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ORIGINAL ARTICLE

Seasonal influence of physicochemical parameters on phytoplankton diversity and assemblage pattern in *Kailash Khal*, a tropical wetland, Sundarbans, India

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Abstract

Studies were carried out from April 2016 to March 2017 for effective understanding of diversity combined with environment-influenced spatiotemporal dynamics of microfloral structure in *Kailash Khal* wetland of Indian Sundarbans. A total of 36 phytoplankton genera were recorded from the study area. Eight major algal groups were in order of: Bacillariophyceae > Cyanophyceae > Chlorophyceae > Coscinodiscophyceae > Xanthophyceae > Euglenophyceae > Conjugatophyceae > Mediophyceae with respect to their quantitative abundance. Mean seasonal abundance was found highest in pre-monsoon (4.32×10^3 cells l^{-1}) followed by post-monsoon (3.88×10^3 cells l^{-1}) and monsoon (1.96×10^3 cells l^{-1}). One-way ANOVA showed that seasonal difference in physicochemical parameters was statistically significant for temperature, DO, specific conductivity, TA, TS, Ca^{++}, nitrate, transparency, salinity, TH, turbidity, Mg^{++} and phosphate ($p < 0.05$). pH, temperature, total hardness, TDS nitrate, phosphate and silicate showed a close affinity with the distribution of phytoplankton community as evident from canonical correspondence analysis. Margalef richness index (3.121–3.774) and Shannon–Wiener diversity index (2.730–2.939) indicated moderately rich phytoplankton diversity in the wetland ecosystem.

Keywords Abundance · Coastal wetland · Hydro-chemical · Nutrients · Phytoplankton diversity

Introduction

Coastal wetlands are one of the biologically diverse and productive ecosystems of this planet (Bijoy et al. 2014). Such sensitive ecosystems act as key habitat in the form of feeding and breeding ground for ecologically important resident and migratory aquatic fauna (Jhingran 1982; Bijoy 2008) and have established as potential fishing areas for small indigenous fishes (SIFs). Located in tide-influenced regions, these water bodies serve as 'pollutant sinks' emanating from nonpoint sources and their biochemical natures, regulated by amplitude of hydrological connectivity to sea and river besides anthropogenic factors (Serrano et al. 2006; Badosa et al. 2008). Biodiversity of coastal wetlands dwindles during high flood pulses, and this reduction in environmental heterogeneity including habitat and biotic communities gradually restores with receding flood (Cardoso et al. 2012). Agro-industries and hydroelectric power plants are markers indicators of rapid economic growth and receive greater attention, compared to their impact on surrounding environment and waste recipient ecosystems. Industrialization and consequent urbanization in this era of economic growth have brought about environmental degradation, stress on coastal ecosystems of India (Stanley 2004) which adversely impact their inherent biota, physicochemical profile of water and productivity. Thus, it is always imperative to understand the existing ecological relationship between primary producers and their surrounding environment in coastal wetlands which can act as baseline information and are of prime interest to biologists and ecologists.

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Productivity of an ecosystem depends upon dynamics of both flora and fauna where the former plays a pivotal role. Phytoplankton population represents the biological wealth of an ecosystem (Boyd 1982). Primary production in an aquatic system depends on phytoplankton biomass and composition which are food for primary consumers in food pyramid including planktivore fishes (Sridhar et al. 2006). Phytoplankton communities in coastal wetlands have adapted to continuous change in hydrodynamic conditions (López-Flores et al. 2006). The sudden changes of phytoplankton biomass and composition in an aquatic ecosystem due to different environmental alterations may affect food chain linkages which diminish biological productivity.

A number of reports are available on phytoplankton community structure of open estuarine system and associated brackish water wetlands, commonly known as *Bheries*, in Indian Sundarbans (Dutta et al. 1954; Shetty et al. 1961; Gopalkrishnan 1971; De et al. 1994; Sarkar and Naskar 2002; Biswas et al. 2004; Manna et al. 2010; Dey et al. 2012; Bhattacharjee et al. 2013). However, studies on phytoplankton community structure in the freshwater-dominant wetlands of the region are quite scarce. Moreover, such wetlands are under severe anthropogenic stress owing to intensive utilization for agriculture, domestic and household purposes which has the potential for drastic alterations in biota including phytoplankton community. Hence, the present study is aimed to investigate the seasonal influence of physicochemical parameters on phytoplankton diversity and spatiotemporal variations in their assemblage pattern in *Kailash Khal* (wetland) of Indian Sundarbans.

Study area

Kailash Khal is situated between latitude 22°6′28.33″N–22°6′1.38″N and longitude 88°51′42.24″E–88°52′28.90″E in Satjelia Island, Gosaba, block of Indian Sundarbans, the important mangrove chunk in the world and connected to *Datta* River in its southern side (Fig. 1). Freshwater resource is scarce in Sundarbans

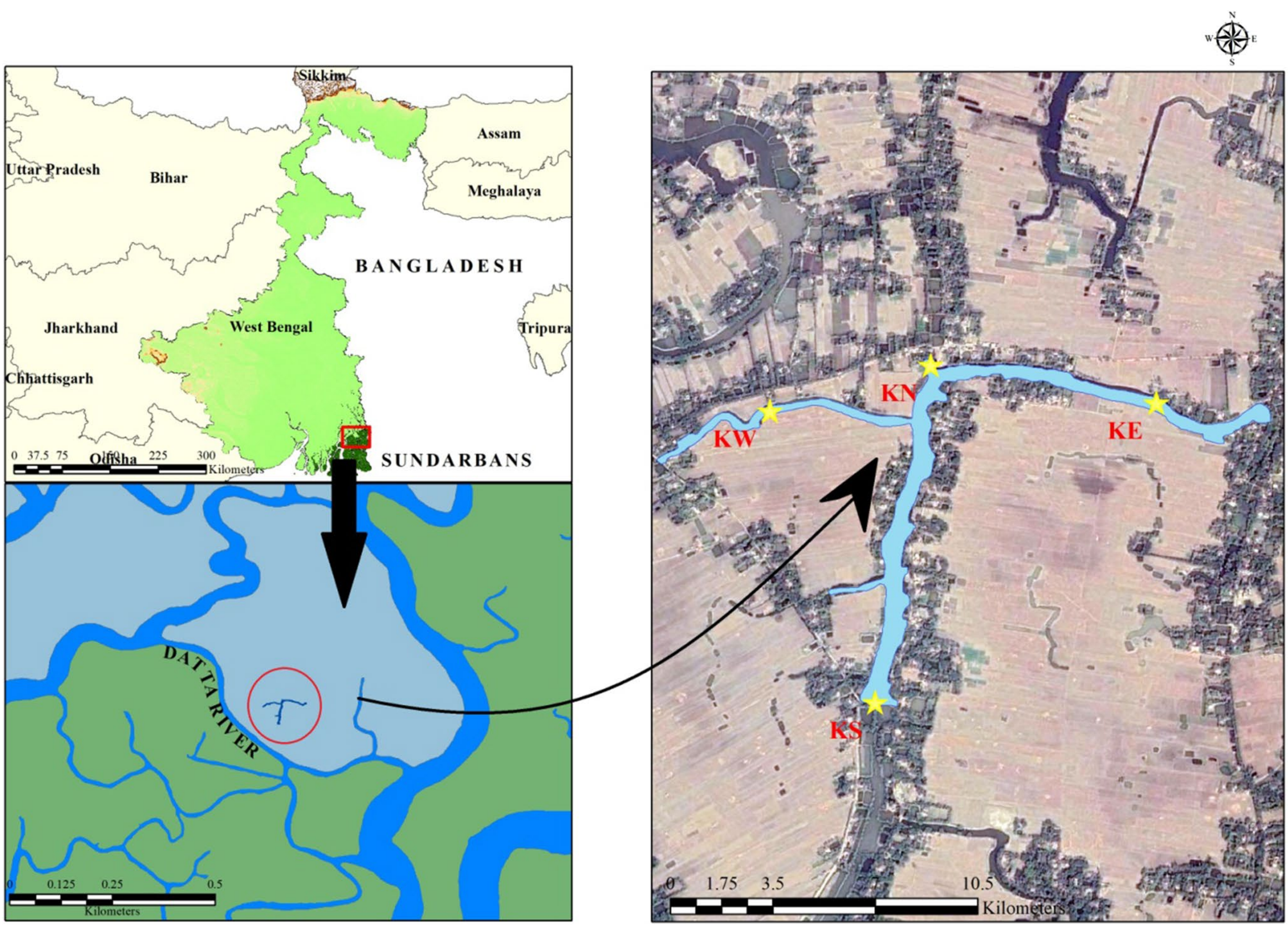

Fig. 1 Map of *Kailash Khal*, Anpur, Sundarbans; KS—*Kailash Khal* south; KN—*Kailash Khal* north; KE—*Kailash Khal* east; and KW—*Kailash Khal* west

though it is bestowed upon numerous creeks and rivulets (Hazra et al. 2015). *Kailash Khal* is a freshwater-dominant wetland which ensures freshwater supply into agriculture field, livestock rearing and other domestic use throughout the year of the local community. It is a biologically diverse and productive ecosystem as it provides home to a variety of both brackish and fresh water flora and fauna. Chanu et al. (2017) reported 27 fish species in the wetland, of which 21 were small indigenous fishes having both ornamental and food values.

Sampling methodology

Four sampling locations were chosen along east (KE), west (KW), north (KN) and south (KS) part of the wetland with salinity ranges from 0.21 to 5.2 ppt. Bimonthly (every 2 months) sampling was performed from April 2016 to March 2017, representing three seasons following Chaudhuri et al. 2012, pre-monsoon (March–June), monsoon (July–October) and post-monsoon (November–February). A small wooden boat (locally known as *dingi*) was used for collection of water samples at each of the sampling stations. Water samples were collected from subsurface (0.5 m depth) at all selected locations by using standard water sampler based on design of 'Ruttner water sampler' and immediately transferred into pre-rinsed polyethylene sample bottles (1.0 l). Water temperature, pH, transparency, specific conductivity, salinity, total hardness (TH), dissolved oxygen (DO), turbidity and total alkalinity (TA) were measured in situ, and water samples were brought to laboratory and preserved in cold condition for analysis of total solids (TS), total dissolved solids (TDS) and nutrients (nitrate, phosphate, silicate, sulfate, Ca^{++} and Mg^{++}).

Water temperature was determined by using a degree centigrade (− 10 to 50 °C) thermometer (P-601466), pH with a digital pH meter (Hanna Instruments), specific conductivity with a digital conductivity meter (MultiLine P4-82362) and turbidity with a nephelometric turbidity meter (Orion AQ 4500). TS, TDS, DO, salinity, TA, TH and nutrients, namely nitrate, phosphate, silicate, sulfate, Ca^{++} and Mg^{++}, were analyzed by the following standard methods (APHA 2012). Transparency was measured by employing Secchi disk (Strickland and Parsons 1972), and light attenuation coefficient (k) was calculated following Quasim et al. (1968).

Phytoplankton sample collection

For phytoplankton community structure study, samples were collected by filtering (20-μm silk bolting mesh plankton net) 50 l subsurface water from the respective locations. The concentrated samples were preserved in 4% buffered formalin. Quantitative analysis was done by employing Sedgwick Rafter counting cell. The total number of phytoplankton cells present was calculated cells per liter (cells l^{-1}) (Santhanam et al. 1989). Identification of phytoplankton was done by employing a trinocular microscope ('Nikon Eclipse—50i') with standard taxonomic identification keys, and genera were arranged as per AlgaeBase (Guiry and Guiry 2018).

Diversity indices

(a) Shannon–Weiner index (H') (Shannon and Weiner 1949)

Species diversity index was calculated as: $H' = -\sum[\text{Pi} \times \log(\text{Pi})]$, where 'Pi' is the proportion of the individuals belonging to the 'i'th species and H' is the species diversity.

(b) Simpson's index (Simpson 1949)

Species dominance index: $D = \sum p_i^2$, where 'p_i' is the proportion of individuals found in species 'i' and Simpson's index of diversity = $1 - D$.

(c) Margalef richness index (d) (Margalef 1958)

$d = (S - 1)/\log N$, where N = total number of individuals and S = total number of species.

(d) Pielou's evenness or equitability index (J') (Pielou 1977)

$J' = H'/\text{Log}(S)$, where H' = Shannon–Weiner diversity and S = total number of species.

Statistical tools Plymouth Routines in Multivariate Ecological Research, Version 6.1.6 (PRIMER v 6.1.6), and Palaeontological Statistics (PAST), version 3.06, were used for univariate and multivariate data analysis. Basic descriptive statistics (mean and standard deviation) were performed in MS Excel, 2010; box plot, one-way ANOVA using post hoc Tukey test and estimation of Karl Pearson's correlation coefficient were performed by SPSS version 20.0. Hierarchical cluster analysis was done to understand the degree of similarity among samples/sampling stations (phytoplankton composition and abundance). To confirm further the fact, multidimensional scaling (MDS) map was drawn to visualize 'dimension' (i.e., distance) in order to explain similarities or dissimilarities among datasets (PRIMER v 6.1.6). Canonical correspondence analysis (CCA) between water quality parameters and different algal groups was done with the help of PAST v 3.06.

Results

Physicochemical factors

Seasonal variations in water quality parameters in *Kailash Khal* wetland are given in Table 1. One-way ANOVA (post hoc Tukey test) of physicochemical parameters showed statistically significant differences ($p<0.05$) for temperature, DO, specific conductivity, TA, TS, Ca^{++}, nitrate, transparency, salinity, TH, turbidity, Mg^{++} and phosphate (Table 1). Analysis of Karl Pearson's correlation coefficient showed positive correlation of DO with temperature ($r=0.55$), specific conductivity ($r=0.67$; $p<0.05$), TA ($r=0.62$; $p<0.05$) and Ca^{++} ($r=0.65$; $p<0.05$), while it was negatively correlated with Mg^{++} ($r=-0.61$; $p<0.05$). Similarly pH had positive correlation with temperature ($r=0.57$) and negative correlation with DO ($r=-0.60$; $p<0.05$). Turbidity showed negative correlation with Mg^{++} ($r=-0.72$; $p<0.05$) and nitrate ($r=-079$; $p<0.05$) and positive correlation with phosphate ($r=0.98$; $p<0.05$) (Table 2).

Phytoplankton abundance and composition

A total of 36 (thirty-six) genera belonging to 8 (eight) taxonomic class groups were recorded from *Kailash Khal* wetland. The phytoplankton species composition was dominated by Bacillariophyceae with 9 genera followed by Chlorophyceae with 7 and Cyanophyceae with 6, details of which are given in Table 3. Percentage compositions of different algal groups are shown in Fig. 2. Mean seasonal abundance was highest in pre-monsoon (4.32×10^3 cells l^{-1}) followed by post-monsoon (3.88×10^3 cells l^{-1}) and monsoon season (1.96×10^3 cells l^{-1}), and on the whole, quantitative spectrum of phytoplankton ranged from 1.16×10^3 cells l^{-1} (KN, during monsoon season) to 7.59×10^3 cells l^{-1} (KS, during post-monsoon season).

The occurrence of Cyanobacteria, viz. *Anabaena*, *Lyngbya*, *Microcystis*, *Merismopedia*, *Oscillatoria* and *Nostoc,* was very common during post-monsoon, whereas genera *Coscinodiscus*, *Odontella*, *Aulacoseira* and *Melosira* were predominant in pre-monsoon season. Chlorophytes abundance was slightly higher during post-monsoon (0.568×10^3 cells l^{-1}) than the monsoon season (0.306×10^3 cells l^{-1}). Similar trend also was observed for the group Euglenophyceae in *Kailash Khal*. The group-wise abundance of phytoplankton in different seasons in *Kailash Khal* is shown in Fig. 3.

Cluster analysis and multidimensional scaling (MDS) map

Cluster analysis (Fig. 4) and MDS were performed to find out the degree of similarity of the species compositions among the stations of *Kailash Khal* water. The hierarchical cluster analysis revealed that similar nature of samples/

Table 1 Seasonal changes of water variables in *Kailash Khal*

Water variables	Pre-monsoon	Monsoon	Post-monsoon
Water temperature (°C)	32.1 ± 0.35^b	33.2 ± 0.28^c	25.7 ± 1.32^a
pH	7.72 ± 0.24^a	7.48 ± 0.58^a	7.37 ± 0.04^a
DO (mg l^{-1})	5.32 ± 0.85^a	5.65 ± 0.02^b	5.80 ± 0.14^b
Specific conductivity (μS/cm)	387 ± 82.5^a	549.5 ± 31.46^{ab}	629.75 ± 56.18^b
Total alkalinity (mg l^{-1})	45.50 ± 6.65^a	56.0 ± 7.34^a	76.50 ± 0.64^b
Salinity (ppt)	4.40 ± 0.30^b	0.33 ± 0.04^a	3.64 ± 0.43^b
Total hardness (mg l^{-1})	600 ± 91.28^b	84.0 ± 1.63^a	737 ± 55.43^b
Total dissolved solids (g l^{-1})	1.70 ± 0.12^a	2.40 ± 0.19^b	2.06 ± 0.22^{ab}
Total solids (g l^{-1})	2.0 ± 0.12^a	3.12 ± 0.12^b	2.71 ± 0.26^b
Turbidity (NTU)	11.0 ± 0.40^a	45.75 ± 2.32^b	8.41 ± 1.52^a
Ca^{++} (mg l^{-1})	42.92 ± 10.39^a	19.55 ± 1.13^a	166.33 ± 45.27^b
Mg^{++} (mg l^{-1})	129.95 ± 17.34^c	24.19 ± 3.13^a	78.28 ± 15.46^b
Nitrate (mg l^{-1})	0.39 ± 0.03^b	0.18 ± 0.004^a	0.03 ± 0.03^b
Phosphate (mg l^{-1})	0.014 ± 0.003^a	0.053 ± 0.002^b	0.009 ± 0.001^a
Silicate (mg l^{-1})	3.89 ± 1.17^a	2.23 ± 0.05^a	2.10 ± 0.56^a
Sulfate (mg l^{-1})	1.43 ± 0.38^a	2.44 ± 0.23^a	2.03 ± 0.39^a
Transparency (cm)	62.0 ± 3.24^b	41.5 ± 2.36^a	60.0 ± 3.48^b

The table included the mean differences of (post hoc Tukey test) 'physicochemical' parameters. Means of the three columns of a particular parameter followed by the same letter (*s*) are not significantly different from each other ($p<0.05$)

Table 2 Intra- and interrelationship (Karl Pearson's coefficient) between various environmental parameters and phytoplankton abundance

	WT	pH	DO	Con	TA	Sal	TH	TDS	TS	TU	Ca^{++}	Mg^{++}	Nitr	Phos	Sili	Sul	TR	BAC	MED	CONJ	CHL	XAN	CYA	COS	EUG
WT	1	0.57	0.55	−0.169	−0.034	−0.238	−0.312	−0.141	−0.049	−0.271	−0.272	−0.092	0.115	0.205	0.141	−0.044	−0.061	−0.292	−0.070	−0.237	−0.419	0.251	0.141	−0.252	−0.141
pH		1	**−0.697**	−0.112	−0.269	0.280	−0.150	−0.409	−0.464	−0.054	−0.303	0.221	0.226	0.047	0.155	−0.131	0.224	0.073	−0.417	−0.200	0.101	−0.302	−0.075	−0.193	0.280
DO			1	**0.655**	**0.616**	−0.163	0.142	0.145	0.250	0.042	**0.710**	−0.611	−0.193	−0.047	−0.335	0.517	−0.256	−0.027	0.380	0.091	0.072	−0.209	−0.074	0.227	−0.549
Con				1	0.412	−0.119	0.015	0.063	0.223	0.064	0.502	−0.425	−0.363	0.092	**−0.729**	**0.734**	−0.239	−0.299	0.288	0.294	−0.019	0.449	−0.535	−0.237	**−0.824**
TA					1	−0.023	0.200	0.198	0.391	−0.180	**0.612**	−0.373	0.148	−0.262	−0.037	−0.009	0.149	0.196	0.438	−0.283	0.264	−0.416	0.049	0.161	−0.336
Sal						1	**0.885**	**−0.736**	**−0.780**	**−0.928**	0.485	**0.765**	**0.722**	**−0.878**	0.226	−0.359	**0.731**	0.361	0.145	−0.438	0.442	−0.067	−0.014	0.235	−0.089
TH							1	−0.485	−0.511	**−0.928**	**0.694**	**0.653**	**0.628**	**0.922**	0.037	−0.292	**0.630**	0.321	0.363	−0.436	0.456	0.180	0.020	0.249	−0.256
TDS								1	**0.855**	−0.502	−0.280	−0.471	−0.360	0.417	−0.252	−0.081	−0.335	−0.185	−0.087	0.143	−0.123	0.037	−0.57	−0.341	−0.248
TS									1	**0.587**	−0.164	**−0.600**	−0.527	0.518	−0.358	0.145	−0.510	−0.141	0.028	0.199	−0.120	0.003	0.064	−0.273	−0.076
TU										1	−0.549	**−0.726**	**−0.788**	**0.985**	−0.218	0.463	**−0.882**	−0.537	−0.225	0.397	−0.427	−0.018	0.066	0.463	0.301
Ca^{++}											1	−0.072	0.219	**−0.684**	−0.140	0.128	0.195	0.410	0.364	−0.257	**0.589**	−0.266	0.006	0.463	−0.452
Mg^{++}												1	**0.646**	**−0.655**	0.157	−0.468	**0.683**	−0.009	0.105	−0.366	0.007	0.491	−0.006	−0.188	−0.068
Nitr													1	**−0.812**	0.432	**−0.614**	**0.900**	0.342	−0.097	−0.400	0.254	0.117	0.218	0.123	−0.085
Phos														1	−0.276	0.514	**−0.861**	−0.405	−0.256	0.423	0.473	−0.028	0.010	−0.276	0.341
Sili															1	**−0.710**	0.422	**0.582**	−0.134	−0.235	0.233	−0.148	0.339	**0.625**	0.326
Sul																1	**−0.631**	−0.524	0.150	0.485	−0.419	−0.087	−0.286	−0.251	−0.142
TR																	1	0.205	0.144	−0.324	0.194	−0.101	−0.080	0.081	−0.274
BAC																		1	−0.410	−0.253	**0.901**	−0.136	0.474	**0.702**	0.196
MED																			1	−0.256	−0.262	−0.080	−0.345	−0.036	−0.315
CONJ																				1	−0.352	0.145	−0.407	−0.092	−0.019
CHL																					1	−0.240	0.249	0.555	−0.050
XAN																						1	0.365	−0.311	0.297
CYA																							1	0.431	0.526
COS																								1	0.167
EUG																									1

The significant correlation coefficient $p < 0.05$ are indicated in bold

DO dissolved oxygen, *Con* conductivity, *TA* total alkalinity, *Sal* salinity, *TH* total hardness, *TDS* total dissolved solids, *TU* turbidity, *Nitr* nitrate, *Phos* phosphate, *Sili* silicate, *Sul* sulfate, *TR* transparency

Table 3 Microfloral profile of *Kailash Khal* wetland (generic level)

Phytoplankton	Monsoon	Post-monsoon	Pre-monsoon
Class: Bacillariophyceae			
Bacillaria sp.	+	+	+
Cymbella sp.	+	+	+
Fragilaria sp.	+	++	++
Gomphonema sp.	+	–	+
Gyrosigma sp.	+	+	+
Navicula sp.	++	++	++
Nitzschia sp.	+	+	+
Pinnularia sp.	+	+	+
Synedra sp.	+	+	+
Class: Chlorophyceae			
Ankistrodesmus sp.	–	+	+
Chlorella sp.	++	+	++
Microspora sp.	+	+	+
Monoraphidium sp.	+	+	+
Oedogonium sp.	+	+	+
Scenedesmus sp.	+	+	++
Ulothrix sp.	+	+	+
Class: Conjugatophyceae			
Closterium sp.	++	++	+
Cosmarium sp.	–	+	++
Spirogyra sp.	++	+	+
Class: Coscinodiscophyceae			
Aulacoseira sp.	+	++	++
Coscinodiscus sp.	+	+	++
Melosira sp.	+	+	+
Odontella sp.	+	+	++
Skeletonema sp.	+	+	+
Class: Euglenophyceae			
Euglena sp.	+	++	++
Phacus sp.	+	+	+
Trachelomonas sp.	+	++	++
Class: Mediophyceae			
Cyclotella sp.	+	+	++
Class: Cyanophyceae			
Anabaena sp.	+	+	++
Lyngbya sp.	+	+	+
Merismopedia sp.	+	–	+
Microcystis sp.	+	–	+
Nostoc sp.	+	+	++
Oscillatoria sp.	++	+	++
Class: Xanthophyceae			
Centritractus sp.	+	++	+
Tribonema sp.	–	++	++

'+' denotes presence; '–' denotes absence; '++' denotes dominance

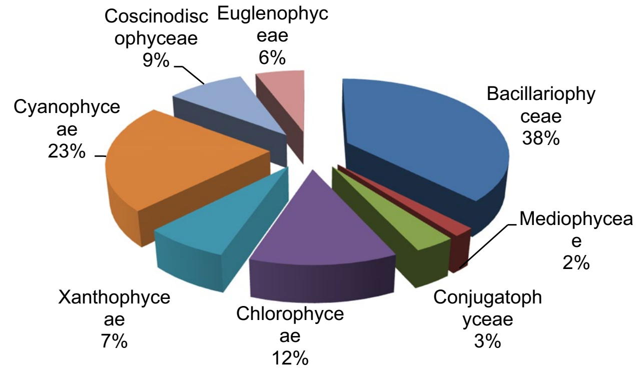

Fig. 2 Percentage compositions of different algal groups in *Kailash Khal*, Sundarbans

sampling stations got clustered individually representing variations in species compositions. The group average similarity among the samples showed the station KE and KS formed the similar pattern, comprising 82.91% similarity followed by the station KW (81%). The study was further confirmed by MDS analysis (Fig. 5) that reflected the analogous pattern of grouping among the samples as observed in cluster analysis. The station KN formed a separate group while other three stations, namely KW, KE and KS, formed another group with 80% similarity. The stress value was found less than 0.01 which is an excellent ordinance pattern that distances among items/samples are perfect and good representations by the observed data.

Nutrients nitrate, phosphate and silicate fractions were compared (season-wise) to determine principal limiting factor for growth of phytoplankton community in the wetland. The results revealed that N:P ratio in *Kailash Khal* water was lower than Redfield ratio (16:1) in all seasons indicating less bioavailability of nitrogen for phytoplankton productivity. The Si:P ratio was much higher than 'modified' Redfield ratio (15:1) (Brzezinski 1958) indicating silicate enrichment in the environment. Hence, this ecosystem seems to be a nitrogen-limited one and growth of phytoplankton can be considered as nitrogen controlled in the wetland.

Influence of physicochemical parameters on phytoplankton distribution

Karl Pearson's correlation

In the present study, it has been observed that turbidity has negative correlation with abundance of Bacillariophyceae, Mediophyceae, Chlorophyceae and Xanthophyceae but showed positive correlation with Cyanophyceae and Euglenophyceae. Silicate has significant positive correlation with Bacillariophyceae ($r = 0.582$; $p < 0.05$)

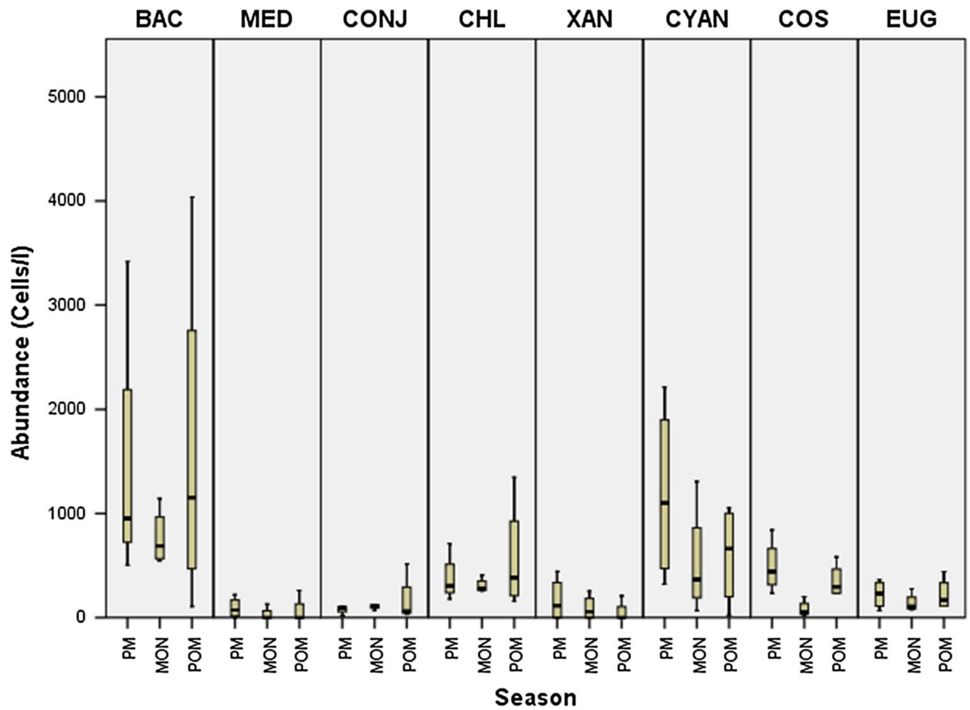

Fig. 3 Season-wise annual mean abundance of algal groups in *Kailash Khal. BAC* Bacillariophyceae, *MED* Mediophyceae, *CONJ* Conjugatophyceae, *CHL* Chlorophyceae, *XAN* Xanthophyceae, *CYAN* Cyanophyceae, *COS* Coscinodiscophyceae, *EUG* Euglenophyceae

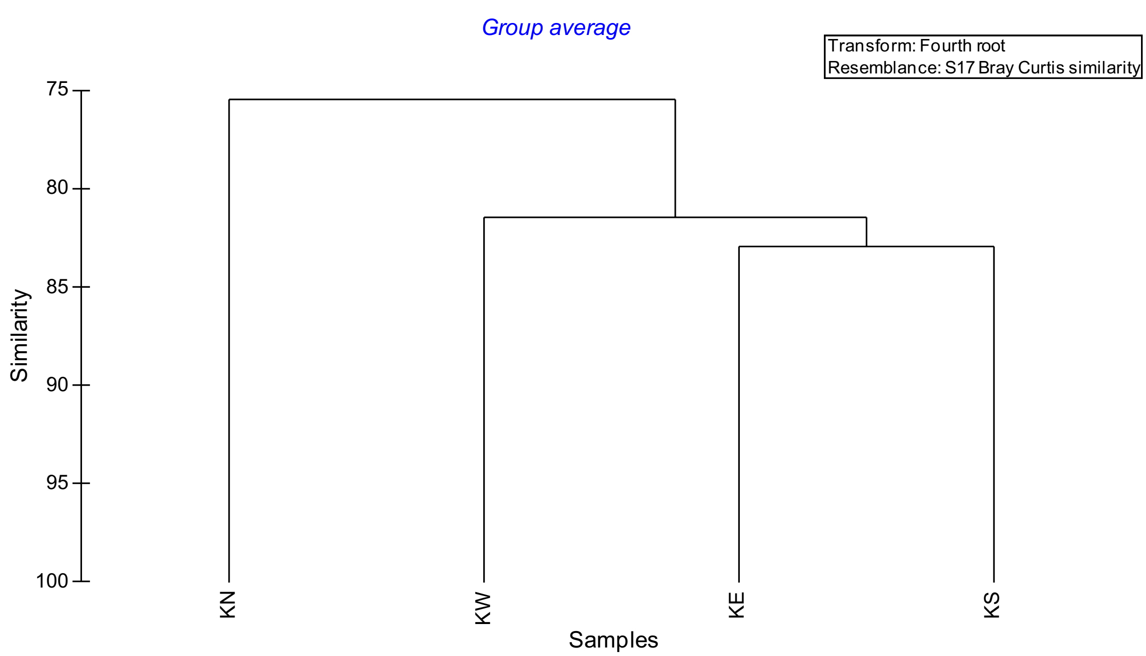

Fig. 4 Dendrogram showing similarity for the phytoplankton in different stations

and Coscinodiscophyceae ($r = 0.625$; $p < 0.05$). A positive correlation between nitrate and abundance of algal groups, Bacillariophyceae ($r = 0.342$), Chlorophyceae ($r = 0.254$), Cyanophyceae ($r = 0.218$) and Coscinodiscophyceae ($r = 0.123$), was observed, details of which are given in Table 2.

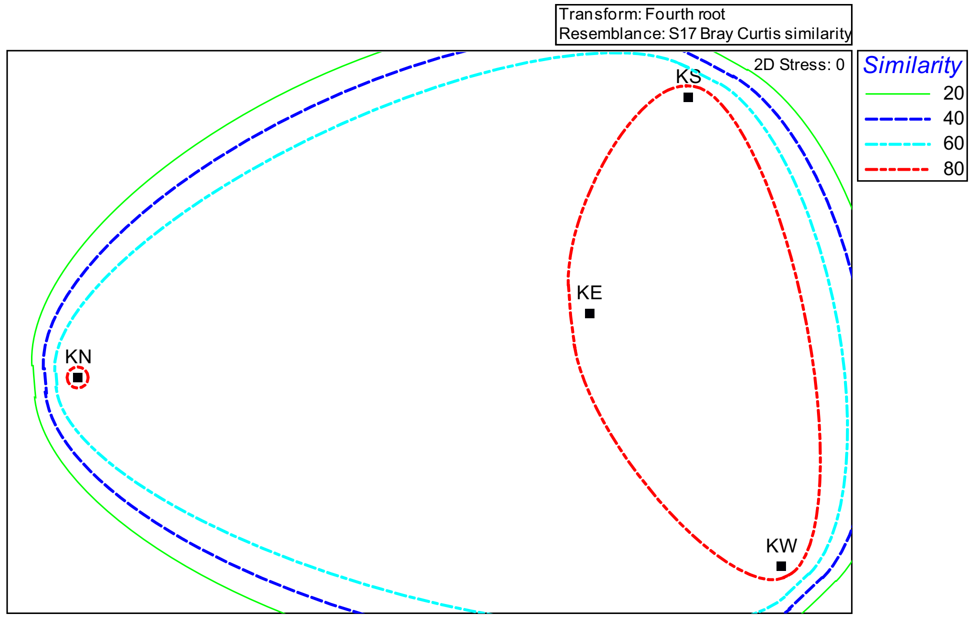

Fig. 5 Multidimensional scaling (MDS) map drawn for the phytoplankton in study sites

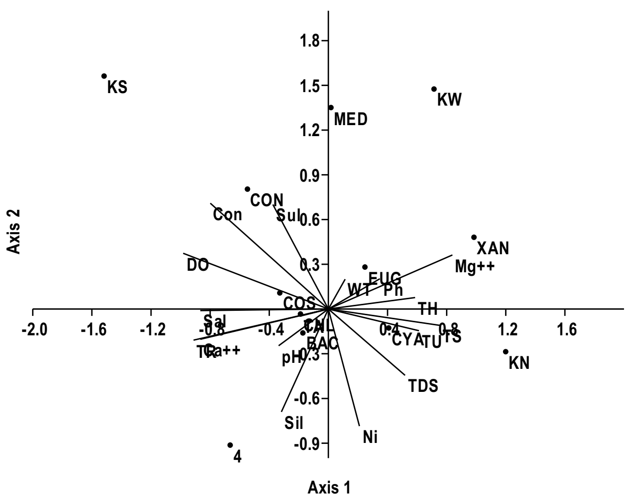

Fig. 6 CCA biplot (sites) drawn between physicochemical parameters and algal groups

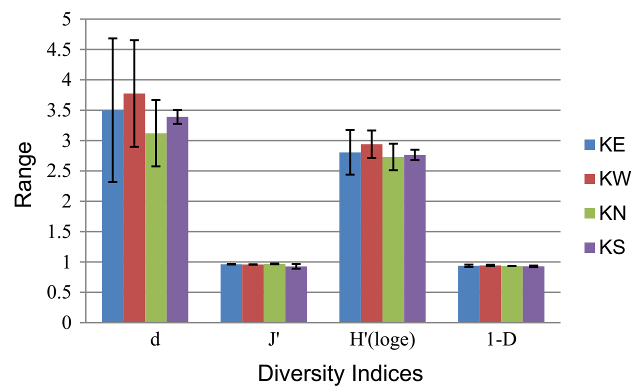

Fig. 7 Station-wise diversity indices of *Kailash Khal*, Sundarbans

Canonical correspondence analysis

To find out the specific coincidences in the distributions of phytoplankton and environmental attributes (WT, pH, DO, conductivity, TA, salinity, turbidity, TH, TDS, TS, Ca^{++}, Mg^{++}, nitrate, phosphate, silicate and sulfate), a CCA plot was created taking into account of all four stations (Fig. 6). The arrow length indicates importance of attributes with positive and negative correlation with the axes 1 and 2. The Eigen value and percentage of variance were calculated higher in axis 1 than in axis 2. This special set of scalars explained 0.1114 and 48.94% of correlation in axis 1 and 0.0857 and 37.64% of correlation in axis 2 between water quality attributes and algal groups. The variables pH, water temperature, total hardness and TDS showed a close relationship with the phytoplankton community. The algal group Bacillariophyceae and Chlorophyceae had negative correlation in axes 1 and 2, whereas Mediophyceae, Xanthophyceae and Euglenophyceae showed positive correlation with both the axes. It was observed that Euglenophyceae, Xanthophyceae and Mediophyceae were positively correlated with the water temperature, Mg^{++} and TH at the station KW, whereas they were negatively correlated with pH, TA, Ca^{++} and salinity at KE. Similarly, Conjugatophyceae and Coscinodiscophyceae were positively correlated with specific conductivity, DO and sulfate at station KS. Algal group Cyanophyceaealso showed positive correlation with turbidity, total solids and nitrate. However, Chlorophyceae and Bacillariophyceae reflected the negative relationships with pH, salinity, Ca^{++} and silicate at the station KE.

Diversity indices

The station-wise mean diversity indices were calculated for four stations of the wetland (Fig. 7). The Shannon–Wiener diversity (H') ranged from 2.730 to 2.939 and highest at station KW during pre-monsoon while lowest at station KN during monsoon season. Margalef species richness also showed similar observations, highest at station KW (3.774) during pre-monsoon and lowest at station KN (3.121) during monsoon season. The Margalef's species richness and Shannon diversity index were found > 2.7 in *Kailash Khal* water which indicated moderately rich phytoplankton diversity in the system.

Discussion

Environmental traits and their relationships

Qualitative properties of water are profoundly influenced by geological, hydrological, climatic and anthropological factors (Bartram and Balance 1996). Surface water temperature in the studied ecosystem showed an increasing trend from post-monsoon to monsoon, mainly influenced by intensity of solar radiation (Das et al. 1997; Senthilkumar et al. 2002; Santhanam and Perumal2003). The wetland exhibited slightly alkaline conditions throughout the study period as seen in Jharkhali estuary, Sundarbans, which was reported by Chaudhuri et al. (2012). Higher alkalinity during monsoon might be attributed to runoff from the nearby agricultural fields, and further rise during post-monsoon is facilitated by faster decomposition of plants and other organic wastes (Chaurasia and Pandey 2007). This observation is also in conformity with the findings of Dhanam et al. (2016) where the author found that total alkalinity levels reached its peak in monsoon and were found to be at its lowest in summer in Ousteri Lake, Puducherry. Saravanakumar et al. (2008) stated that low salinity level in brackish water habitats such as backwaters, estuaries and mangrove waters is due to influx of freshwater from land runoff caused by monsoon or by tidal variations, which supported our present findings. Lower concentration of dissolved oxygen was recorded during pre-monsoon, which might be due to increased temperature, salinity and biological activity (Levinton 2001). Turbidity was recorded highest in monsoon and lowest in pre-monsoon owing to the silt laden runoff from surrounding areas. These findings were in agreement with Perumal et al. (2009). Mean TDS value ranged between 1.83 and 2.29 g l^{-1} in *Kailash Khal* wetland which was much higher compared to WHO standards (500 mg l^{-1}). High value of TDS was recorded during monsoon, which might be due to addition of domestic waste, garbage and sewage (Verma et al. 2012; Choudhary et al. 2014).

Nutrient dynamics

Non-uniform seasonal trend has been observed among nutrients in the present study. Utilization of nitrate by photosynthetic organisms also could be one of the reasons for lower nitrate level during post-monsoon. It was observed during the course of study that highest magnitude of nitrate was found during pre-monsoon season which is contrary to various previous works (Dhanam et al. 2016; Verma et al. 2012). High concentration of phosphate during monsoon might be due to flow of freshwater and land runoff (Satpathy et al. 2009), and at the same, time lower concentration during post-monsoon season might be due to its utilization by photoautotrophs and buffering action of sediment under various environmental conditions (Rajasegar 2003; Perumal et al. 2009). Our findings are also in agreement with Adeyemo et al. (2008), Vajaravelu et al. (2017). Higher values of silicate were observed as compared to other nutrients (nitrate, phosphate) and showed similar trend with nitrate. The high Si:P ratio in the wetland may be attributed to runoff from the residential areas, waste produced from adjacent households and animal sheds. The low post-monsoonal value might be attributed to uptake of silicate by autotrophs for biological activity (Ramakrishnan et al. 1999). Many workers have established the fact that Sundarban eco-regions are highly productive with regard to nutrient concentrations (Biswas et al. 2004; Manna et al. 2010). However, Choudhury and Bhadury (2015) reported that seasonal estimates of N:P ratio mostly remained below the Redfield ratio of 16:1, indicating nutrient (nitrogen)-limited condition in Sagar Island, Sundaraban, which is in line with our present findings. Redfield (1958) approached to a conclusion that atomic ratios of elements in the biochemical cycle of plankton were statistically uniform and follow the stoichiometric ratio of C:N:P = 106:16:1 and this variation is mainly due to synthesis or decomposition of organic matter.

Phytoplankton abundance, composition and distribution

Numerous studies on diversity and assemblage pattern of phytoplankton in open estuarine system of Sundarbans had been carried out. Manna et al. (2010) reported 64 phytoplankton taxa belonging to six classes from *Bara Herobhanga Khal*, Sundarbans; 52 genera of phytoplankton (≥ 10 µm) were recorded from *Chemaguri* creek, Sundarbans (Bhattacharjee et al. 2013), which were higher compared to the present study. Centric diatoms were predominant in post-monsoon and pennates in pre-monsoon and monsoon in the present study which is in conformity with previous observation made by Manna et al. (2010). Centric forms (21 genera) constituted major part of the diatom assemblage in

Chemaguri creek and Mooriganaga River estuary, Sundarbans, previously reported by Bhattacharjee et al. (2013) while pennate diatoms were dominated in our study across all stations. Banerjee and Santra (1999) reported 48 species of diatoms from Hooghly–Matlah estuarine system, Sundarbans. Similarly, Biswas et al. (2004) also documented the ascendancy of diatoms (36 genera) encompassing three sites of the northeast coast of Bay of Bengal (off Mooriganga, Saptamukhi and Thakuran estuaries). Arumugum et al. (2016) have surmised that marked differences in phytoplankton diversity could be attributed to disparity in ecological distributions in types of organisms and variability of climatic and geographical locations. Increasing trends in abundance of Coscinodiscophytes coincides with salinity rise in post-monsoon and reached peak during pre-monsoon season in the present study. At the same time, dominance of Cyanophytes in pre-monsoon season in the present study showed conformity with dominance of Cyanobacteria in summer season from Zhongxin Lake which was probably due to the strong summer wind (Li et al. 2013). This finding was also in good agreement with Roshith et al. (2018) which showed that estuarine wetlands are mainly inhabited by Cyanobactertia. The author reported 91 species of phytoplankton from tidal freshwater zone, with dominance of green algae (41 species) followed by diatoms (34 species) from Hooghly–Matlah estuarine system.

Community structure in the present study was in line with Vajaravelu et al. (2017) that speculated comparatively higher species composition in post-monsoon as compared to pre-monsoon and monsoon. Higher abundance of chlorophytes in post-monsoon might be due to rich nutrients received from land runoff. *Bheries*, estuarine wetlands in Sundarbans, remain stagnant which favors the growth of phytoplankton, periphytic and epiphytic algal forms, ascendancy by Cyanophytes and Chlorophytes (Sarkar 2011). The maximum abundance of phytoplankton in pre-monsoon in this study could be related to the stable hydrographical conditions (Babu et al. 2013) and intermittent rainfall which facilitate nutrient enrichment coupled with higher abundance of euryhaline species during this season. Lower abundance of phytoplankton in monsoon might be due to sudden changes of hydrographical parameters (Sahu et al. 2012; Babu et al. 2013) which influenced their regeneration.

Temperature has an important effect on algal growth and reproduction through regulation of their physiological mechanism (Smith 1950; Munn et al. 1989), and thus, a positive correlation between temperature and phytoplankton abundance was seen in the present study. Based on the Pearson correlation matrix, it has been accounted that algal group Bacillariophyceae, Mediophyceae, Chlorophyceae and Xanthophyceae was inversely related to aquatic turbidity, which is in conformity with the findings of Sharma et al. (2016). Multivariate analyses are more sensitive than univariate analysis for detecting the changes in complicated biotic and abiotic parameters. They are also extremely useful for analyzing differences between communities at spatiotemporal scales and for illustrating how these communities vary along gradients of environmental conditions (Xu et al. 2008, 2011). The similar pattern of grouping among the stations in hierarchical cluster analysis and MDS in the present study is in line with Arumugum et al. (2016). In their observations, the authors stated that MDS plot revealed same groups as cluster, which was again demonstrating the variations in species composition and abundance in different zones of Muthupet mangroves. In this study, water variables pH, temperature, total hardness, TDS and nutrients showed a close affinity with the distributions of phytoplankton community. Algal group Euglenophyceae, Xanthophyceae and Mediophyceae were positively correlated with the water temperature, Mg^{++} and total hardness at the station KW while being negatively correlated with pH, TA, Ca^{++} and salinity at station KE. These loadings indicated that the main variation in algal density is related to the parameters pH and TA at the station KE. Similar results also are observed by Zhao et al. (2017) from a Hai River reservoir, Tianjin City. In our study, it was seen that spatial variation in algal groups accurately reflects the water conditions of the wetland. It should be noted that phytoplankton biomass is dependent on nutrient levels as reported by Harris (1986). Similarly, Potapova and Charles (2003) opined that conductivity and abundance of major ions (bicarbonate, carbonate, chloride), sulfate, calcium, magnesium, sodium, potassium explained a statistically significant amount of variation in assemblage composition of diatoms, which is seen in our study, especially with regard to specific conductivity.

Measures of diversity are frequently seen as indicators of the status of ecological systems (Cardoso et al. 2012). Pielou's evenness index value >0.92 across all seasons in the study indicated even distribution of phytoplankton in all stations of the wetland. De et al. (1994) reported the evenness index ranged from 0.65 to 0.92 in Hooghly estuarine system. The Margalef's species richness and Shannon diversity index were found >2.7 in *Kailash Khal* wetland which indicated moderately rich phytoplankton diversity in the system which coincides with the observation by Arumugum et al. (2016). However, our findings contradict with Manna et al. (2010) where the author reported the species diversity index declined with phytoplankton biomass during pre-monsoon and increased steadily during post-monsoon season in *Bara Herobhanga Khal*, Sundarbans.

Conclusion

Microfloral community of *Kailash Khal* wetland exhibits a total of 36 genera under 8 algal groups with Bacillariophytes as top contributor followed by Cyanophytes, Chlorophytes, Coscinodiscophytes, Xanthophytes, Euglenophytes, Conjugatophytes and Mediophytes. In this study, the spatial variations in phytoplankton community structure were significantly correlated with certain environmental variables (pH, temperature, total hardness, TDS and nutrients like nitrate, phosphate and silicate) which were evident from CCA. Hence, this finding agreed upon the spatiotemporal variation in algal groups accurately reflects water conditions of the study area. Margalef's richness (*d*) and Shannon diversity index (H') calculated more than 2.70 which indicated moderately rich phytoplankton diversity in the system. Phytoplankton biomass is primarily depending on the nutrients present in water. Our study reflected that N:P ratio was lower than the proposed Redfield ratio (16:1) in the wetland which indicated nitrogen-limited environment. Acceleration of high organic load during monsoon season coupled with phosphate, silicate and nitrate plays important role for successions of phytoplankton in forthcoming seasons in the wetland. Information presented on algal abundance, distributions and their relationships with various environmental attributes will contribute to our understanding further in ecological interactions of these communities. Wealth of recorded phytoplankton genera throughout the study period might be directly linked to their growth rates and indirectly through interactions of environmental gradients. We encourage more in-depth studies in *Kailash Khal* wetland assessing plankton communities with special focus on phytoplankton dynamics and ecological interactions of these communities.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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