *Trichodesmium* sp., and three species of green algae such as *Dunaliella salina* (dominant with abundance of 17 cells/ml), *Chlorella salina* and *C. marina* (Table 5). Studies on inter-annual variation of phytoplankton taxa at Lothian Island located within Saptamukhi estuary (western part of Matla estuarine system) confirmed that the phytoplankton population attained their peak abundance during winter (38784 cells/L) and the lowest abundance (13142/L) in monsoon season (Chowdhury et al., 2012).

5. Phytoplankton community in relation to environmental variables

Globally, the tropical estuarine waters exhibit complex biogeochemical and hydrodynamic conditions which are subjected to spatio-temporal variations. The phytoplankton community structure of these waters is not just a mere indicator of the pattern of abundance of life-forms. They manifest a complex assemblage of taxonomically diverse photo-autotrophic organisms, evolved and structured by the dynamic hydro-ecological regime resulting from the interactions of two antagonistic hydrological processes, *i.e.*, riverine freshwater run-off and tidal influx of marine waters.

Unlike estuaries of the west coast of India and other east coast estuaries, the Hooghly-Matla estuary represent a complex and highly dynamic aquatic environment where the environmental parameters such as salinity, nutrient loads and turbidity show great spatial and temporal variations. This can be attributed to the contrasting hydro-ecological conditions, with the Hooghly receiving a continuous supply of riverine freshwater from the Ganges-Bhagirathi system owing to freshwater discharge from Farakka barrage; while the estuaries of the Matla system (except Ichamati/Raimangal system) are deprived of any riverine freshwater supply due to siltation of Bidyadhari river since 15th century.

The phytoplankton populations of the Hooghly-Matla estuary are mainly influenced by environmental drivers such as temperature, salinity, turbidity and influx of nutrient rich freshwater from rivers. Generally the phytoplankton density is lowest during monsoon due to dilution of populations by the riverine influx as well as the turbid water conditions which restrict the light penetration. The phytoplankton density becomes highest during winter as the calm weather conditions allow the nutrient-laden riverine sediments to settle down thereby increasing the euphotic zone resulting in increased primary production. Even though the riverine influx is lower during summer; the plankton density is lesser than in winter due to high temperature and high salinity which was beyond the threshold tolerance level of majority of phytoplankton species (Chowdhury et al., 2012). Moreover, enhanced tidal activity during summer (March-June) increases turbidity resulting in suspension of sediments and limited light penetration.

It has been mentioned in earlier sections (section 3.2) that the majority of phytoplankton taxa reported from the Hooghly-Matla system have their origin from coastal marine waters (tidal ingress), or were introduced to the system during peak riverine influx. Phytoplankton communities within an estuary are also influenced by exchanges across a third interface, *i.e.* between the sediments and overlying (Cloern and Dufford, 2005). This is clearly evident from the occurrence of several benthic, epiphytic or periphytic micro algal species among phytoplankton assemblages in tropical estuarine systems. These microalgae constitute an ecologically significant group known as tychoplankton which includes those benthic, epiphytic as well as periphytic species that are periodically re-suspended from the bottom (by tidal activity) and integrated into the phytoplankton community. Many of the common diatom species recorded from the Hooghly-Matla estuarine system such as *Nitzschia sigma*, *Ceratoneis closterium*, *Pleurosigma normanii*, *Gyrosigma acuminatum*, *G. balticum*, *Cyclotella striata*, *C. meneghiniana*, *Paralia sulcata*, *Thalassiosira decipiens*, *Aulacoseira granulata*, *Surirella fastuosa*, *Diploneis weissflogii*, *Cymbella marina*, *Cocconeis* sp. and *Achnanthidium* sp. are tychoplanktonic and abundant in phytoplankton assemblages. Our studies on the phytoplankton communities of the tidal freshwater stretch of Hooghly reported the dominance of tychoplanktonic species, *Aulacoseira granulata* throughout the stretch.

6. Ecological significance

6.1. Phytoplankton production and trophic status

The productivity of any aquatic ecosystem is mainly controlled by the phytoplankton population dynamics (Choudhury and Pal, 2012), and the dynamic structure of these communities directly reflects the health of aquatic ecosystems. Chowdhury et al. (2012) studied the phytoplankton productivity in relation to trophic status of Sundarban estuarine region at Jharkhali (situated in the Matla zone) and estimated the net ecosystem metabolism (NEM) to evaluate the role of estuary as net source or sink of carbon. They estimated that the phytoplankton standing crop ranged from 3.9×10^{10} cells/m^3 in winter to 1.34×10^9 cells/m^3 in summer and 1.39×10^9 cells/m^3 in monsoon. Phytoplankton primary productivity (expressed as milligrams of carbon per square metre per day) also followed a seasonal cycle being highest ($597.3\,mgC\,m^{-2}\,d^{-1}$) in the month of February (winter) and lowest ($311.0\,mgC\,m^{-2}\,d^{-1}$) in the month of August (monsoon). The study inferred that the estuarine water remained phosphorus limited during winter; while it was nitrogen limited during summer and monsoon. There was seasonal shifting of autotrophic and heterotrophic conditions in the estuary, which remained autotrophic for five months (November–March) of the year (Chowdhury et al., 2012). During this time the primary production is greater than community respiration resulting in export or burial of organic matter through conversion of inorganic matter and carbon dioxide. The estuary remained heterotrophic during the remaining seven months (April–October) as community respiration was greater than primary production during that period and allochthonous material is re-mineralized leading to production of inorganic nutrients and carbon dioxide. According to that study, the Sundarbans estuary can be considered as a net source of CO_2 considering the NEM of entire year.

6.2. Role in augmenting fisheries production

Being the primary producers, phytoplankton influences the aquatic food chain directly or indirectly, and it has been well established that the movement of commercial fish stocks in estuarine and coastal waters is greatly influenced by phytoplankton population dynamics. This holds great significance with respect to the Hooghly-Matla estuary that forms one of the main inland capture fisheries resources of India, where the bulk of the fish production comes from a unique fishing practice called the 'winter migratory bag net fishing' practiced during winter season. The higher CPUE (catch per unit effort) during winter bag net fishing can be attributed to the increased abundance of different fish species resulting from winter plankton blooming near estuarine mouth as well as the adjacent coastal waters which attracts the planktivorous fishes and shrimps to congregate around the region. The carnivorous and predatory fishes also migrate to this zone to feed on the dense assemblage of small fishes and shrimps. According to Dutta et al. (1973), these plankton blooms result from nutrient enrichment since large amounts of organic matter, detritus and other washed off materials due to monsoonal flow are deposited near the estuarine mouth and adjacent coastal waters which fortify these waters thereby inducing plankton bloom. Plankton production, especially phytoplankton reaches a peak in these regions during winter months (Shetty et al., 1961). Moreover, the anadromous hilsa shad (*Tenualosa ilisha*) which forms the prime fishery resource of Hooghly estuary is planktivorous with diatoms constituting one the major part its diet. It has already been proven that the diatoms, viz., *Fragilaria oceanica* and *Hemidiscus hardmannianus* are indicators of abundance of hilsa shad in the Hooghly estuary (Mitra, 2013).

A central principle of an ecosystem-based approach to fisheries management is the recognition that fishery yields are ultimately limited by ecosystem primary production and the environmental mechanisms that determine the magnitude of ecosystem-level production have received a great deal of attention owing to the necessity to predict future fisheries yields (Friedland et al., 2012). Mapping of phytoplankton distribution in the estuary, thus helps in identification of potential fish-rich zones as well as in identification of factors responsible for abundance and growth of phytoplankton. Mapping the zones of abundance of phytoplankton in the coastal waters has been tried successfully, using the Ocean Colour Monitor data from Indian Remote Sensing satellites.

6.3. Phytoplankton as indicators of eutrophication

The eutrophication of coastal waters is a problem of epidemic proportion and has disastrous short- and long term consequences for water quality and resource utilization (Nixon, 1995; Paerl, 1997). Even though there is considerable debate over the extent of "top-down control" over nutrient enrichment, in many instances, heavy nutrient loading dramatically increased phytoplankton biomass, promoting an excess accumulation of organic matter (Paerl et al., 2007). This increased phytoplankton production affect nutrient cycling, favours algal bloom formation, reduces water clarity and results in expanded hypoxia (Paerl et al., 2007).

In India, Hooghly-Matla estuary is particularly vulnerable to anthropogenic perturbations due to high nutrient loads from riverine discharge, increasing human population density and rapid economic growth (Biswas et al., 2009). However, very few studies have addressed this accelerating ecological threat in Hooghly-Matla system and the only available information is from studies conducted at the Sundarbans estuarine area at Jharkhali in the Matla zone (Manna et al., 2010; Chowdhury et al., 2012). These studies relied on the chlorophyll-a concentration to evaluate the trophic status of the estuary. The concentration of chlorophyll-a is highly useful in assessing the interactive effects of nutrient loading on phytoplankton production and can be used as an indicator of eutrophication (Paerl et al., 2007). The observed chlorophyll-a concentrations from the Sundarbans estuary indicated that the concentrations remained greater than 10 μg/L for ten months in a year, with May-June being exceptions when the concentration of chlorophyll-a was below 10 μg/L; indicating that the estuary was mesotrophic only for two months, and remained eutrophic over the remaining months (Manna et al., 2010; Chowdhury et al., 2012). The eutrophication induced changes are reflected in the phytoplankton community. This has been evident from the presence of toxic dinoflagellates (*Polykrikos schwartzii*, *Dinophysis norvegica* and *Prorocentrum concavum*) and cyanophyceans (*Anabaena* sp., *Oscillatoria* sp.) in phytoplankton assemblages of Sundarban estuary (Manna et al., 2010). Higher abundance of the dinoflagellates (mean abundance, 625 cells/L) such as *Noctiluca* sp. have been reported in the lower marine stretch of Hooghly estuary during succeeding weeks after the Gangasagar event (a holy religious congregation), indicating the deteriorated water quality due anthropogenically induced nutrient loading (Bhattacharjee et al., 2013).

6.4. Phytoplankton as indicator of water quality

The Canonical Correspondence Analysis axes 1(horizontal) and axes 2 (vertical) explained 82.1% and 17.9%. A positive correlation was observed between Cyanobacteria and total dissolved solid (TDS); diatoms with total suspended solids (TSS) and dissolved oxygen (DO); green algae with N, Ca, NO_3, total alkalinity (TA) and transparency while, temperature showed its negative influence on green algae. With this correlation it can be concluded that dense distribution of green algae might be attributed to relatively higher concentration of N, Ca, NO_3, total alkalinity (TA) and transparency which may lead to eutrophication-like conditions which directly indicate the water quality.

Moreover, there are different types of phytoplankton based indices used for assessing the water quality in terms of tropic status *i.e.* the multimetric phytoplankton Index (Bazzoni et al., 2013), numerical index (Marchetto et al., 2009) and phytoplankton tropic index (Phillips et al., 2013).

6.5. Impact of climate change on phytoplankton communities

Impacts of climate change and associated sea level rise on the mangrove ecosystem of Indian Sundarbans received global attention since Sundarbans have been categorized as one of the global hotspots that is worst affected by climate change and sea level rise. According to Mitra et al. (2009), the surface water salinity decreased by 46.2% in the western sector of Sundarbans (lower stretch of Hooghly); whereas it increased by 40.5% in the central sector (Matla zone) over a time period of 27 years (1980–2007). Specifically, the temperature in these waters has risen at a rate of 0.5 °C per decade, much higher than that observed globally or for the Indian Ocean. These changes in hydro-ecological conditions affected the phytoplankton community structure with the appearance of more freshwater and euryhaline species in the Hooghly system due to varied salinity regimes; while the increased salinity conditions along the Matla system paved way for stenohaline marine forms to penetrate into the estuary. Raha et al. (2012) have reported the abundance of stenohaline marine phytoplankton taxa, *viz*., *Cymbella marina*, *Asterionella formosa*, *Ditylum brightwelli*, *Triceratium jentacrinus*, *Pleurosigma salinarum* and *Fragillaria oceanica* from the central sector of Indian Sundarbans due to gradual rise in salinity. Akhand et al. (2012) reported the occurrence of the dinoflagellate *Ceratium symmetricum* for the first time in Hooghly-Matla estuary and observed that the lower abundance of this species is an indication of the steady rise in sea surface temperature of the region.

7. Future prospects

The status of inland open waters can be assessed with indices like Carlson's Trophic State Index (CTSI) based on Seechi disc depth, chlorophyll *a* concentration and total phosphorus content along with other Biological Quality Elements (BQEs) and standard health card approach. BQEs are the group of organisms which integrate the effects of multiple stressors such as nutrient enrichment, acidification, hypoxia or habitat degradation (Hering et al., 2013). From fisheries and aquaculture perspective, the BQEs to be investigated are; phytoplankton, aquatic flora, benthic invertebrates and fish.

8. Epilogue

Being the largest estuarine system of India, Hooghly-Matla estuary harbours the most diverse phytoplankton community with 378 defined species. This is highest recorded phytoplankton diversity with respect to all other Indian estuaries and amongst the highest in the world. Our survey on the phytoplankton communities of the tidal freshwater zone recorded 91 species of phytoplankton taxa, with dominance of green algae (41 species) followed by diatoms (34 species). It has been observed that most of the phytoplankton taxa in the tidal freshwater zone have their origin from the Ganges river system and got introduced into the estuary due to increased freshwater discharge. In the Matla system, however, the prevalence of high saline conditions throughout the year due to deprival of any perennial freshwater discharge has enabled many stenohaline marine phytoplanktons to invade the estuarine system. The phytoplankton population of the Hooghly-Matla estuary is mainly influenced by environmental factors such as temperature, salinity, turbidity and influx of nutrient rich freshwater from rivers. Though, intensive scientific studies on phytoplankton communities have been carried out for estuaries of India's west coast (Mandovi-Zuari, Cochin backwaters, etc.), phytoplankton of Hooghly-Matla system have not received much attention. The majority of studies in recent past dealt with the lower Sundarban region and focused on microplanktonic taxa (size higher than 20 μm); while other significant groups such as nanoplankton and picoplankton have almost been excluded from these studies. It is advisable to use advanced DNA based molecular techniques to address ambiguity of many traditional identifications that are based on morphological traits. Despite rapid developments in molecular methods, taxonomists have been slow to incorporate molecular information in a formal way into species descriptions. Likewise, molecular biologists have often been less than thorough about making precise identifications of the species they sequence, as the large number of sequences in the public databases that are linked to unidentified species demonstrate. Therefore, both approaches as total evidence may be used to identify the planktons more precisely (McManus and Katz, 2009). Recently, Bhattacharjee et al. (2013) by employing molecular techniques (sequencing of rbcL gene) detected several nanoflagellates and picoplanktonic forms from Sundarban mangroves; thereby highlighting the importance of such emerging frontiers in phytoplankton research. A holistic study of the phytoplankton communities and their population dynamics along the entire estuarine complex will provide a greater insights on the global issues of climate change and sea level rise.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.flora.2018.01.001.

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