



Temporal and spatial variations in carbon and nutrient loads, ion chemistry and trophic status of the Ganga River: a watershed-scale study

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Abstract

Ganga, a river of global significance, is under increasing pressure from excessive release of carbon and nutrients. We conducted the first detailed watershed-scale study to assess water quality status and possible drivers in different segments of the Ganga River. For this, we analyzed 24 water quality variables from March 2016 to February 2018, at 7 study sites, along a 2320-km river stretch. The data revealed large spatiotemporal variations in total dissolved solids, major ions, nutrients, dissolved organic carbon, biological oxygen demand (BOD), chemical oxygen demand, chlorophyll *a* biomass (Chl *a*) and gross primary productivity. Principal component analysis identified three major determinants (source input, stream flow, and tidal influence) explaining over 84% of the total variance. A high concentration of oxygen-demanding chemicals, especially in the middle segment, underscores the importance of restoration efforts that address BOD reduction alone. This work advances our understanding with respect to inter-segment variations and factors regulating Ganga River water quality and demonstrates the significance of watershed-scale studies for integrated river basin management.

Keywords Eutrophication · Ganga River · Indicator · Integrated river basin management · Pollution

Introduction

Rivers are very important inland water resources that support wide human needs including agriculture, industry, transportation and public water supply. While passing through cities and other areas of intense human activities, rivers receive a large number of contaminants released from domestic activities, industries, and agriculture (Yadav and Pandey 2017). Over the past few decades, accelerating rates of water quality degradation has prompted an increasing number of studies to examine how rivers respond to anthropogenic

perturbations (Muangthong and Shrestha 2015; Pandey et al. 2017). Because of the seasonal and regional differences in river hydrology and water quality, identifying spatial and temporal trends in water quality, and addressing the causal relationships at watershed scale has become a major focus of river research (Huang et al. 2014).

Urban-industrial releases constitute a constant polluting source, while surface runoff is a seasonal process mainly affected by landscape features, hydrology and climate of the basin (Pandey et al. 2014; Siddiqui et al. 2018). Systematic data on water quality, together with factors that account for downstream impacts are needed for action plans to offset high stressor levels. Traditional approaches to water quality assessment are based on comparisons of the measured response variables with their respective standards, which provide fragmented information on the overall water quality. In a step to obtain more accurate information, water quality indices have been used in freshwater quality monitoring programs (Sun et al. 2016; Sharma et al. 2014; Yadav and Pandey 2017). The assessment of Ganga River water quality relies mainly on fragmented data, seriously limiting the success of protection and rejuvenation plans (Sarin et al. 1989; Khwaja et al. 2001; Khan et al. 2017). Watershed-scale

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spatial analyses have not yet been applied in the formal assessment, despite a recognized need.

Watershed-scale information on changes in water quality and the causal relationships are important for developing watershed management plans and integrated river basin management (IRBM) strategies. The data so far available on water quality of the Ganga River are based on short-stretch site-specific studies (Khwaja et al. 2001; Tare et al. 2003; Beg and Ali 2008; Bhutiani et al. 2016; Yadav and Pandey 2017). Systematic watershed-scale data on water quality of this river are altogether lacking. Another shortcoming of previous studies on this river system is that they do not explicitly consider integrating the effects of spatial and temporal perspectives. Some studies have investigated temporal trends using annual means at a few selected sites, ignoring the spatial and seasonal dependence of the water quality (Dwivedi et al. 2018). Other studies have investigated local-scale spatial trends in water quality using mean values of selected parameters for different monitoring sites while ignoring changes in the landscape (Sharma et al. 2014). Here we present the results of the first watershed-scale study conducted along a 2320-km river stretch considering 24 parameters and 4 indices to collectively address the spatiotemporal perspectives of Ganga River water quality.

Materials and methods

Study area

This watershed-scale study was conducted from March 2016 to February 2018 covering a 2320-km stretch of the Ganga River. The Ganga River originates as Bhagirathi in the Himalaya at an elevation of 3892 m above mean sea level. At Devprayag it joins its tributary Alakananda and the combined stream is called the Ganga River. The basin (1,086,000 km²; 73°30′–89°E; and 22°30′–31°30′N) covers four countries, namely India, Nepal, Tibet, and Bangladesh. In India, it covers about 26.2% geographical area of the country. The Ganga River basin has a sub-tropical to tropical monsoon climate, with over 80% of precipitation occurring in monsoon months (July–October). The year shows distinct seasonality: a hot and dry summer (March–June), a moist rainy season (July–October) and a cold winter season (November–February). The average annual rainfall ranges from 78 cm in the upper part through 144 cm in the middle stretch to 182 cm in the lower delta region. Alluvium represents the major soil type of the basin, with a variable combination of sandy, loamy and clay soils.

Sampling and analysis

Water quality

We tested 24 water quality parameters for trend analysis and status evaluation. Sub-surface (25 cm depth) water samples were collected seasonally from seven sampling sites selected along a 2320-km river stretch (Fig. 1). We refer to Devprayag as a reference, owing to it being the least human-disturbed site. Samples were collected in triplicate from three sub-sites of each study site from the mid-stream of the river in pre-washed plastic bottles and preserved in an ice box. Temperature, pH, and conductivity were measured on site using a multi-parameter tester (PCSTestr 35). Total dissolved solids (TDS) and total hardness were measured following a standard method (APHA 1998). Dissolved oxygen was measured following Winkler's azide modification method and BOD after 5-day incubation (APHA 1998). Chemical oxygen demand (COD) was measured following standard methods (APHA 1998). Nitrate was estimated using the phenol disulphonic acid method (Nicholas and Nason 1957). Total nitrogen was measured using a Kjeldahl nitrogen analyzer, and ammonium nitrogen following Park et al. (2009). Orthophosphate in water samples was measured following the stannous chloride ammonium molybdate method (APHA 1998). Dissolved silica (DSi) was determined following Sauer et al. (2006) and biogenic silica (BSi) following Michalopoulos and Aller (2004). The dissolved organic carbon (DOC) and total organic carbon (TOC) were quantified using a TOC analyzer (Lotix). Sulfate and chloride in water samples were determined using volumetric analysis. Chlorophyll *a* (Chl *a*) was extracted in acetone and measured spectrophotometrically (Maiti 2001). Gross primary productivity (GPP) was measured following the light and dark bottle method (APHA 1998).

Water quality index

The water quality index (WQI) was determined from a calculation based on a weighted arithmetic index (Brown et al. 1972):

$$\text{WQI} = \frac{\sum_{n=1}^n q_n w_n}{\sum_{n=1}^n w_n},$$

where q_n = quality rating and w_n = unit weight of various water quality parameters. The quality rating was calculated by the following relationship:

$$q_n = 100(V_n - V_i)/(V_s - V_i),$$

where V_s = standard value, V_n = observed value, and V_i = ideal value. $V_i = 0$ except for pH, dissolved oxygen (DO) etc. For pH it is 6.5–8.5 and for DO it is 14.6.

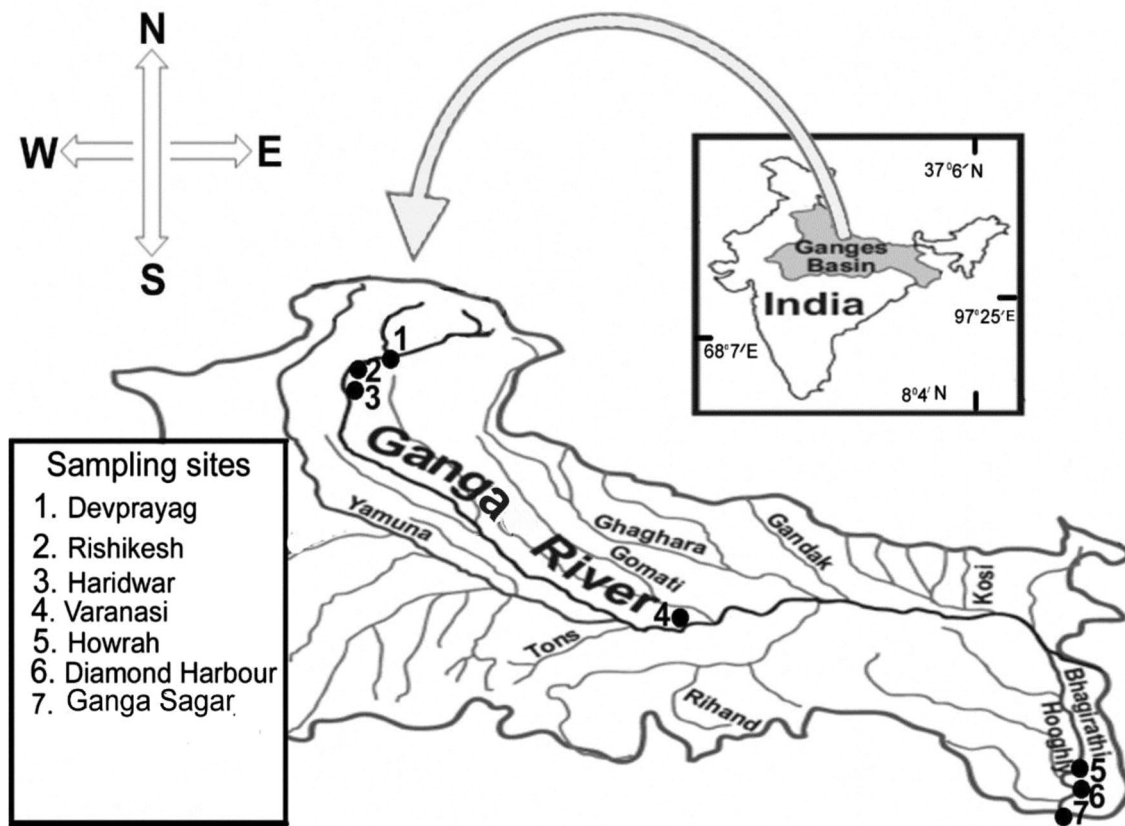


Fig. 1 Map showing the locations of study sites. Each site (1–7) is representative of three sub-sites

The unit weight (w_n) for various water quality parameters was calculated as:

$$w_n = k/S_n,$$

where S_n = standard permissible limit for the parameter and k = proportionality constant.

Based on the WQI, the status of water quality is classified as: 0–25, excellent water quality; 26–50, good water quality; 51–75, poor water quality; 76–100, very poor water quality; > 100, unsuitable for drinking.

Comprehensive pollution index

The comprehensive pollution index (CPI) was calculated considering the total number of parameters (n) as below:

$$CPI = 1/n \sum PI_i.$$

The pollution load of the i th parameter (PI_i) was calculated as:

$$PI_i = C_i/S_i,$$

where C_i is the measured concentration of the i th parameter and S_i is the standard concentration.

The CPI is used to classify water bodies as: 0–0.20 (clean); 0.21–0.40 (sub-clean); 0.41–1.00 (slightly polluted); 1.01–2 (moderately polluted); and > 2 (severely polluted).

Trophic state index

The trophic state index (TSI) was calculated following Carlson’s modified trophic state index (Aizaki et al. 1981):

$$TSI(\text{Chl } a) = 10 \left(2.46 + \frac{\ln(\text{Chl } a)}{\ln 2.5} \right),$$

$$TSI(\text{P}) = 10 \left(2.46 + \frac{6.71 + 1.15 \ln(\text{P})}{\ln 2.5} \right).$$

The TSI classifies water bodies as: < 30, oligotrophic; 30–50, mesotrophic; > 50, eutrophic.

Sodium absorption ratio

The sodium absorption ratio (SAR) was calculated using the concentration (milliequivalent per liter) of main alkaline and alkaline earth cations:

$$\text{SAR} = \text{Na}^+ / (\text{Ca}^{2+} + \text{Mg}^{2+}/2)^{1/2}.$$

SAR values > 9 are considered unsuitable for irrigation.

Statistical analysis

Hierarchical clustering was performed on the normalized data set by Ward's method, using squared euclidean distance as a measure of similarity. Principal component analysis (PCA) of normalized variables was performed to extract significant PCs. Correlation analysis was used to test the significant relationship between variables. Analysis of variance (ANOVA) was used to test the level of significance in spatiotemporal variations. Analyses were done on Excel, Sigma plot, SPSS package (version 16) and past (version 16).

Results and discussion

Physico-chemical characteristics

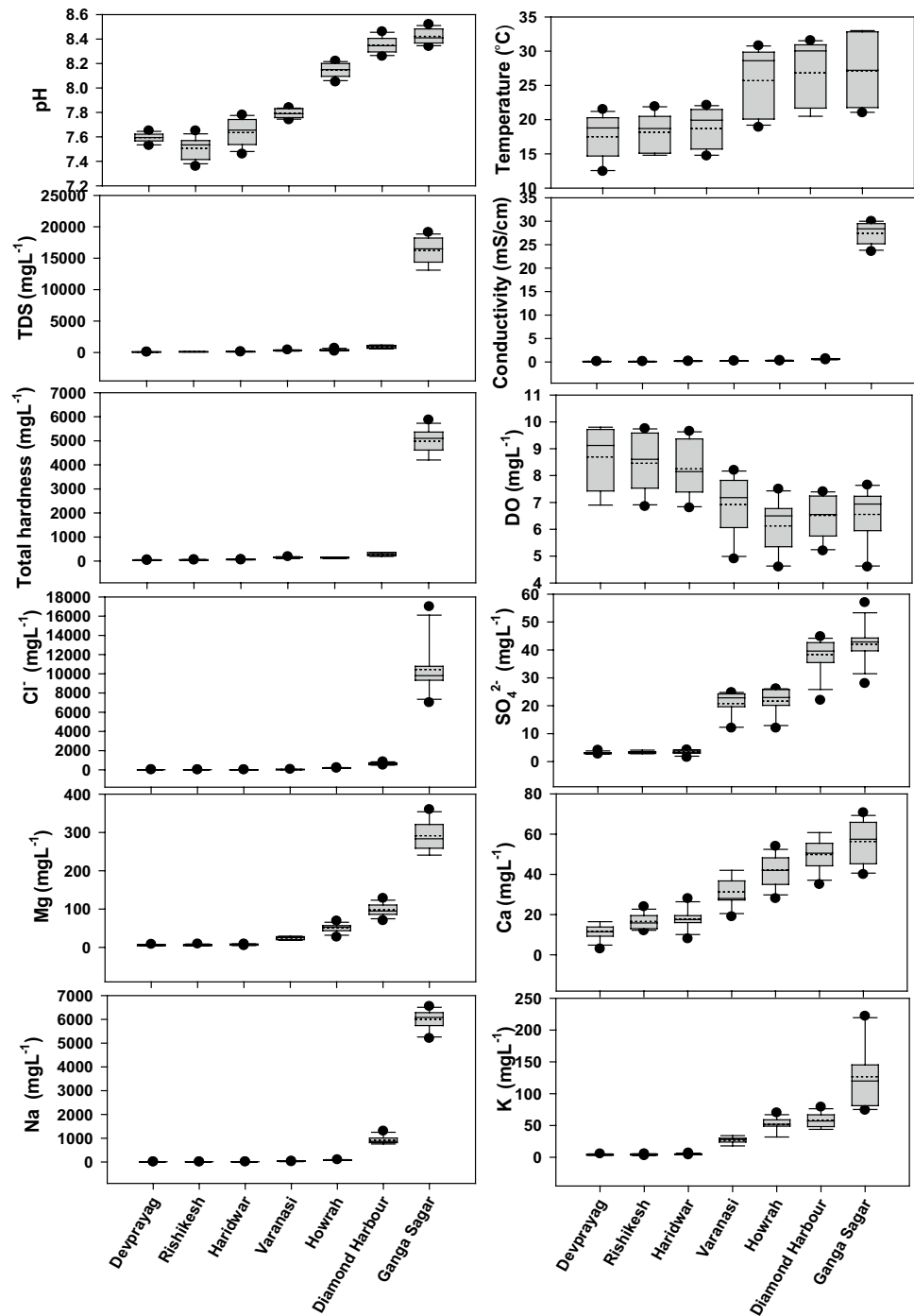
This part of the study aimed mainly to analyze: (1) spatiotemporal trends and sources of major ions, nutrients and oxygen-demanding substances in the Ganga River, and (2) inward tidal influences of the Bay of Bengal driving the changes in these variables. River water pH ranged from 7.32 to 8.46, increased downstream, and remained highest in summer (Fig. 2). Lower temperature ranges, recorded at upper reaches, could be associated with altitudinal and latitudinal differences. Conductivity, total dissolved solids (TDS) and total hardness increased downstream with values several folds higher at Ganga Sagar (Fig. 2). The high values at lower reaches (Howrah, Diamond Harbour, and Ganga Sagar) are due to the tidal influence of the Bay of Bengal. High DO towards the headwaters (Fig. 3) was due to low temperature and fewer anthropogenic perturbations. Biological oxygen demand (BOD) and chemical oxygen demand (COD) showed marked spatiotemporal variations and were found to be highest at Varanasi followed by Howrah, Diamond Harbour, Ganga Sagar, and lowest at Devprayag (Fig. 4). Higher BOD and COD at Varanasi and Howrah could be linked to a high load of organic matter and other oxygen-demanding substances. Concentrations of DOC and NH_4^+ were high at these sites. Elevated levels of chloride, sulfate and other ions (Na^+ , K^+ , Ca^{2+} and Mg^{2+}) at lower reaches (Fig. 2) indicate that

the tidal action of the Bay of Bengal alters the chemistry of lower reaches over 120 km inward. Chemical weathering and anthropogenic activities and sea-driven wet and dry deposition invariably influence the concentration of these ions (Sarin et al. 1989). Furthermore, weathering of calcite, dolomite, and gypsum releases a significant quantity of Ca, Mg and SO_4^{2-} in surface waters (Holland 1978). Groundwater intrusion during base flow and salt precipitation in the dry season further contributes to enhancing the concentration of these ions (Sarin et al. 1989).

The concentration of nitrate and ammonia in the river ranged from 81.37 to 400.00 $\mu\text{g l}^{-1}$ and 12.34 to 70.66 $\mu\text{g l}^{-1}$, respectively (Figs. 2, 3). The concentration of phosphate ranged from 21.00 to 119.00 $\mu\text{g l}^{-1}$ with values being highest at Varanasi. Urban-industrial releases, domestic sewage, agricultural runoff and atmospheric deposition all add a large amount of N and P to the surface waters (Shen et al. 2014; Pandey et al. 2014; Yadav and Pandey 2017). These sources predominate in the middle and lower parts of the Ganga River Basin (Siddiqui et al. 2018). The river receives N and P input from 29 megacities, 23 small cities and 48 townships (CPCB 2013) and the density of point and non-point sources increase downstream to Howrah. The variations in NO_3^- could also be attributed to a large proportion of leachable NO_3^- from agricultural lands (Beman et al. 2005). The relatively higher concentration of phosphate was recorded at middle-downstream locations, especially at Varanasi and Howrah, indicating strong urban and agricultural influences (Pandey et al. 2014; Yadav and Pandey 2017). The summer season high concentrations of N and P can be explained by reduced stream flow, shrinkage of water volume, reduced dilution effect, and consistent input from point sources. Additionally, summer season P released from sediments (Houser and Richardson 2010) and groundwater N intrusion (Sprague et al. 2011) could also contribute during lean flow.

The concentration of dissolved silica (DSi) varied between 190.00 and 700.00 $\mu\text{g l}^{-1}$ with values being highest at Diamond Harbour (Figs. 4, 5). Weathering and erosion contribute a large quantity of DSi in rivers, and therefore its concentration increases in the rainy season. However, a major part of it is transported to the ocean (Onderka et al. 2012). Damming of the river is an important likely cause of reducing DSi in summer. Terrestrial vegetation, including agricultural crops, efficiently take up silica, leading to a decline in its concentration in surface runoff. The concentration of BSi in the river ranged from 56.00 to 143.36 $\mu\text{g l}^{-1}$ (Figs. 4, 5). The BSi values recorded here are higher than those reported by Cary et al. (2005). Previous studies show that phytolith is an important source of BSi to the rivers (Cary et al. 2005). However, summer season BSi, when surface runoff sources remain at a minimum, could be linked,

Fig. 2 Box plots showing spatial variation in pH, temperature, total dissolved solids (TDS) conductivity, total hardness, dissolved oxygen (DO) and major ions in the Ganga River. The *dotted lines* indicate the mean values



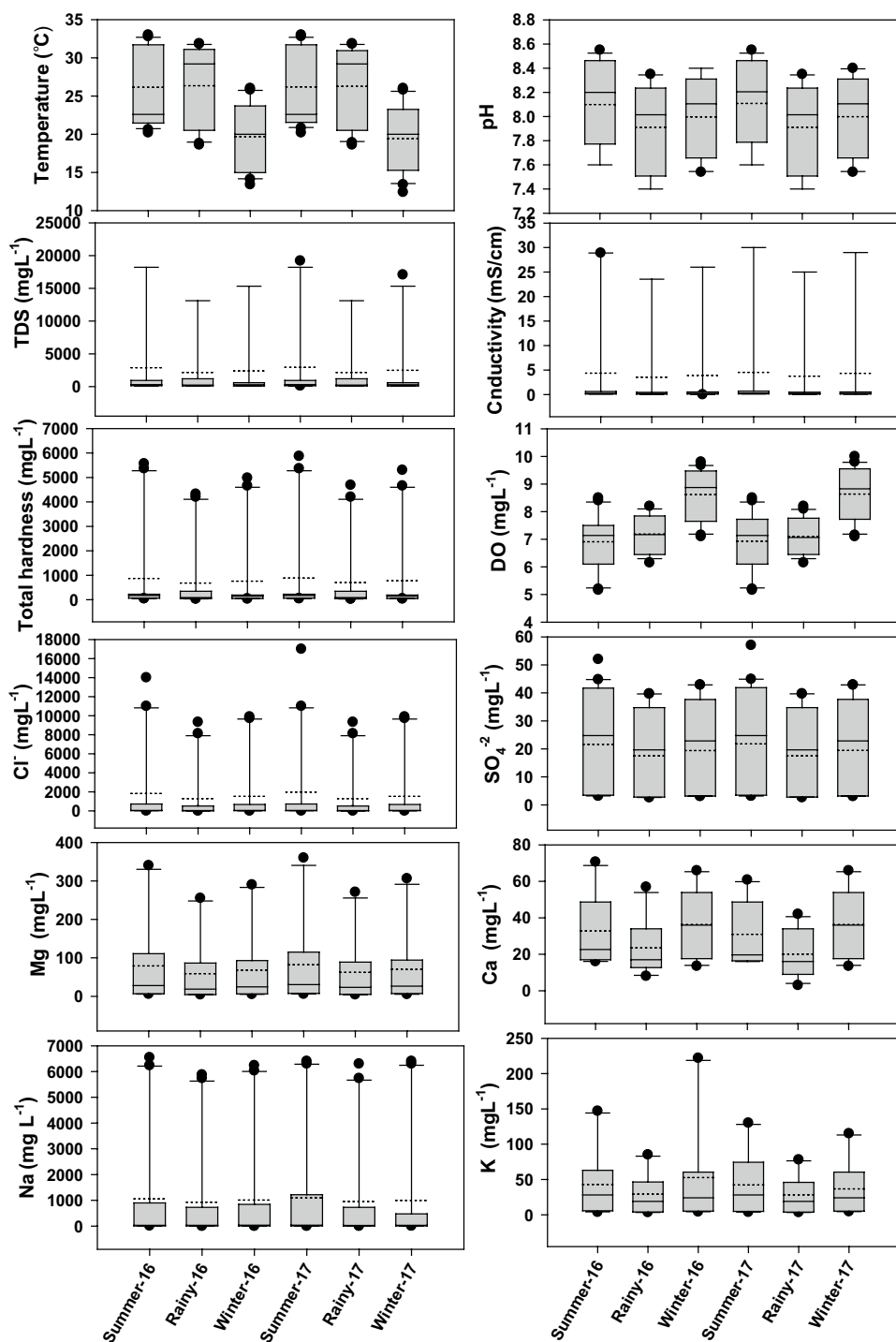
in a major way, with those of diatom origin (Pandey et al. 2017).

Productivity and trophic status

This is the first watershed-scale study to describe spatiotemporal patterns in phytoplankton productivity, chlorophyll *a* (Chl *a*) biomass, and trophic status in the Ganga River over two annual cycles. Chl *a* biomass and gross

primary productivity (GPP) in the river ranged from 4.5 to 34.45 $\mu\text{g l}^{-1}$ ($\text{cv} = 28\text{--}42\%$) and 1.2 to 12.57 $\text{mg C m}^{-2} \text{h}^{-1}$ ($\text{cv} = 26\text{--}41\%$), respectively, with values being highest at Varanasi (Fig. 4). A similar range of Chl *a* has been reported for the James River (Bukaveckas et al. 2011) and the Brazos River (Roach et al. 2014). Our estimates on GPP are similar to Ochs et al. (2013) on the lower Mississippi River. On a temporal scale, irrespective of site, Chl *a* and GPP were found to be the highest in summer

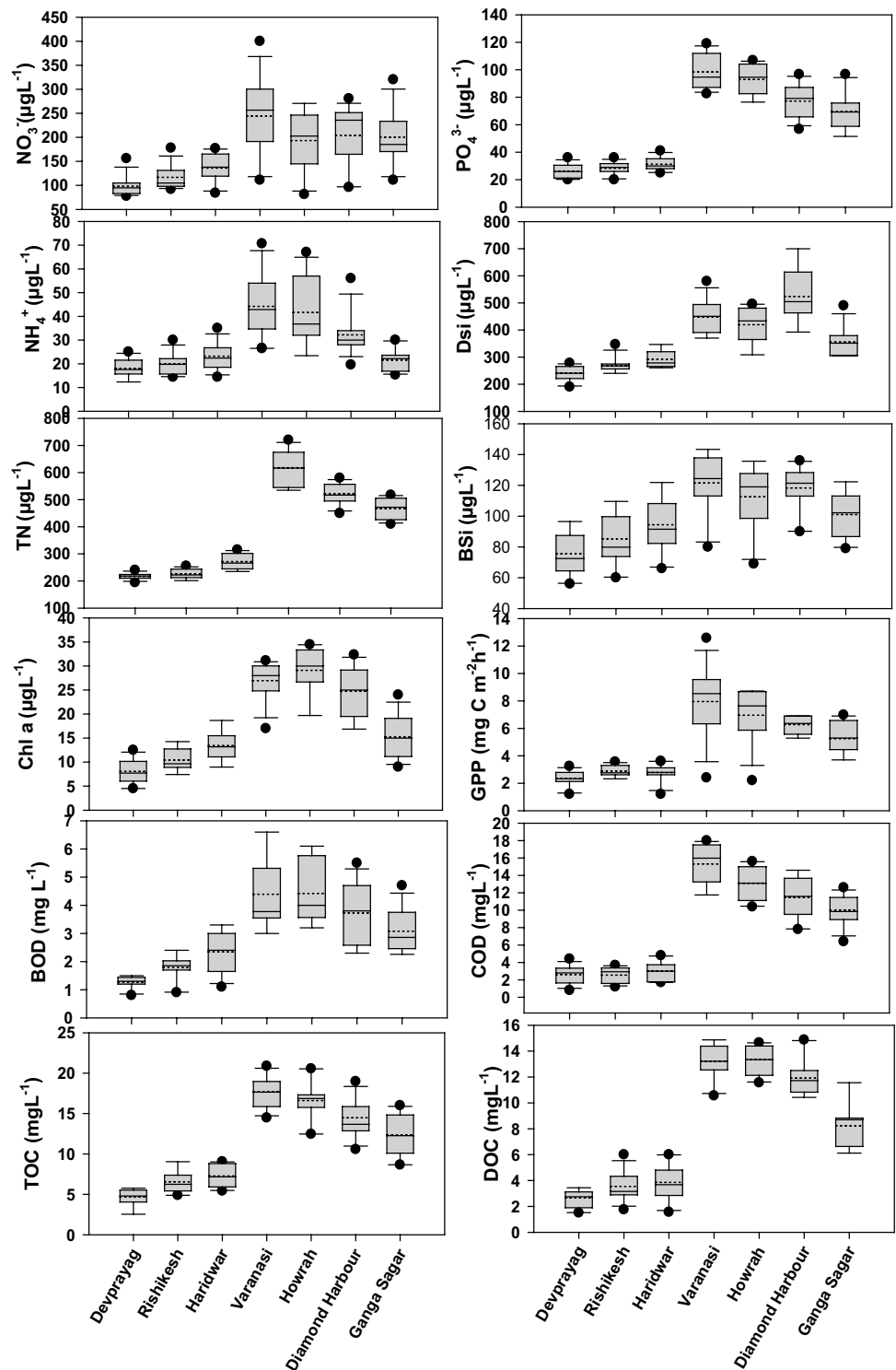
Fig. 3 Box plots showing temporal variation in pH, temperature, total dissolved solids (TDS), conductivity, total hardness, dissolved oxygen (DO) and major ions in the Ganga River. The dotted lines indicate the mean values



(Fig. 5). Spatiotemporal variations in Chl *a* and GPP were significant ($p < 0.001$; ANOVA). The high summer season productivity could be attributed to decreased river discharge, low turbidity and high concentrations of nutrient. Chl *a* and GPP showed a significant positive correlation ($p < 0.01$; Table S1) with critical nutrients such as N, P and Si, indicating nutrient driven production of phytoplankton. The GPP and Chl *a* maxima at Varanasi were associated

with high nutrient flushing from anthropogenic sources (Pandey et al. 2014; Pandey and Yadav 2017). During peak discharge, the river drains a large amount of sediments and organic carbon of allochthonous origin that enhances turbidity, which, coupled with enhanced channel turbulence, reduces the primary production during monsoon. This trend appears consistent with earlier studies (Pandey et al. 2014; Siddiqui et al. 2018). Massive production of

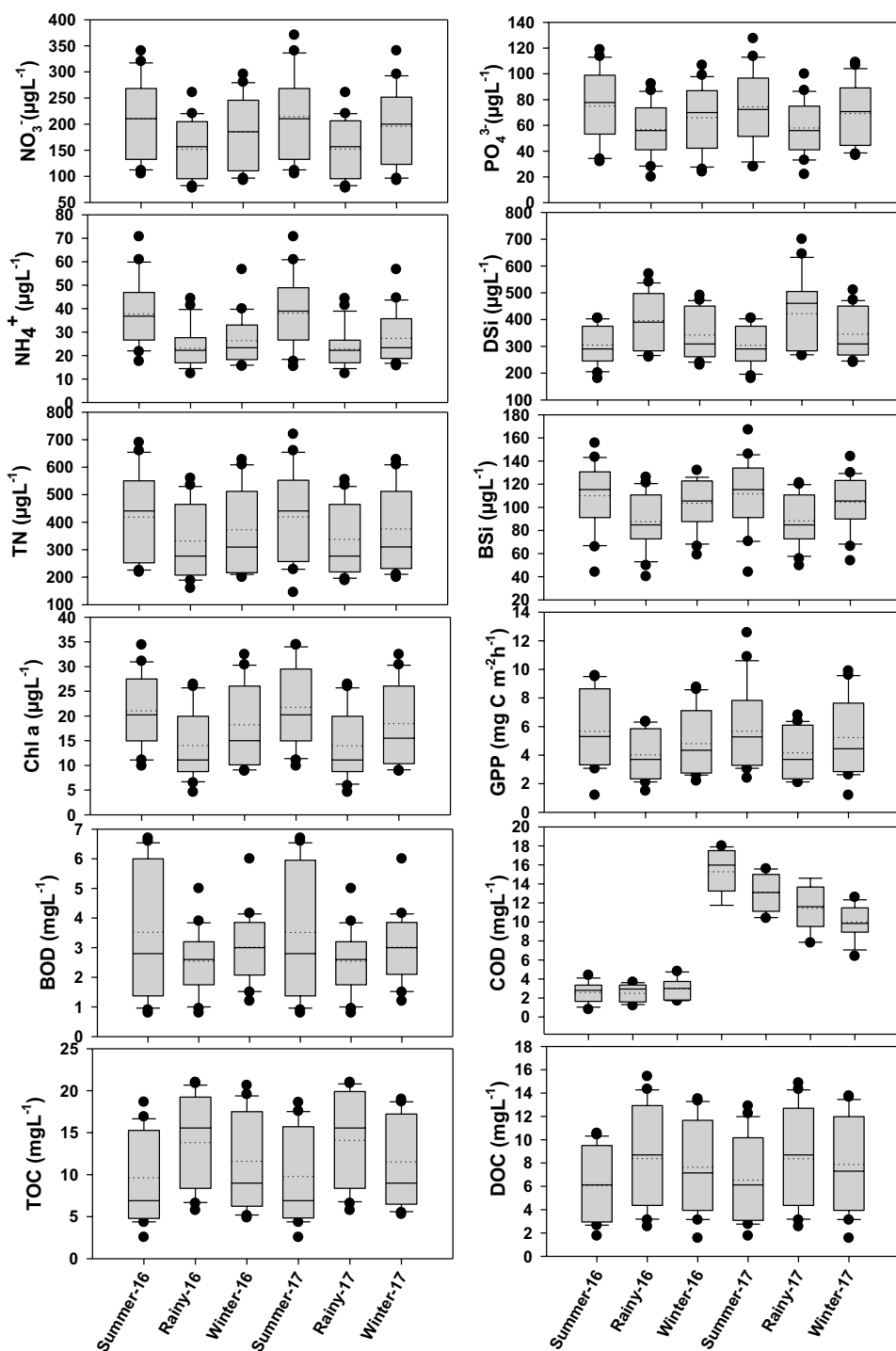
Fig. 4 Box plots showing spatial variation in nutrients, organic carbon, productivity variables and oxygen demand in the Ganga River. *TN* total nitrogen, *DSi* dissolved silica, *BSi* biogenic silica, *Chl a* chlorophyll *a*, *GPP* gross primary productivity, *BOD* biological oxygen demand, *COD* chemical oxygen demand, *TOC* total organic carbon, *DOC* dissolved organic carbon. The dotted lines indicate the mean values



in situ organic matter in middle and lower reaches indicated that management imperatives associated with control of allochthonous carbon loading alone, will not work. If nutrient enrichment continues, the autochthonous-C and associated increases in BOD will continue to degrade the water quality of the Ganga River.

Very high values of GPP and Chl *a* at Varanasi and Howrah sites during low flow indicate that the river at some locations is moving towards seasonal eutrophy. We attempted to assess the trophic state of the river using the modified Carlson trophic state index (Aizaki et al. 1981). The TSI (Chl *a*) ranged from 46.32 to 61.10 and TSI (P),

Fig. 5 Box plots showing temporal variation in nutrients, organic carbon, productivity variables and oxygen demand in the Ganga River. *TN* total nitrogen, *DSi* dissolved silica, *BSi* biogenic silica, *Chl a* chlorophyll *a*, *GPP* gross primary productivity, *BOD* biological oxygen demand, *COD* chemical oxygen demand, *TOC* total organic carbon, *DOC* dissolved organic carbon. The dotted lines indicate the mean values



from 46.10 to 63.00 (Table 1). Sites at upper reaches of the river (Devprayag, Rishikesh, and Haridwar) were found to be mesotrophic (TSI 30–50) while those situated in middle and lower reaches appeared to be eutrophic (TSI > 50). The middle and lower reaches of the river are characterized by very high human population densities, and also high densities of point- and non-point sources of nutrient input. Further, the lower reaches experience estuarine influences

and consequently nutrient enrichment from the forward and backward flushing.

Pollution status

In India, organic loading is a key contributor to surface water pollution in general and to the Ganga River in particular (CPCB 2013). Here, we explore how human perturbation

influences organic pollution status, oxygen demand, and heterotrophy in the Ganga River. The determinants of eutrophy (TOC, DOC, BOD) showed marked spatiotemporal variation along the study stretch (Figs. 4, 5). The concentration of TOC ranged from 2.54 to 20.87 mg l⁻¹ with values being highest at Varanasi. The concentration of DOC followed a similar trend with values ranging from 1.6 to 14.87 mg l⁻¹. The upper ranges of DOC recorded here were considerably higher than those reported for the Yangtze River (Qi et al. 2014) and Yukon River (Wickland et al. 2012). High concentrations of TOC and DOC in the rainy season indicate a large contribution of allochthonous carbon. A large area of the basin is intensively agricultural with patches of woodlands, causing massive C input of terrigenous origin. These high levels of TOC and DOC during the rainy season are unlikely to have a significant effect on the water quality of the river because the high river discharge disperses and transports these pollutants during this period. Sewage adds a large amount of DOC to the river (CPCB 2013), which is more evident during the dry season due to shrinkage of water volume. The Ganga River at Varanasi receives 141 million liters of treated sewage and 41 million liters of untreated sewage per day (CBCB 2013). Additionally, the river receives 66.4 million liters of mixed wastewater daily through the Assi drain. This creates a strong urban influence on river water quality evidenced through markedly high carbon loads recorded in this region.

Biological oxygen demand (BOD) ranged from 0.79 to 6.60 mg l⁻¹ and showed trends almost synchronous to organic load. The BOD increased downstream, reaching a maximum at Howrah. At Varanasi and Howrah sites, BOD was several folds higher than at Devprayag. Higher values were found during summer low flow, irrespective of the site, indicating that the water quality during summer low flow, when surface runoff remains negligible, is primarily regulated by point sources (Yadav and Pandey 2017). Chemical oxygen demand (COD) ranged from 0.80 to 18 mg l⁻¹ with values being highest in summer. On a spatial scale, the COD remained highest at Varanasi (Fig. 4). The COD mainly results from point sources, including urban sewage and industrial discharge (Liu et al. 2011) containing a large amount of oxygen-demanding chemicals such as Fe, Mn, and NH₄⁺.

We used data, generated along a 2320-km river stretch for two consecutive years, to calculate water quality indices for the Ganga River. Water quality index (WQI) values at Devprayag, Rishikesh, and Haridwar were 37.43, 39.82 and 44.82, respectively (Table 1). These values lie in the good water quality range (Srivastava et al. 2011). The WQI values at Varanasi, Howrah, Diamond Harbour, and Ganga Sagar were 68.00, 66.76, 66.76 and 64.00, respectively, indicating poor water quality. The water quality analysis clearly showed that the water in the upper mountainous region (sites 1, 2 and

Table 1 Water quality indices and trophic state index (TSI) for different study sites of the Ganga River

Sampling site	WQI	CPI	SAR	TSI (Chl <i>a</i>)	TSI (P)
Devprayag	37.34	0.29	3.04	46.32	46.10
Rishikesh	39.83	0.30	3.35	48.63	47.10
Haridwar	44.96	0.34	4.24	49.63	48.90
Varanasi	68.00	1.89	7.21	61.20	63.00
Howrah	66.66	1.87	11.65	60.79	61.70
Diamond Harbour	66.76	1.79	106.00	57.70	59.00
Ganga Sagar	64.23	1.74	456.00	53.94	57.80

The TSI was calculated separately based on chlorophyll *a* (Chl *a*) and phosphorus (P) data

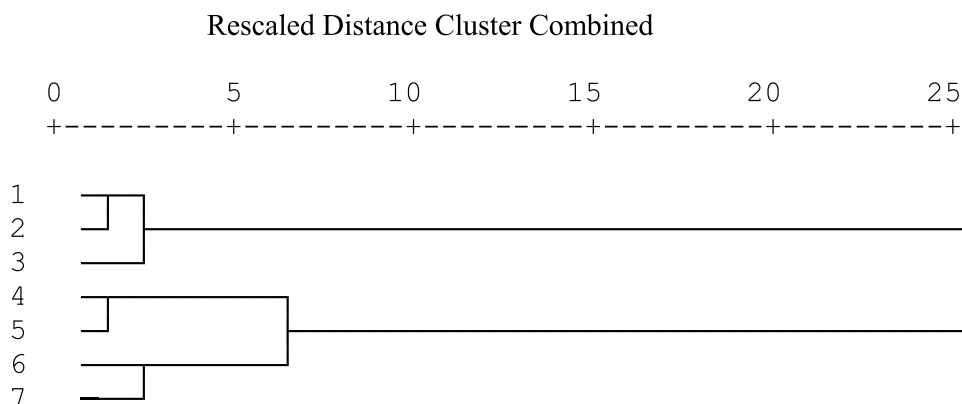
WQI water quality index, CPI comprehensive pollution index, SAR sodium absorption ratio

3) of the river was the only water fit for drinking. The water in the middle (site 4) and lower reaches (sites 5, 6 and 7) are not suitable for drinking. The middle and lower reaches are highly polluted due to high population density, rapid urban-industrial growth and intensive non-point sources of pollution (Yadav and Pandey 2017). The comprehensive pollution index (CPI) ranged from 0.29 to 1.89 (Table 1) with values lowest at Devprayag and highest at Varanasi. The CPIs recorded at Varanasi were very similar to those recorded at Howrah. The CPIs at Devprayag, Rishikesh, and Haridwar remained well below 0.40, and thus can be classified under the sub-clean category. At Varanasi, Howrah, Diamond Harbour, and Ganga Sagar the values were between 1 and 2, classifying these sites as moderately polluted. The SAR ranged from 3.04 (Devprayag) to 456 (Ganga Sagar) (Table 1). The water at Devprayag, Rishikesh, Haridwar, and Varanasi with SAR < 9 is suitable for irrigation. The water of lower reaches, representing the influence of the Bay of Bengal, is unsuitable for irrigation (SAR > 9). These observations are supported by Aktar et al. (2010), who showed high SAR values around Kolkata.

Principal component analysis

We performed principal component analysis (PCA) using normalized water quality data to more concisely account for the compositional patterns and identifying factors influencing these patterns. The first three PCs on varimax rotation (henceforth called varifactors; VFs) explain 84.97% of the total variance (Table S2). Varifactor 1, which explains 48.32% of the total variance, shows strong positive loadings of BOD, DOC, TOC, phosphate, DSi, GPP, total nitrogen and COD; moderate positive loadings of pH, temperature, Chl *a*, SO₄²⁻, BSi, and Ca; and negative loading of DO. The VF1 points to organic pollution and nutrient pollution and can be explained as an anthropogenic contribution from domestic sources, waste disposal and agricultural activities

Fig. 6 Dendrogram showing clustering of sampling sites based on 24 water quality variables measured in the Ganga River. Sites 1–7 are explained in Fig. 1



(Zhou et al. 2007). Signatures of eutrophy such as DOC, TOC, BOD, GPP, and Chl *a*, associated with VF1, represent combined influences of nutrient-driven autochthonous C build-up and allochthonous C input, mainly through point sources.

Varifactor 2 explains 28.11% of the total variance, with strong positive loadings of total hardness, chloride, TDS, conductivity, Na, K and Mg and moderate loadings of pH, SO_4^{2-} , and Ca. These variables are considered as a salinity factor, where the Ca, Mg Na, K, Cl, and SO_4^{2-} are determined more by natural weathering than by anthropogenic sources (Kumarasamy et al. 2014). Common causal relationships such as the dissolution of limestone, marl and gypsum (Razmkhah et al. 2010) and/or tidal influence of the Bay of Bengal in the lower reaches (Mitra et al. 2012) could be linked with these variables. Varifactor 3, which explains 8.54% of total variance, has strong loadings of NH_4^+ and moderate loadings of BSi. Together with urban point sources (sewage), the presence of ammonia can be attributed to surface runoff originating from agricultural lands. Moderate loading of BSi at VF1 and VF3 indicates its in situ (diatomaceous silica) as well as terrigenous origin. Overall, Table S2 clearly demarcates determinants of eutrophy from those of salinity variables and their causal factors, anthropogenic and weathering, respectively.

Cluster analysis

We performed hierarchical agglomerative cluster analysis using normalized datasets considering euclidean distance as a measure of similarity. Based on 24 water quality variables, three distinct clusters appear (Fig. 6). Cluster 1 grouped sites, namely Devprayag, Rishikesh, and Haridwar; cluster 2 grouped Varanasi and Howrah, and cluster 3 Diamond Harbour and Ganga Sagar. Sampling sites Devprayag, Rishikesh and Haridwar (cluster 1), are located headwards. Devprayag and Rishikesh, situated in hilly areas, are characterized by dense forest cover and less human disturbance. This sub-watershed has a relatively small human population with the

least industrial activity, and water quality is moderately polluted by agricultural activities (Jain 2002). Cluster 2 represents the most polluted study sites. Varanasi region receives pollutants from treated and untreated sewage, together with industrial effluents, agricultural runoff and an equally effective proportion of atmospheric deposition. Howrah site, including Kolkata city, represents an equally polluted river stretch. Diamond Harbour and Ganga Sagar, grouped in cluster 3, are situated in the lower reaches. These two study sites are under the tidal influence of the Bay of Bengal where the salinity factor dominates. The analysis clearly separated the upper reach sites (1, 2 and 3) from the highly polluted sites situated in the middle and lower reaches (Fig. 6).

Conclusions

The results of this watershed-scale study clearly showed marked spatiotemporal variations in physicochemical and biological attributes of the Ganga River. Anthropogenic factors seemed to be the principal drivers causing a discernible impact on the river all along its course. Spatial changes in water quality showed a strong dependence on input sources; while seasonal patterns showed an important role of stream flow. The severity of water quality changes increased downstream. Elevated levels of carbon, nutrients, Chl *a*, GPP, BOD and COD in Varanasi region reflected source intensities, while high levels of these variables at Howrah were associated with a combination of source input and backward flushing from the Bay of Bengal. Our results suggest that the drivers of COD, especially during lean flow, be considered in future studies to unravel the contribution of non-biological oxygen demand constraining river health. The study not only generates a large database highly relevant for river rejuvenation and management but also highlights the need to advance our understanding of source partitioning, groundwater linkages and freshwater–seawater coupling to design and implement integrated river basin management (IRBM) plans.

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