Environmental Research Communications

PAPER

Unusual abundance of bloom forming *Aulacoseira* spp. diatom populations in an anthropogenically impacted stretch of lower part of the River Ganga

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Keywords: River Ganga, dissolved nutrients, diatom, *Aulacoseira*, bloom, water pollution

Supplementary material for this article is available online

Abstract

The River Ganga is reeling from pressures of rapid urbanization and resulting anthropogenic forcings. In this study, phytoplankton community assemblages were deduced from the Dakshineswar site located in the lower stretch of River Ganga to quantify and understand the health status of this river. Surface water samples were collected from six pre-defined stations of Dakshineswar spanning across monsoon and post-monsoon seasons of 2019 and 2020. Stations were categorized into point source and surface water based on proximity to municipal discharges. Measurement of *in situ* environmental parameters showed significant differences in values for dissolved oxygen, total dissolved solids, electrical conductivity and suspended particulate matter between the two seasons during the study period. In particular, concentrations of dissolved nitrate and silicate were found to be higher in point source stations compared to surface water stations. The concentration of Chlorophyll-a (Chl-a) was found to be higher in post-monsoon compared to monsoon seasons. Phytoplankton communities consisted of 23 diatom taxa and 14 green algal taxa and they showed distinct seasonal and spatial variations in the study site. Phytoplankton communities were dominated by diatom taxa namely *Aulacoseira, Bacillaria, Coscinodiscus,* and green algal taxa such as *Ulothrix, Chlorella,* and *Scenedesmus.* There was a dramatic increase in cell abundance of *Aulacoseira* spp. in post-monsoon seasons indicating a bloom-like scenario. Moreover, the rapid increase in cell abundance of *Aulacoseira* spp. also coincided with an increase in Chl-a and a sharp fall in the concentration of dissolved silicate. Some of the encountered phytoplankton taxa such as *Tetraedron, Cosmarium, Nitzschia* and *Scenedesmus* showed strong co-occurrence patterns indicating possible association at ecological scales. Four distinct clusters were formed in nMDS ordination plot based on the influences of environmental variables on encountered phytoplankton taxa. Network analysis revealed evidence of co-occurrence patterns between several diatoms and green algal taxa.

Abbreviations

PS Point Source
Stn Station
Chl-a Chlorophyll-a
DO Dissolved Oxygen
SW Surface water

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Introduction

Rivers represent the primary source of freshwater for sustenance of human populations globally by providing usable water for drinking, agriculture, industrial and recreational activities (Chen et al 2006, Anawar and Chowdhury 2020). However, due to rapid growth of human population along the banks, many riverine systems have witnessed uncontrolled water pollution and deterioration in water quality. River Ganga, which forms the lifeline of India, traverses a length of ~2500 before meeting the coastal Bay of Bengal. The river supports a population density of ~400 people/sq. km along its banks while traversing through important cities of Haridwar, Varanasi, Prayagraj, Kanpur, Patna and Kolkata.

As the River Ganga enters its last stretch in West Bengal in the eastern part of India, there is a rapid increase in width along with a decrease in flow rate which is further regulated by barrages including the Farakka Barrage. Downstream of the barrage, the river splits as the right leg, known as Bhagirathi-Hooghly, flows through the state of West Bengal and drains into the coastal Bay of Bengal, and the left leg known as Padma River flows into the Bangladesh. Natural disturbances along with rampant population growth resulting in anthropogenically induced disturbances have collectively led to an increase in pollution along River Ganga. Regulatory bodies such as the Central Pollution Control Board (CPCB) estimates ~8250 million l d⁻¹ (MLD) of wastewater is being generated from human settlements residing along the banks of River Ganga. Of this, ~2550 MLD is discharged directly into the river without any prior treatment. Discharge of wastewater has also led to an increase in faecal coliform counts, especially in the stretch between Dakshineswar and Diamond Harbour sectors of West Bengal. Deterioration of the water quality in Dakshineswar is of immediate concern as this site is visited by millions of people on an annual basis due to its significance as a site for pilgrimage and therefore bathing activities are undertaken in the holy River Ganga.

Unabated release of waste, both solid waste and wastewater, has led to high concentration of dissolved forms of nutrients causing eutrophication, decrease in dissolved oxygen concentrations and harmful algal bloom formation, in turn lowering the water quality of the surface water of Bhagirathi-Hooghly (Sarkar et al 2019, Kumar et al 2021, Muduli et al 2021). In Bhagirathi-Hooghly, water quality has been found to marginally improve during post-monsoon owing to high seasonal precipitation that spans over July to September and often stretches to October (Kumar et al 2021). Local rainfall results in excess disposal of wastewater into the surface water of many rivers in India (Singh et al 2004). Estimation of water quality index (WQI) allows to quantify the effects of several water quality parameters in a single unit-less value (Horton 1965) and provides a holistic idea about the water quality of riverine systems.

Altered surface water quality in rivers shape the resident biological communities including phytoplankton assemblages. Phytoplankton are the photosynthetic primary producers that form the basis of food chain in riverine ecosystems. Large rivers with high nutrient supply provide suitable conditions for phytoplankton growth (Reynolds and Descy 1996, Wehr and Descy 1998). Dominant phytoplankton taxa have faster growth rates and can withstand high turbidity and low light conditions (Reynolds 1988). Environmental parameters including water quality thus play a key role in controlling the structure and function of phytoplankton assemblages in rivers. Previous reports indicate that changes in environmental conditions including retention time have favoured the growth of limnetic phytoplankton but inhibited phytoplankton growth in large rivers such as River Seine in France (Billen et al 1994, Gamier et al 1995); the Moselle in France and Germany (Schöl et al 1999, Descy et al 2003), The Rhine in Germany and Netherlands (Scherwass et al 2010) and the River Ganga in India (Khanna et al 2012).

One of the earliest studies undertaken in the Varanasi sector of the River Ganga was focused on investigating the productivity and periodicity of phytoplankton in link with physical and chemical characteristics (Lakshminarayana 1965). The author reported dominance of diatoms communities and also found that water level, transparency and temperature affected the growth of phytoplankton communities. Subsequently, several studies have looked at the relationship between anthropogenic influences and phytoplankton communities in upper stretch of the River Ganga (e.g. Matta et al 2018, Mohanty et al 2022). However, majority of the studies are focused either on upper middle stretch of the River Ganga while only one study has been reported from lower stretch of the River (Sarkar et al 2019 and references herein) looking into the effect of barge trafficking on phytoplankton assemblages. The Bhagirathi-Hooghly has been referred to as the lower stretch of the River Ganga throughout the remaining part of this study.
Based on the available information, the objectives of this study were to (a) elucidate phytoplankton community assemblages in Dakshineswar site representing lower stretch of the River Ganga (b) identify environmental parameters that could lead to bloom-like conditions in the surface water of Dakshineswar site.

Materials and methods

Study site
This study was conducted in Dakshineswar (22°39′19.55″N, 88°21′28.3′E), a site frequented by religious devotees, offering prayers to the famous Dakshineswar Temple, located on the bank of the River Ganga [Supplementary figure S1 (available online at stacks.iop.org/ERC/4/045011/mmedia)]. Each year thousands of devotees visit the temple to offer prayers and take a dip in the holy River. In addition to human-induced direct activities, there are several small to medium-sized industries which release effluent into the River. Six sampling points in the Dakshineswar site were identified after initial rigorous monitoring (see details in Kumar et al 2021). The points immediately in the vicinity of municipal discharge drains and industrial effluent release zone were earmarked as point sources or PS stations. Water samples were collected from PS stations and colour of the water was found to be visibly black or grey irrespective of the time of sampling. The area beyond this black or grey region of the PS stations were designated as surface water or SW stations. Three such PS and SW stations were identified and monitored in monsoon and post-monsoon over a span of two years. Site selection criteria and sampling strategies have been discussed previously (Kumar et al 2021). The station nomenclature as laid out previously (Kumar et al 2021) has been modified in this manuscript and detailed in table S1.

Sampling
Sampling was conducted one time in monsoon (September 2019 and October 2020) and one time in post-monsoon (February 2020 and March 2021). During the time of sampling, in situ environmental parameters were measured in triplicates. Surface water samples were collected from six stations spanning PS and SW stations using wide-mouthed pre-cleaned HDPE amber bottles of 1 l capacity (Tarsons, India) and immediately fixed with 4% buffered formalin (Merck, India) for dissolved nutrients analysis and for estimation of suspended particulate matter (SPM). Surface water samples (50 ml) was collected in sterile centrifuge tubes (Tarsons, India) from all six stations for phytoplankton count and identification spanning the sampling seasons.

Measurement of in situ environmental parameters
In situ environmental parameters were measured in triplicates at each station during the time of sampling. Air temperature (AT) and surface water temperature (SWT) were measured using a digital thermometer (Digi-sense RTD single input Thermometer 20250-95, NIST-Traceable Calibration). Other parameters namely, dissolved oxygen (DO) (DO; Oakton DO 6+, Eutech Instrument Pte Ltd., Singapore), pH (Oakton pH 5+, Eutech Instrument Pte Ltd., Singapore), electrical conductivity (EC; HM Digital EC/TDS/TEMP COM-100 Myron L Company), total dissolved solids (TDS; HM Digital EC/TDS/TEMP COM-100 Myron L Company, USA) and Secchi depth (Secchi disc, LaMotte, France) were also measured. The total depth of the water was measured with a graduated yardstick and only for stations where the bottom sediment could be reached this was noted. To obtain accurate results, all instruments were calibrated in the laboratory first and then again in the field during each time of sampling.

Estimation of dissolved nutrients and SPM
Dissolved nutrients were analyzed by filtering the samples through a 0.45 μm 47 mm nitrocellulose filter paper (Millipore, Germany). Dissolved nutrients including nitrate (Finch et al 1998), ortho-phosphate (o-phosphate) (Strickland and Parsons 1972), nitrite (Strickland and Parsons 1972), ammonium (Liddicoat et al 1975) and silicate (Strickland and Parsons 1972) using UV–vis Spectrophotometry (U2900, Hitachi Corporation, Japan). All estimations were performed in triplicates. SPM in surface water from PS and SW stations were measured following published protocol (Choudhury et al 2015).

Phytoplankton quantification, taxonomy and estimation of pigments
Formalin-fixed surface water samples (50 mL) were concentrated by centrifugation at 3000 rpm for 5 min. The concentrate was used for slide preparation. Slides were prepared by drop count method (Verlencar and Desai 2004) and the abundance of identified taxa were extrapolated to obtain their corresponding abundance per litre. Taxonomic identification and documentation of phytoplankton with a focus on members of Bacillariophyceae (diatom) were performed at 400X magnification using bright field microscopy (Olympus BX-53, Japan). Pigments such as Chl-a and Carotenoids were measured from 1 L surface water collected from each station following published protocols (Choudhury et al 2015, Kumar et al 2021).
Statistical analysis
A two-way analysis of variance (ANOVA) was performed to identify significant differences in the concentration of environmental parameters between PS and SW stations across studied seasons. Shannon diversity index was calculated using the diversity function of vegan in R (Oksanen et al. 2017). A co-occurrence network was constructed using cocor and vizNetwork functions in R. The nMDS coordination plot was performed using metaMDS function of vegan in R. Palmer index was calculated to estimate the possible presence of organic pollutants in the studied stations (Palmer 1969).

Results

Seasonal and spatial variation in environmental parameters
In-situ parameters
Environmental parameters which were measured across all the stations during the sampling regime are detailed in table S1. Air temperature (AT) in the studied stations ranged from 28.2 °C–30.37 °C in monsoon 2019 and 26.30 °C–33.60 °C in post-monsoon 2019. No significant difference in AT was observed in studied stations and seasons (p > 0.05). AT increased during monsoon in the following year and ranged from 32.8 °C–33.8 °C in the monsoon of 2020 and 31.5 °C–32.5 °C in post-monsoon of 2020. The surface water temperature (SWT) was ~29 °C in monsoon, 2019 which lowered marginally in post-monsoon (2019) (21.5 °C–24.30 °C) but significantly increased in the next year (p < 0.05). The recorded SWT in 2020 ranged from 30.2 °C–32.2 °C in monsoon and 25.8 °C–27.7 °C in post-monsoon of 2020. The concentration of DO ranged between 4.0–4.87 mg l⁻¹ in monsoon (2019) which increased significantly in post-monsoon of 2020 and ranged from 6.50–8.90 mg l⁻¹ (p > 0.05). DO showed a wider range in the monsoon of 2020 (2.6–8.6 mg l⁻¹) but changed only marginally in post-monsoon 2020 (4.3–6.8 mg l⁻¹) (table S1). There was a significant difference in DO concentration between the PS and SW stations and between the studied seasons (p > 0.05). In both the years, DO was significantly lower in monsoon than post-monsoon for all stations except Stn2_PS_Mon20 (table S1). The pH value recorded in the monsoon of 2019 ranged from 6.8–7.70 with the lowest value in Stn2_PS_Mon19 (6.8) and 7.0–7.90 in post-monsoon 2019, with the lowest value recorded in Stn1_SW_PM19 (7.0) (table S1). No significant change was observed in the monsoon of 2020 (7.0–8.1) and post-monsoon (2020) (7.1–7.6). In the monsoon of 2020, lowest value (7.9) was recorded in Stn1_PS_Mon20 and in post-monsoon 2020, the lowest value (7.1) was recorded in Stn3_SW_PM20. Electrical conductivity (EC) in monsoon 2019 ranged from 138–147 μS cm⁻¹ and 200–676 μS cm⁻¹ in post-monsoon of 2019 (table S1). Similar to 2019, EC values ranged from 122–706 μS cm⁻¹ in monsoon 2019 and 122–163 μS cm⁻¹ in post-monsoon of 2020. Even though no significant difference was noted in EC between the season, EC significantly varied between the PS and SW stations. EC was always higher at PS stations as compared to SW stations during the sampling period in all seasons. In the monsoon of 2020 highest EC was recorded in Stn1_PS_Mon20 (706 μS cm⁻¹) and the second-highest value of 676 μS cm⁻¹ was recorded in post-monsoon of 2019 in Stn1_PS_PM19. In the monsoon of 2019 TDS ranged from 65.10–78.3 ppm. TDS was significantly increased in the next year (p < 0.05) which increased significantly in post-monsoon of 2020 and ranged from 6.50–8.90 mg l⁻¹ (p > 0.05). DO showed a wider range in the monsoon of 2020 (2.6–8.6 mg l⁻¹) but changed only marginally in post-monsoon 2020 (4.3–6.8 mg l⁻¹) (table S1). There was a significant difference in DO concentration between the PS and SW stations and between the studied seasons (p > 0.05). In both the years, DO was significantly lower in monsoon than post-monsoon for all stations except Stn2_PS_Mon20 (table S1). The pH value recorded in the monsoon of 2019 ranged from 6.8–7.70 with the lowest value in Stn2_PS_Mon19 (6.8) and 7.0–7.90 in post-monsoon 2019, with the lowest value recorded in Stn1_SW_PM19 (7.0) (table S1). No significant change was observed in the monsoon of 2020 (7.0–8.1) and post-monsoon (2020) (7.1–7.6). In the monsoon of 2020, lowest value (7.9) was recorded in Stn1_PS_Mon20 and in post-monsoon 2020, the lowest value (7.1) was recorded in Stn3_SW_PM20. Electrical conductivity (EC) in monsoon 2019 ranged from 138–147 μS cm⁻¹ and 200–676 μS cm⁻¹ in post-monsoon of 2019 (table S1). Similar to 2019, EC values ranged from 122–706 μS cm⁻¹ in monsoon 2019 and 122–163 μS cm⁻¹ in post-monsoon of 2020. Even though no significant difference was noted in EC between the season, EC significantly varied between the PS and SW stations. EC was always higher at PS stations as compared to SW stations during the sampling period in all seasons. In the monsoon of 2020 highest EC was recorded in Stn1_PS_Mon20 (706 μS cm⁻¹) and the second-highest value of 676 μS cm⁻¹ was recorded in post-monsoon of 2019 in Stn1_PS_PM19. In the monsoon of 2019 TDS ranged from 65.10–78.3 ppm. TDS was significantly higher in PS stations compared to SW stations (p > 0.05).

The SPM in monsoon 2019 ranged between 126.20–705 mg l⁻¹ (average in PS-138 mg l⁻¹, SW-387 mg l⁻¹), and 12.27–618.40 mg l⁻¹ in post-monsoon of 2019 (average in PS-302 mg l⁻¹, SW-49 mg l⁻¹), while in monsoon 2020 SPM ranged from 10.53–125.6 mg l⁻¹ (average in PS-58 mg l⁻¹, SW-49 mg l⁻¹); in post-monsoon 2020 SPM values varied between 99.4–126.7 mg l⁻¹ (average in PS-124 mg l⁻¹, SW-113 mg l⁻¹). The highest SPM value was recorded in Stn2_SW_Mon19 and Stn3_PS_PM19. No significant variations in SPM were noted between the sampling seasons and stations. Total alkalinity (TA) measured in monsoon of 2019 ranged from 110–160 mg l⁻¹ CaCO₃ (average in PS-140 mg l⁻¹, SW-146 mg l⁻¹), while in post-monsoon 2019, TA was found in the range of 180–330 mg l⁻¹ CaCO₃ (average in PS-280 mg l⁻¹, SW-186 mg l⁻¹). In monsoon of 2020, TA changed to 113.3–163.3 mg l⁻¹ CaCO₃ (average in PS-132 mg l⁻¹, SW-128 mg l⁻¹) and 86.67–126.7 mg l⁻¹ CaCO₃ in post-monsoon of the same year (average in PS-138 mg l⁻¹, SW-103 mg l⁻¹). Changes in TA did not show significant variation across studied seasons and stations. In the monsoon of 2019 total hardness ranged between 125–150 ppm CaCO₃, in post-monsoon 2019 ranges were from 125–275 ppm CaCO₃ whereas in the monsoon of 2020 the values varied between 66.7–275 ppm CaCO₃ and in post-monsoon 2020 it ranged between 125–175 ppm. Maximum values were recorded in Stn1_PS_Mon19 and Stn3_PS_PM19 stations. The box plots show the observed variation of all environmental parameters representing monsoon and post-monsoon seasons of both years [figure S2(a)].
Profiles of Chl-a and Carotenoids

The Chl-a pigment concentration ranged 1.81–4.13 mg l\(^{-1}\) (average in PS-2.44 mg l\(^{-1}\), SW-2.7 mg l\(^{-1}\)) in monsoon of 2019 to 8.13–54.34 mg l\(^{-1}\) (average in PS-11 mg l\(^{-1}\), SW-51 mg l\(^{-1}\)) in post-monsoon of the same year. In monsoon of 2020, Chl-a ranged from 1.75–10.49 mg l\(^{-1}\) (average in PS-4.8 mg l\(^{-1}\), SW-2.8 mg l\(^{-1}\)) and in post-monsoon it was 2.17–17.29 mg l\(^{-1}\) (average in PS-8.2 mg l\(^{-1}\), SW-16 mg l\(^{-1}\)) (table S1). The lowest value of Chl-a was recorded in Stn2SW_Mon20 in monsoon (2020) (1.75 mg l\(^{-1}\)) (table S1). The highest value was recorded in Stn3SW_PM19 of post-monsoon (2019). The Chl-a value was found to be higher in SW stations compared to PS stations during the sampling period but in the monsoon of 2020 Stn3PS_Mon20 and Stn4PS_Mon20 had higher values than SW stations. Though estimated Chl-a were similar across the stations, there was significant variation between the stations and seasons (p < 0.05). The concentration of Carotenoids ranged between 0.8–1.8 mg l\(^{-1}\) in the monsoon of 2019 to 3.1–22.0 mg l\(^{-1}\) in post-monsoon 2019 whereas in the monsoon of 2020 the value ranged from 0.2–3.1 mg l\(^{-1}\) and 1.0–6.5 mg l\(^{-1}\) in post-monsoon of 2020. The lowest value of Carotenoids was recorded in stations of Stn2_SW_Mon20 and Stn3_SW_Mon20 in the monsoon of 2020 (0.2 mg l\(^{-1}\)). The highest value was recorded in Stn3_PS_PM19 (22.0 mg l\(^{-1}\)) during the post-monsoon of 2019. Except for three stations namely Stn3_PS_Mon19, Stn2_PS_Mon20 and Stn3_PS_Mon20, in the monsoon of 2020 all the remaining SW stations had higher values of Carotenoids. The box plot shows the variation of observed concentrations of Chl-a and Carotenoids in both years (figure S2(b)).

The concentration of dissolved nutrients

During monsoon of 2019, dissolved ammonium concentration ranged from 0.42–0.89 μM while in post-monsoon the observed values ranged between 0.073 μM in post-monsoon (table S1). In the subsequent year, ammonium concentration ranged from 0.05–2.09 μM in monsoon while in post-monsoon the values were from 0.1–21 μM. The highest concentration of ammonium was recorded in Stn3_PS_Mon20 (2.09 μM) during the monsoon of 2020. A significant difference (P < 0.05) was observed between the seasons for ammonium concentrations. Dissolved nitrate concentration in the monsoon of 2019 ranged from 84.72–100 μM and 60–491.5 μM in post-monsoon which was similar to nitrate concentrations obtained in the following year (63.55–180 μM in the monsoon of 2020 and 35.16–69.68 μM in post-monsoon of 2020). The PS stations generally showed significantly higher nitrate concentrations [highest in Stn3PS_Mon19 and Stn1_PS_Mon20 (p > 0.05)]. Similar trends were seen for dissolved nitrite concentrations (0.15–1.33 μM in the monsoon of 2019; 0.11–1.90 μM in post-monsoon of 2019; 0.17–1.92 μM in the monsoon of 2020 and 0.09–0.34 μM in post-monsoon of 2020) in SW stations (Stn3_SW_PM20 in post-monsoon of 2020) whereas high concentrations were estimated in PS stations (Stn2_PS_Mon19 in the monsoon of 2019, post-monsoon of 2019 and Stn2_PS_Mon20 during the monsoon of 2020). Silicate concentration showed no significant difference between studied stations and seasons (p > 0.05). The o-phosphate concentration in the monsoon season of 2019 ranged from 9.74–21.32 μM and 6.91–35.26 μM in post-monsoon of 2019. In 2020, o-phosphate concentrations in monsoon and post-monsoon seasons were found to be 1.4–37.3 and 0.9–2.7 μM respectively. The o-phosphate concentration showed no significant difference between studied stations and seasons (p > 0.05). Similarly, in the monsoon of 2019 dissolved silicate concentration ranged from 65.19–97.41 μM and during post-monsoon, the values were from 26.88–43.75 μM. In the monsoon of 2020, the values ranged from 66.88–120.31 μM while in post-monsoon the observed values were from 65.31–113.13 μM. In general, silicate concentrations were found to be higher in PS stations compared to SW stations (table S1). There was a significant difference in silicate concentration (P < 0.05) between the studied seasons. The box plot depicts the observed variability of the concentration of dissolved nutrients representing both the years (figure S2(b)).

Phytoplankton cell abundance assemblages

Phytoplankton cell abundance varied from ~1.3 × 10\(^5\) cells l\(^{-1}\) in monsoon 2019 to ~9 × 10\(^5\) cells l\(^{-1}\) in post-monsoon of 2019 (table S1). In 2020, cell density ranged from ~5 × 10\(^5\) cells l\(^{-1}\) in monsoon to ~1 × 10\(^6\) cells l\(^{-1}\) in post-monsoon. Except in post-monsoon 2020, phytoplankton cell abundance was always higher in SW stations compared to PS stations. The highest abundance of phytoplankton cells was encountered in Stn1_PS_PM20 while the lowest abundance was encountered in Stn3_PS_Mon20 (table S1). In total 23 diatom taxa and 14 green algal taxa were identified using bright-field microscopy from all the studied stations. Among diatoms, 20 pennate diatom taxa and 3 centric diatom taxa were identified namely Aulacoseira spp., Bacillaria sp., Coscinodiscus spp., Cosmioneis spp., Cyclotella spp., Cymbella spp., Diatomia sp., Diatomella sp., Fragilaria spp., Fragilariforma sp., Gomphonema spp., Gyrosigma spp., Navicula spp., Nitzschia sp., Pinnularia sp., Seniorbis sp., Skeletonema sp., Stauroeis sp., Suirella sp., Synedra sp., Thalassionema sp., Thalassiosira spp., and Triceratium sp. (figure 1). Shannon diversity index was comparable between the stations across studied seasons with a marginally lower value in the monsoon of 2020. All identified taxa showed distinct seasonal and spatial variations across the stations whereas in Stn3_PS_Mon20 the cells comprised of only Aulacoseira spp. Among these, Aulacoseira spp. were abundant in all studied stations through the sampling period (figure 2). Aulacoseira
spp cell density ranged between $5 \times 10^5$ cells $l^{-1}$ in the monsoon of 2019 and $4 \times 10^5$ cells $l^{-1}$ in the post-monsoon of 2019 (table S1). In monsoon 2020, only $1 \times 10^6$ cells $l^{-1}$ were encountered which drastically increased to $7 \times 10^5$ cells $l^{-1}$ in post-monsoon of 2020. The abundance of *Aulacoseira* spp. was mostly
comparable between the PS and SW stations. Other diatom taxa identified as part of this study showed distinct seasonal variation.

A total of 14 green algal taxa belonging to *Ulothrix* spp., *Chlorella* sp., *Scenedesmus* spp., *Merismopedia* sp., *Tetraedron* sp., *Cosmarium* sp., *Coelastrum* sp., *Tetrastrum* sp., *Micractinium* sp., *Eudorina* spp., *Pediastrum* sp., *Westella* sp., *Dictyosphaerium* sp. and *Actinastrum* sp. were identified (figure 3). In addition, some filamentous algal members represented by *Oscillatoria* sp. belonging to Cyanobacteria were also encountered. The most abundant green algal taxa identified in this study were represented by *Ulothrix* spp. and *Scenedesmus* spp. No cells of *Ulothrix* were found in collected surface water samples of monsoon 2019 and monsoon of 2019 except in Dak_Stn1_PS. Their abundance was significantly higher in the post-monsoon seasons of 2019 and 2020 (average cell abundance of $1 \times 10^5$ cells l$^{-1}$). Cells of *Scenedesmus* populations were overwhelmingly dominant in monsoon 2020 and absent in monsoon 2019. Cells representing the taxa *Merismopedia* sp., *Actinastrum* sp., and *Dictyosphaerium* sp. were found in the post-monsoon of both years but was absent in the monsoon season of both years.

**Bloom of *Aulacoseira* cells**
A dramatic increase in cell abundance of *Aulacoseira* spp. population indicate possible bloom during the post-monsoon season in the study site. *Aulacoseira* spp. abundance was higher in PS stations (average abundance $\sim 7 \times 10^4$ l$^{-1}$) compared to SW stations (average abundance $\sim 5 \times 10^3$ l$^{-1}$) during monsoon. During post-monsoon, cell abundance increased to $\sim 9 \times 10^4$ l$^{-1}$ with a comparable abundance in both PS and SW stations. The highest cell density of *Aulacoseira* spp. was encountered in Stn2_SW_PM20 (1266667 cells l$^{-1}$) while in Stn3_PS_Mon20 only 1667 cells l$^{-1}$ were encountered. Only in the Stn1_PS_Mon20, *Aulacoseira* cells were not encountered. Increase in cell abundance of *Aulacoseira* spp. corresponded with a sharp increase in Chl-a concentration and a decrease in dissolved silicate as well as $o$-phosphate concentrations ($R^2 = 0.67$). The trends of regression analysis are detailed in figures S3(a) and (b) for monsoon and post-monsoon seasons respectively.

**Co-occurrence patterns**
The occurrence of most phytoplankton genera including diatoms and green algae appears to be independent of other genera. There was strong positive interaction between *Tetraedron-Cosmarium-Nitzschia-Scenedesmus* and *Scenedesmus-Merismopedia-Navicula*. Positive interaction was also found between *Scenedesmus-Triceratium-Synedra-Cylotella, Thalassiosira, Scenedesmus-Diatom* and *Coscinodiscus-Fragilaria-Pediastrum*. Negative
co-occurrence patterns were observed between Scenedesmus-Skeletonema, and Skeletonema with both Nitzschia and Triceratium (figure S4). Occurrence patterns were further reinstated by the nMDS ordination plot which showed strong seasonal trends. Four distinct clusters were observed based on nMDS analysis (figure 4). The phytoplankton community structure of monsoon (2019) appeared to be shaped by several environmental parameters including SPM, total hardness and SWT. The phytoplankton community structure of post-monsoon (2019) was influenced by surface water DO in Stn1_SW_PM19 and Stn2_SW_PM19 while in monsoon (2020) the same stations appeared to be influenced by pH. No distinct environmental parameter measured in this study showed direct control towards shaping the observed phytoplankton community structure of post-monsoon (2020).

**Discussion**

Rapid urbanization and resulting anthropogenic forcings have led to disproportionate pressure on water usage in the River Ganga. Consequently, water quality has significantly deteriorated in several stretches of the river owing to high load of pollutants that has further amplified downstream of the river. The lower stretch of the River Ganga, also known as Bhagirathi-Hooghly as it enters West Bengal, exhibit poor to very poor water quality based on the water quality index (WQI) (Kumar et al. 2021). A previous study focusing on estimating the spatial and temporal trends of WQI along the lower stretch of River Ganga revealed a distinct declining trend in the Dakshineswar site irrespective of the season of sampling (Kumar et al. 2021).

Variation in water quality is directly impacted by alterations in environmental conditions including pH and DO, in addition to forms of dissolved nutrients such as nitrate. The PS stations of Dakshineswar exhibited lower DO concentrations compared to SW stations which could indicate the possible presence of pollutants including organic matter in these stations. Low DO could be owing to the oxidation of organic matter. Low DO values found in monsoon could be also attributed to the presence of industrial organic effluents as reported in other rivers such as the Sutlej (Tripathi et al. 2008). Higher DO in post-monsoon in both the years could be influenced by lower SWT. The concentration of DO in surface water thus serves as an important environmental proxy and is frequently used in determining the water quality index of the River Ganga (Matta et al. 2020, Kumar et al. 2021, Muduli et al. 2021). Degradation in DO concentration owing to anthropogenic activities has been documented in other rivers of India including the Brahmaputra and Gomti (Singh et al. 2005, Girija et al. 2007). To meet with CPCB Water Quality Criteria for outdoor bathing (Class B) and Propagation of Wildlife and Fisheries (Class D), DO levels should be >4 mg L⁻¹. The strong seasonal trends along with abrupt variations in DO concentrations between short stretches of the river are reasons for concern. Long-term monitoring of these stations would therefore, be critical to understand underlying causes of observed low DO concentrations and quantify the consequences including in terms of riverine ecosystem functioning. Other environmental parameters including AT, SWT and SPM also showed distinct seasonal variation in the Dakshineswar site that could be resulting from influences of seasonal precipitation. Increased freshwater input from local precipitation along with higher
inflow from upstream could increase SPM coming from terrestrial runoff and underlying sediment resuspension (Corbett 2010). This also leads to the release of nutrients including inorganic forms of nitrogen and phosphorus from the benthic layer, thus increasing their concentrations in the interstitial water (Corbett 2010). These nutrients are then transported into the water column through exchange and have consequences for benthic–pelagic coupling processes in aquatic ecosystems (Sinha et al 2021). Such phenomena are frequently observed in large tropical rivers including the Amazon, Orinoco and Maroni in South America (Rousseau et al 2019), Pearl River in the southern part of China (Ni et al 2008). Studies on the River Ganga has also indicated the direct relationship between precipitation, high SPM load and an increase in concentrations of dissolved nutrients as well as heavy metals in surface water (Samanta and Dalai 2018).

Despite high nutrient concentrations during monsoon, phytoplankton communities do not proliferate owing to SPM limiting photic depth (Sarma et al 2009, Choudhury et al 2015). Low phytoplankton diversity has been commonly reported from other rivers including the Godavari (Acharyya et al 2012). Lower SPM allows sufficient light availability that allows phytoplankton to reach high growth rates and consequently dominate at population scales. Phytoplankton taxa such as Aulacoseira and Nitzschia are typically attenuated by low water transparency and high flow rates which could be attributed to their low abundance during the monsoon of both years in Dakshineswar. These taxa are also commonly encountered in both parts of the lower stretch of River Ganga where they dominate surface water (Sarkar et al 2019). The high abundance of cells representing in Aulacoseira spp. as seen in Stn_3_PS_Mon19 during monsoon 2019 and monsoon 2020 coincided with low SPM (~126 mg l^-1 and ~67 mg l^-1 respectively) load across these stations. These groups are usually succeeded by small centric diatoms such as Cyclotella and Thalassiosira, which are subsequently succeeded by a high diversity of green algal assemblages. Increased water transparency in post-monsoon favoured the growth of green algal taxa such as Actinastrum, Coelastrum, Dictyosphaerium, Micractinium, Pediasstrum and Scenedesmus. Such succession patterns have been observed in other major riverine systems including the Loire in France (Descy et al 2012) but have not been reported before from the River Ganga.

The seasonal dynamicity of phytoplankton communities also acts as an indicator of organic pollution and water quality. An increase in abundance representing the taxa namely, Cyclotella, Gomphonema, Navicula, Synedra, Chlorella, Nitzschia, Scenedesmus, Phacus and Oscillatoria during post-monsoon also indicates the increase in organic pollutant content of the surface water in Dakshineswar. Increased terrestrial run-off could explain the increase in organic pollutant content. In post-monsoon, Palmer index total score (table S2) indicated higher organic pollution in PS stations compared to SW stations which indicate industrial outflows and domestic drains to be a potential source of organic pollutants falling into the River Ganga directly in Dakshineswar site. Flushing by rainfall along with increased river water volume and flow velocity resulted in rapid dispersion of particles leading to a lower concentration of pollutants during monsoon season. Because of considerable reduction in water velocity in post-monsoon, longer residence time of water directly impacts the rapid dispersion of particles leading to a lower concentration of pollutants during monsoon season. Because of considerable reduction in water velocity in post-monsoon, longer residence time of water directly impacts the nutrient uptake dynamics and resulting phytoplankton growth (Guhr et al 2000, Ockenfeld and Guhr 2003). Upstream sites of the River Ganga are also dominated by phytoplankton observed in the Dakshineswar site indicating possible similar water conditions prevailing as found in the lower stretch (Sarkar et al 2019).

Many of the green algal taxa encountered during the study are known to thrive in riverine ecosystems which also tend to be contaminated with different types of pollutants including inorganic nutrients such as forms of nitrogen and phosphorus (Zhu et al 2010, Zhou et al 2018). In the present study, occurrence of cell abundances representing several green algal taxa such as Scenedesmus sp. indicates the potential declining water quality in the lower part of Ganga. An increase in concentrations of dissolved nitrate in post-monsoon also resulted in bloom-like conditions of cells of Aulacoseira spp. in Dakshineswar. The rapid increase in cell abundance resulted in the significant removal of o-phosphate from the surface water. This removal of o-phosphate subsequently limits bioavailability for recycling within the photosynthetic zone and ultimately inhibits primary production. Removal of phosphorus from surface water through sedimentation of bloom formed in post-monsoon has been also referred to as the ‘nutrient-sponge’ as it influences phytoplankton community structure during warmer summer months (Reynolds 1998). An increase in bloom abundance over time in response to nutrient concentrations leads to eventual depletion of dissolved silicate from the water column (Conley et al 1993) and the same trend has been observed in the present study. The subsequent increase in diatom production (seen in terms of Chl-a concentration) from high nutrient availability during post-monsoon eventually decreases the efficiency of nutrient recycling through nutrient removal. Cells of Aulacoseira spp. are known to have high silica demand relative to other diatoms (Kilham and Kilham 1990) and diatoms tend to have robust genetic mechanisms such as high-affinity transporters for rapid uptake of nutrients (Bhadury et al 2011). Bloom formation in post-monsoon also led to the formation of larger filaments of Aulacoseira cells in the study site and also reported in other studies (Poister et al 2012). Therefore, it seems that the biovolume of Aulacoseira cells may have increased in the post-monsoon season which indicated favourable nutrient stoichiometry prevailing in the study site of the lower stretch of River Ganga. Moreover, co-occurrence pattern as revealed by network analysis highlights the strong interaction between some of the diatom and green algal taxa leading to their persistence and could be triggered by deteriorating water quality in the study site. This is also supported by the WQI values which did not show any
marked improvement in the study site. Such observed co-occurrence patterns between phytoplankton taxa may also lead to succession and dominance of blooming forming taxa such as the *Aulacoseira* bloom-like scenario documented in the present study. Interestingly, this is the first study on the River Ganga in which network analysis of phytoplankton assemblages was undertaken to address ecological interaction among members of the assemblages.

**Conclusions**

Changes in nutrient dynamics directly influence the water quality of riverine surface water. Estimation of WQI indicated a marginal increase in water quality in Dakshineswar during post-monsoon. This study showed the dominance of populations representing *Aulacoseira* spp. in surface water of the lower stretch of River Ganga and reflected a bloom-like scenario. Given that the populations of this taxon exhibited very high abundance it also reflected that the study site was strongly influenced by environmental factors including available forms of dissolved nutrients that led towards the eutrophic-like condition. Such conditions can have long-term adverse ecological consequences on the aquatic ecosystem of the River Ganga including on higher trophic levels such as resident fish populations. It is important to highlight that several green algal taxa were encountered in lesser abundance compared to diatom cells in the study site but their presence is usually considered as a potential indicator of deteriorating water quality. Although the present study has looked at the phytoplankton assemblages across two seasons in successive years, nevertheless vital information regarding phytoplankton assemblages and their pattern as well as the tracking of the development of a bloom-like scenario of *Aulacoseira* cells were generated. Moreover, the development of bloom-like and the eutrophic condition of the lower stretch of River Ganga also highlights the need towards developing a new biotic index based on algal co-occurrence patterns for early monitoring and mitigation of deteriorating water quality of the River Ganga.

**Acknowledgments**

This work is supported by Department of Science & Technology (Govt. of India) grant [DST/TMWTI/2K16/124] awarded to Punyasloke Bhadury.

**Data availability statement**

All data that support the findings of this study are included within the article (and any supplementary files).

**Conflict of interests**

The authors declare no conflict of interests

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