Variations of surface water quality in selected tidal creeks of Sagar Island, Indian Sundarban eco-region: a multivariate approach

Sanghamitra Basu¹ · Subarna Bhattacharyya¹ · Pranab Gogoi² · Suryasis Dasgupta¹ · Sanjoy Kumar Das²

Received: 26 November 2019 / Accepted: 3 March 2021 / Published online: 24 March 2021
© The Author(s) 2021

Abstract

Sagar Island in Indian Sundarbans is bestowed with numerous tidal creeks providing a suitable home to its inherent aquatic biota. The present study investigated the variation in the surface water quality in selected tidal creeks of Sagar Island, Indian Sundarbans to understand the present status of water quality for wildlife propagation and fisheries. Ten water parameters were taken into consideration for analysis on monthly basis from four stations (tidal creeks) from September 2015 to August 2016. One-way ANOVA showed five parameters (water temperature, salinity, dissolved oxygen, turbidity and chemical oxygen demand) varied significantly between seasons ($p \leq 0.05$). Factor analysis exhibited four factors explaining 53.21% total variance in the observed data. Salinity and turbidity showed a maximum annual range of variations followed by dissolved oxygen. The fluctuations of physicochemical parameters throughout the year hinted toward the ever-changing nature of the estuarine ecosystem with possible human-induced impacts. Pronounced variation in turbidity seemed to be the effect of ferrying/transportation, monsoonal runoff and other human-induced activities. In the present study, water parameters viz., water temperature, dissolved oxygen and turbidity were the deterministic parameters influencing the variables in the system. The other important parameters were found to be COD, BOD₃ and nitrate concentrations during the study period. The study shall provide baseline information in formulating the management measures in terms of water quality in wildlife propagation and fisheries.

Keywords Water parameters · Creeks · Multivariate approach · Sundarbans

Introduction

Sundarbans, the largest deltaic stretch of mangrove forest in the world, is formed at the estuarine phase of the Ganges—Brahmaputra river system (Chaudhuri et al. 2012). The area of Sundarbans is characterized by a low flat alluvial plain covered with mangrove swamps and marshes, and it is criss-crossed by a large number of tidal rivers, estuaries, creeks and saline water courses (Bagchi 1972). The biodiversity of Indian Sundarbans is extremely rich and also consists of extremely rich coastal, estuarine and marine fisheries. Taking this into consideration, it has been declared as world

heritage site by United Nations Educational, Scientific and Cultural Organization (1987) which shall go a long way to protect and conserve biodiversity (Sreelekshmi et al. 2020). Recently, in February 2019, the Indian Sundarbans has also been designated as ‘Wetland of International Importance’ (Ramsar site) (Sreelekshmi et al. 2020). Gopal and Chauhan (2006) stated the extensive spatiotemporal changes in hydrological regimes, topography and texture of the substratum, salinity and their interactions cause habitat heterogeneity in the mangrove ecosystems which affects the aquatic vegetation and fauna directly, and also causing damage especially to the seabirds. The author also stated that there is continuous threat to biodiversity due to the burgeoning human population, pollution, growing industrialization, oil spills, oil exploration, global climate change and sea level rise.

Tidal creeks are extremely abundant in Sundarbans estuarine systems which serve as feeder rivers, providing food control, storm water drainage and habitat to wildlife. It is ecologically important for the transfer of materials from terrestrial to marine biome, habitat to nursery ground for

✉ Sanghamitra Basu
oomphsenorita090@gmail.com

¹ School of Environmental Studies, Jadavpur University, Kolkata 700032, India

² Kolkata Centre, ICAR-Central Inland Fisheries Research Institute, C.G.O. Complex, 2nd Floor, Sector-1, Kolkata, West Bengal 700 064, India

commercial fisheries (Mallin and Lewitus 2004; Saliu and Ekpo 2006). There has been a considerable loss of creeks due to overuse, pollution, diversion, land filling, etc., and Indian Sundarbans is also not an exception thereof. The nature and distribution of biodiversity are primarily ruled by variations in the physicochemical properties of water (Murugan and Ayyakkannu 1991). It is also responsible for supporting aquatic life and maintaining the aquatic environment and is likely to have an impact on the growth of the organisms as well as the productivity of the ecosystems (Das 2012). The physicochemical properties of the estuarine environment are highly dynamic due to the influx of fresh water. Surface waters are the most vulnerable and are exposed to rapid pollution due to their easy accessibility both the natural and anthropogenic causes (Singh et al. 2004; Barakat et al. 2016). These creeks are also acting as the probable channels for carrying pollutants (municipal and industrial wastes run off from agricultural land) to the estuarine core. Barletta et al. (2019) opined that the estuaries are often found to have the hard-hit zones with respect to the heavy metals and pesticides, and usually it has a high residence time for pollutants. In addition, the seasonal variation of precipitation, surface runoff, is a seasonal phenomenon which also supports to constitute the polluting source, largely affected by climate. Since estuaries and the supported creeks are highly fecund ecosystems and provides congenial home for the inherent biota, it is necessary to prevent and control the sources of pollution and to have reliable information on quality of water for effective management. Therefore, it is imperative to understand the changes in water quality variables from time to time for the quality assessment of the ecosystem (Chang 2008). The gradual increase in human activities for developing coastal areas also have resulted in loss of ecological values of the tidal creeks (Vernberg and Vernberg 2001). The large variability in hydrological parameters in coastal water influences, topographic heterogeneity and their interactions, has resulted in a biodiversity explosion in the Sundarbans mangrove eco-region (Ansari et al. 2017). Although such creek ecosystems are highly vulnerable to environmental changes and anthropogenic interferences, yet their ecological significance is underestimated as very less studies on these systems have been so far conducted relative to larger, better-known estuarine systems (Mallin and Lewitus 2004). Therefore, the present study evaluated the water quality status of four creeks (Costala, Gangasagar, Chemaguri and Mooriganga) in the Sundarban eco-region. Reports are available on fluctuations of physicochemical parameters in various parts of Sundarbans (Sarkar et al. 1986; Mitra et al. 2009; Manna et al. 2010; Das 2012; Chaudhury et al. 2012; Rakshit et al. 2015); however, the studies on spatiotemporal variations of water quality in tidal creeks, at Sagar Island are still scarce. The island had been affected by natural coastal processes, storm waves and artificial constructions such as

seawalls and jetties, etc. (Mondal et al. 2017). The effects of climate change are also well documented in and around Sagar Island (Mitra et al. 2009).

The multivariate statistical approaches have become popular in recent times due to their ability to treat large volume of spatial and temporal data from variety of monitoring sites (Barakat et al. 2016). Different multivariate statistical techniques such as cluster analysis, principal component analysis, factor analysis and discriminant analysis are used to interpret the complex data matrices for a better understanding of the water quality and ecological status of the studied ecosystems (Vega et al. 1998; Noorie et al. 2010; Wang et al. 2014). It also allows the identification of possible factors that have an impact on water systems and provides an essential tool for reliable management of water resources (Wunderlin et al. 2001; Reghunath et al. 2002; Simeonova et al. 2003). Helena et al. (2000) stated that multivariate statistical techniques facilitate to characterize and evaluation of surface water quality, which will be useful further in verifying spatial and temporal patterns linked to seasonality. Wang et al. (2007) evaluated the spatiotemporal variations of water quality of 19 rivers by applying the cluster analysis and factor analysis. Similarly, Kumarasamy et al. (2014) and Khan et al. (2016) applied cluster analysis and factor analysis to investigate the variability of hydrochemistry from Tamrapani river, Southern India and Ramganga river (Ganga basin), respectively. The correlation analysis, principal component analysis and canonical correlation components were used by Noori et al. (2010) to study the seasonal variation of water variables, relationship between physical and chemical parameters and selection of principal and non-principal monitoring stations in the Karoon river basin, Iran. Sharma et al. (2015) also applied former multivariate techniques to identify the potential sources of pollution and clustering of monitoring stations of Ganga and Yamuna River in Uttarakhand, India. Furthermore, usefulness of cluster analysis, principal component analysis and factor analysis for interpreting the complex data sets, identifying the attributes responsible for pollution as well as water quality management previously reported by several workers (Shreshtha and Kazma 2007; Noori et al. 2010, 2012; Wang et al. 2012, 2014; López-López et al. 2014; Bostanmaneshrad et al. 2018). In the recent times, several authors have evaluated the underlying relationship between macro-scale parameters (land use, population density, geology, erosion, etc.) with the micro-scale attributes, i.e., water quality parameters (Bostanmaneshrad et al. 2018; Chimwanza et al. 2014; Liu et al. 2016). Bostanmaneshrad et al. (2018) quantified the significant relationship between land use and phosphorus, total solids and turbidity, erosion levels and electrical conductivity, and erosion and total solids in their study from Siminehrood river basin. All the previous studies showed that the multivariate statistical methods are

important tools to determine the relationships between the water quality parameters, and identify particular attributes responsible for the relationship. With this view, the present study is an attempt to understand the present ecological health and status of tidal creeks in the mangrove ecosystems of Sagar Island by approaching multivariate techniques. The basic objective of the study is to evaluate the spatiotemporal variability in physicochemical parameters of surface water samples collected from the selected tidal creeks.

Study area

Sagar Island (between latitude $21^{\circ} 37'$ and $21^{\circ} 52'$ N and longitude $88^{\circ} 03'$ and $88^{\circ} 11'E$), part of the Hooghly-Matlah estuary is subjected to intense tidal and wave actions (Majumdar et al. 2002). The island has unique mangrove vegetation and surrounded by the river Hooghly on the north and the west, Mooriganga on the eastern side, while the southern part faces the Bay of Bengal. The island is inundated by various natural tidal creeks and artificial canals which are a source of saline surface water in the island (Chakraborty 1995). The island experiences a semidiurnal tidal regime with high tide zone ranges from 5 to 6 m (Paul and Bandhopadhyay 1987). The island is also highly vulnerable to environmental degradations, burgeoning population

and erosion which accounted for approximately 30 km^2 net land loss in the last three decades (Hazra et al. 2002). Among the tidal creek system at Sagar, Chemaguri creek is the most prominent one with planted mangroves along its length (Mitra et al. 2009). The present study was carried out from September 2015 to August 2016 in 4 (four) major creeks viz. Costala ($21^{\circ} 48' 829'' \text{ N } 88^{\circ} 09' 93'' \text{ E}$), Gangasagar ($21^{\circ} 41' 222'' \text{ N } 88^{\circ} 02' 80'' \text{ E}$), Chemaguri ($21^{\circ} 40' 745'' \text{ N } 88^{\circ} 07' 695'' \text{ E}$) and Mooriganga ($21^{\circ} 48' 828'' \text{ N } 88^{\circ} 09' 93'' \text{ E}$) (herein referred as S1, S2, S3 and S4, respectively) at Sagar Island, Indian Sundarbans. The sampling sites were designed to cover a wide range of determinants of key sites, which reasonably represent the water quality of the creeks in the Island. The sites were selected mainly based on their mangrove vegetation covers and also ranging from region with high riverine influence (Costala and Mooriganga) to brackish water regions and mangrove vegetation (Chemaguri and Gangasagar). The geographical locations of the sampling sites and study area in Sagar Island, Sundarbans are shown in Fig. 1.

Fig. 1 The map showing the geographical locations of the sampling sites and study area in Sagar Island, Sundarban

Sampling procedure

Surface water samples were collected in pre-cleaned acid washed polyethylene bottles (1.0 L) during low tide before noon from the selected locations. Water temperature (WT) was measured on field by using a mercury thermometer (0–100 °C); pH with a digital pH meter (Model No. 101 E), and turbidity (Nephelometric turbidity unit) was measured by a turbidity meter (Model No. EI 331E). The in situ estimation of dissolved oxygen (DO) and salinity (ppt) was done by the titrimetric method (APHA 2005). Collected water samples were brought to the laboratory in cold conditions for nutrient analysis. Nutrients such as nitrate, phosphate and silicate were analyzed following standard methods described in APHA (2005). For analysis of chemical oxygen demand (COD) and biochemical oxygen demand (BOD), water samples were collected separately in 500 ml polyethylene bottles. COD was measured by the open reflux method, and BOD was estimated by a 3-days BOD incubation (BOD₃) (APHA 2005). All the methods were standardized as per ambient conditions and blank measurements were taken into consideration for the estimation procedures. HPLC grade water was used throughout the laboratory works. Since determination of BOD (BOD₃ and/or BOD₅) is a long-time estimation process, several attempts have been made to shorten the process by applying alternate analytical methods (Noori et al. 2011, 2013). The analytical model such as reduced-order neural network model (RONNM) and reduced-order adaptive neuro-fuzzy inference system (ROANFIS) model fed with input vectors [latitude (N), longitude (E), suspended solids, water temperature, river discharge, DO, electrical conductivity, nitrate and total phosphorus] is developed which indicated the best fitted online predictions of BOD₅ (Noori et al. 2011, 2013).

Data treatment

Statistical computations such as one-way ANOVA, Pearson correlation, clustering dendrogram and factor analysis were performed with the help of software applications (SPSS v. 23 and XLSTAT v. 2018). The environmental data were normalized by transforming $\log(x+1)$ prior to analysis. The water quality parameters of different seasons were subjected to one-way analysis of variance (ANOVA) and Duncan's multiple range tests (DMRT) post-hoc test using SPSS v.23. The post-hoc test was carried out to find out the significant variations of measured water variables between seasons. Pearson correlation (2-tailed) was conducted to comprehend the interdependence among the physicochemical parameters. This minimizes the effect of between stations correlations and between sampling campaigns relationships (Barakat et al. 2016). Further, the correlation

coefficient – 1 or 1 indicated the strongly negative or positive relationship between the two variables, whereas its value closer to 0 defined no linear relationship between them at 0.05 significance level (Kumar et al. 2006; Barakat et al. 2016). Hierarchical agglomerative cluster analysis was performed to understand a measure of similarity using Euclidean distances (Zhao et al. 2011; Singh et al. 2004; Sharma 1996). The hierarchical cluster analysis is the most common approach where the clusters are formed based on the similar nature attributes and forming higher clusters step-by-step (Willet 1987). Generally, the Euclidean distance portrayed the proximity between two samples and 'distance' which is represented by the 'difference' between the obtained values from both the samples (Otto 1998), and it is illustrated through a dendrogram (Forina et al. 2002). Further, non-metric dimensional scaling (NMDS) was also performed to visualize the dimensions to understand the similarity or dissimilarities among data sets. Likewise, factor analysis was performed (XLSTAT v.18) on the water quality data to find out the factors related to influence each of them. The first step of factor analysis is to standardize the raw data and make them dimensionless. The correlation coefficient matrix, eigen values and eigen vectors were determined to yield the covariance matrix (Wang et al. 2014). The factors with eigen values that exceed 0.5 were considered in this study, whereas only three factors obtained that exceed one. Varimax rotation is an important second step in factor analysis used for maximizing the sum of the variance of the squared loadings, where 'loadings' means correlations between variables and factors. The varimax rotation on the factor loading infers the rotated principal factors (Singh et al. 2004, 2012; Noori et al. 2010; Ghahremanzadeh et al. 2018).

Table 1 Seasonal variation of water quality parameters in the study sites of Sundarbans

Water variables	Pre-monsoon	Monsoon	Post-monsoon
pH	7.67 ^a ± 0.29	7.65 ^a ± 0.52	7.50 ^a ± 0.50
Water temperature (°C)	27.67 ^a ± 3.00	26.29 ^a ± 3.07	20.88 ^b ± 0.97
Salinity (ppt)	25.59 ^a ± 6.10	5.83 ^b ± 6.82	13.54 ^c ± 5.74
Dissolved oxygen (mg l ⁻¹)	5.97 ^a ± 1.32	5.96 ^a ± 1.57	4.69 ^b ± 0.83
Turbidity (NTU)	43 ^a ± 22.83	65 ^b ± 18.11	36.93 ^a ± 28.78
Phosphate (mg l ⁻¹)	2.64 ^a ± 2.39	2.90 ^a ± 4.47	4.0 ^a ± 3.35
Nitrate (mg l ⁻¹)	1.29 ^a ± 0.73	1.40 ^a ± 0.65	1.10 ^a ± 0.57
Silicate (mg l ⁻¹)	12.94 ^a ± 7.26	16.6 ^a ± 7.97	13.18 ^a ± 6.30
COD (mg l ⁻¹)	23.93 ^a ± 8.39	17.87 ^b ± 6.09	17.0 ^b ± 4.03
BOD ₃ (mg l ⁻¹)	2.20 ^a ± 0.77	1.86 ^a ± 0.67	1.81 ^a ± 0.49

Values are means ± SE means followed by the same letter are not significantly different at 5% probability level

Results and discussion

The variation of water quality parameters in different seasons (pre-monsoon, monsoon and post-monsoon) is documented in Table 1. One-way ANOVA showed that, out of ten parameters, five parameters (WT, salinity, DO, turbidity and COD) varied significantly between the seasons ($p \leq 0.05$). The water remained neutral to alkaline throughout the study period well within the predicted range between 7.36 and 8.16. The result is in agreement with the findings of Manna et al. (2010) and Choudhury et al. (2012) from Sundarban waters. The rate of photosynthesis process, which removes CO_2 from water through bicarbonate degradation, freshwater influx and decomposition of organic matter, could have contributed to the fluctuation of pH (Rahman et al. 2013). The alkaline nature of water ($\text{pH} > 7.0$) with low variations between the sampling stations, suggested that the water mass remained well buffered throughout the study period, and it indicated the presence of biodegradable organic matter in the water column. Surface water temperature varied significantly ($p \leq 0.05$) from post-monsoon to pre-monsoon. Water temperature of the tidal creeks showed a forecasted range of variability with lowest in post-monsoon in the month of January (19.34°C), and had a maximum in pre-monsoon in the month of June (31.13°C). In tidal influenced estuarine environment of the Sundarbans, temperature values undergo a wide diurnal and seasonal variation. A gradual increase in salinity was observed from post-monsoon to pre-monsoon, recorded maximum in May (28.08 ppt) and lowest in October (0.79 ppt). The distinct temporal variation of salinity in the present study was similar to Saravankumar et al. (2008); Choudhury et al. (2012) and Gogoi et al. (2019). Saravankumar 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 precipitations or by tidal variations, which supported our present findings. Manna et al. (2010) also reported similar findings with the lower salinity during winter months (November–February; avg. 16.7 PSU) as compared to summer months (March to May; 23.5 PSU) from *Bara Herobhanga Khal* (Jharkhali waters), Sundarbans. Moderate concentrations of dissolved oxygen were recorded across the stations with its maximum in October at the station Chemaguri (7.8 mg l^{-1}) and minimum in December at Mooriganga (3.29 mg l^{-1}). Dissolved oxygen and water temperature were influenced to a greater extent by atmospheric conditions and sampling times (Debels et al. 2005); as a result, its concentrations vary during various moments of the day and under different weather conditions. Lower concentrations of DO during post-monsoon may be due to increased salinity, temperature and biological activity (Levinton 2001). Our observation is in conformity with Sarkar

and Bhattacharya (2010) where the authors stated that dissolved oxygen concentration in the surface water of Sundarbans mangrove wetland ranged from 5.18 to 6.49 mg l^{-1} with an average value 4.0 mg l^{-1} , indicating that surface waters are moderately oxygenated. Turbidity was recorded in the expected level with its peak during monsoon which might be due to riverine influx bearing excess suspended load coupled with high monsoon precipitations. The steady expansion of waterway transportation/vessel trafficking was also one of the reasons for the enhancement of turbidity at the stations under study. The mean value of turbidity was highest at Chemaguri in the month of November and the lowest at Gangasagar in December. The observed range of COD was 8.0 – 40.0 mg l^{-1} across the stations with an average value $19.60 \pm 7.0\text{ mg l}^{-1}$, which exceeds the permissible range of World Health Organization, i.e., $< 10\text{ mg l}^{-1}$. The precipitation causes dilution during monsoon which could be the reason for lower concentration of COD during monsoon. The moderate concentration of COD in the present study was indicating toward pollution of the aquatic ecosystem due to natural and anthropogenic stresses. Bhattacharya et al. (2015) reported high range of COD values (101.28 – 111.31 mg l^{-1}) in their studies from Jambu Island, Sundarbans and stated that it is derived from the primary production of the dense mangrove forests. High COD values in a tropical coastal wetland in Southern Mexico were also previously reported by Hernández-Romero et al. (2004), and it was associated with mangrove-enriched organic matters which supported the present findings. The BOD_3 ranges between 1.62 and 2.23 mg l^{-1} with an average 1.96 mg l^{-1} , where maximum and minimum were recorded at Gangasagar and Mooriganga, respectively. An average value of 2.04 mg l^{-1} BOD was reported previously by Rahman et al. (2015) from Sundarban waters, Bangladesh which is in line with our present observations.

Non-uniform seasonal trend for nutrients was observed throughout the study period. In general, nutrients are sufficient to support primary productivity in an estuarine environment. Tidal fluctuation is the main driving force for the distribution of nutrients in Indian Sundarbans, where its dispersion primarily depends on the tidal motions of the water body (Chaudhuri et al. 2012). No significant ($p \geq 0.05$) variations of nutrients (phosphate, nitrate and silicate) were observed across the seasons. Phosphate concentration was estimated to be highest at station Mooriganga (11.7 mg l^{-1}) in the month of October while the lowest at Gangasagar (0.4 mg l^{-1}) in March. Lower concentration of phosphate during pre-monsoon season might be due to its utilization by photoautotrophs, and buffering actions of sediments in various environmental conditions (Rajasegar 2003). Silicate and nitrate showed higher concentration in monsoon as compared to post-monsoon and pre-monsoon during the study period. Higher values of nitrate and silicate in monsoon may

be attributed to freshwater influx and land runoff (Sathpathy et al. 2009; Ramakrishnan et al. 1999). Similarly, Karuppasamy and Perumal (2000) stated that higher magnitude of nitrate during monsoon might be caused by the organic matter being enriched by the monsoonal flow and decomposition of terrestrial runoff from the catchment areas. Sarkar and Bhattacharya (2010) also opined that land-based nutrients, especially from the agricultural fields in proximity, contributed to a greater extent to the enrichment of nutrient concentrations during monsoon. The inverse trend was observed with regard to phosphate concentrations that recorded the maximum during post-monsoon. Silicate values were found to be relatively higher as compared to the nitrate and phosphate in the present study, which is in line with Vajravelu et al. (2018). Maximum concentration of nitrate and silicate was observed in the month of October (3.20 mg l^{-1} ; at Chemaguri) and August (31.7 mg l^{-1} at Costala), and lowest in the month of April (0.62 mg l^{-1} at Gangasagar) and March (4.24 mg l^{-1} at Chemaguri), respectively. The high silicate and phosphate ratio (Si:P) in the present study is corroborated with the findings of Chaudhuri et al. (2012) and Sarkar and Bhattacharya (2010). However, the Si:P ratio was somewhat lower than 'modified' Redfield ratio (15:1) (Brzezinski 1958), and our present observations in seasonal estimates of silicate indicated broad seasonal fluctuations in the creek environment. Similarly, Choudhury and Bhadury (2015) reported that seasonal estimates of N:P ratio remained below the Redfield ratio (16:1), indicated nutrient limited (nitrogen) environment in Sagar island which is in line with our present observation from Sagar Island. Arumugum et al. (2016) also showed low N:P ratio than the Redfield ratio in Muthupet mangrove waters depicted a low bio-availability of nitrogen for primary production which confirms to our estimates. 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. The estimated ratio of nitrate, phosphate and silicate is shown in Table 2.

Intra-relationship of various environmental variables (Karl Pearson's correlation coefficient) showed significant positive correlation of water temperature with salinity ($r=0.42$; $p \leq 0.01$), DO ($r=0.55$; $p \leq 0.01$), silicate ($r=0.40$; $p \leq 0.01$); COD ($r=0.38$, $p \leq 0.01$), and it was negatively correlated with phosphate ($r=-0.11$). According to Osibanjo et al. (2011) and Şener et al. (2017), one very common but essential parameter, pH governs various other parameters like alkalinity, solubility and also the hardness. The pH had significant positive correlation with DO ($r=0.31$; $p \leq 0.05$). Similar observation was also reported by Gogoi et al. (2019) in their study from *Kailash Khal*, Sundarbans; depicted that pH had a positive correlation with water temperature and also salinity with the water temperature and DO. The strong positive correlation was observed between salinity and COD ($r=0.39$ $p \leq 0.01$), and nutrients such as nitrate ($r=0.35$ $p \leq 0.01$) and silicate ($r=0.41$ $p \leq 0.01$). Gogoi et al. (2020) also found similar observation in their study from Sundarban waters, where salinity had a positive correlation with the nutrient parameters (phosphate, silicate and sulfate).

Multivariate approach

Cluster analysis was performed season-wise to understand the percentage similarity among various stations. The hierarchical group average showed the variations in water parameters by clustering similar nature of samples/sampling stations. It formed two clusters with the maximum similarity between the stations Chemaguri and Costala during pre-monsoon, while showed maximum dissimilarity between the station Chemaguri during monsoon and Gangasagar during pre-monsoon (Fig. 2). The freshwater influx with its high allochthonous inputs during the rainy season also could be a reason for variations of water attributes during monsoon. Further, NMDS also showed the similar nature of ordination pattern among samples/sampling stations that were observed in cluster analysis (Fig. 3). The stress value was found less than 0.14 which is good ordination pattern that distance among items/samples are perfect. In this study, water parameters such as dissolved oxygen and turbidity were found to be strong parameters influencing their variables in the system. The other important parameters were found to be COD, BOD_3 and phosphate concentrations during the study period (Table 3).

Results of the factor analysis showed, four factors were extracted which explained 53.21% of the total variance in the observed data (Table 4 and Fig. 4). The eigen value and cumulative percentage variability of the extracted factor from the data set are shown in the scree plot (Fig. 5). Factor 1 accounts for 22.62% variance where the parameters

Table 2 Nutrient parameters: nitrate, phosphate and silicate (N:P:Si) ratio in the study sites of Sundarbans

Months	N:P	Si:P
September	0.29	2.10
October	0.27	1.89
November	0.37	4.93
December	0.67	7.78
January	0.19	2.14
February	1.14	6.45
March	0.95	4.98
April	0.37	2.26
May	0.48	5.59
June	0.45	8.76
July	0.44	7.34
August	0.55	8.90

Fig. 2 Dendrogram showing the similarity of stations in seasons

Fig. 3 NMDS showing the environmental variables recorded in various stations and seasons (1: pre-monsoon; 2: monsoon; 3: post-monsoon)

(loadings) such as pH, WT, salinity, DO, silicate and COD were positively correlated, while the attributes viz., turbidity, phosphate and nitrate were negatively correlated. Similar observations also reported by Sarkar and Bhattacharya (2010), where they stated that, the factors appear (negative correlation of nitrate, phosphate and BOD) to be originated from the combined effect from the anthropogenic activities. Factor 2 explained the 15.88% total variance, and it was negatively loaded with variables; DO, turbidity and nitrate. The causes may be due to gradual increase in water transportation/fishing vessels and agriculture expansions. Likewise, factor 4 represents the 6.68% total variance. The factor

loading revealed that parameters such as phosphate, COD and BOD₃ were negatively correlated with each other. Since these causes of these parameters (phosphate and COD) are primarily from the source of agricultural land and industrial activities. BOD represents the high organic load, which enriching the growth of microorganisms in the mangrove patches. From this analysis, it is reflected that the major causes of the water quality variations/degradation seemed to be more usage of nitrogenous and phosphate-rich fertilizers, discharge of untreated industrial effluents, increasing waterway transportation which accelerates the oil spills in river/estuary and also the other non-point sources. With the best uses of Sundarban waters in different aspects such as fishing, irrigation, ferry service, boating and tourism, some water quality parameters are still well within the permissible limits, where it is seemed to be suitable for bathing, aquatic biodiversity, fisheries and recreation, etc., according to the criterion placed from the various best designated use prescribed by the World Health Organization, US Environmental Protection Agency and Pollution Control Board, India (Table 5).

Conclusion

The present study reflected the changes in some important hydrological factors round the year which hinted toward the dynamic nature of the estuarine ecosystem due to climate change and human-induced impacts. Salinity and turbidity showed the maximum annual range of variation followed

Table 3 Intra-relationship of environmental variables in Sundarbans

Variables	pH	WT	Sal	DO	Tur	Phos	Nitr	Si	COD	BOD ₃
pH	1									
WT (°C)	0.15	1								
Sal (ppt)	-0.04	0.42**	1							
DO (mg l ⁻¹)	0.31*	0.55**	0.23	1						
Tur (mg l ⁻¹)	0.01	0.07	-0.36*	0.08	1					
Phos (mg l ⁻¹)	-0.03	-0.11	-0.18	-0.22	0.13	1				
Nitr (mg l ⁻¹)	0.15	0.03	-0.01	0.35*	0.24	0.28*	1			
Si (mg l ⁻¹)	0.21	0.40**	0.17	0.41**	0.06	-0.05	-0.03	1		
COD (mg l ⁻¹)	0.12	0.38**	0.39**	0.18	-0.24	-0.02	-0.25	0.31*	1	
BOD ₃ (mg l ⁻¹)	0.08	0.16	0.16	-0.14	-0.14	-0.01	-0.08	-0.07	0.40**	1

Sal salinity, Tur turbidity, Phos phosphate, Nitr nitrate, Si silicate

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

Table 4 Factor analysis of the water quality parameters after varimax rotation

Variables	F1	F2	F3	F4
pH	0.2278	-0.2161	-0.1467	-0.1480
WT (°C)	0.6762	-0.1446	-0.1032	-0.0195
Salinity (ppt)	0.7200	0.2571	0.5586	0.3216
DO (mg l ⁻¹)	0.6617	-0.5841	-0.2197	0.1836
Turbidity (mg l ⁻¹)	-0.1716	-0.3797	-0.1834	-0.0815
Phosphate (mg l ⁻¹)	-0.2117	-0.1346	0.1579	-0.3197
Nitrate (mg l ⁻¹)	-0.0216	-0.8382	0.4983	-0.2208
Silicate (mg l ⁻¹)	0.4702	-0.1529	-0.2742	-0.0090
COD (mg l ⁻¹)	0.6732	0.3670	-0.0626	-0.4624
BOD ₃ (mg l ⁻¹)	0.2128	0.2824	0.1310	-0.3691
Variability (%)	22.6281	15.8826	8.0111	6.6847
Cumulative (%)	22.6281	38.5107	46.5218	53.2065

Bold values indicating the highest loading for the variables

Fig. 4 Scree plot of the factor analysis after varimax rotation **Fig. 5** Factor loading of water quality parameters after varimax rotation

by dissolved oxygen in the present study. Other parameters did not show any significant annual range of variation in the present study, though phosphate and COD values were higher in post-monsoon and pre-monsoon seasons, respectively. As there were no significant industrial activities in the near vicinity; therefore, the higher COD might be due to the presence of mangroves at sampling sites. Water variables such as dissolved oxygen, water temperature, salinity, turbidity and nitrate were the effective factors influencing their variables in the creeks, which was evident from factor analysis. The higher magnitude of COD in this study doesn't seem to indicate pollution in the study area. Higher turbidity seemed to be due to monsoonal runoff and ferrying activities in the creeks. Long-term monitoring approach is required to look for time-scale changes to comprehend the climatic emergencies and anthropogenic stress. Also, studies on

Table 5 Water quality standards for aquatic biodiversity propagation

Water variables	BIS	CPCB	EPA	Present study
pH	6.5–8.5	6.5–8.5	6–8.5	7.50–7.67
DO (mg l ⁻¹)	4.0	5.0 or 60% saturation value, whichever is higher	> 5.5	4.69–5.97
Phosphate (mg l ⁻¹)	0.1	–	–	2.64–4.0
BOD ₅ (mg l ⁻¹)	–	< 3 (20 °C for 5 days)	–	1.81–2.20
COD (mg l ⁻¹)	–	< 10 (Outdoor bathing)	–	17–23.93
Turbidity (NTU)	10	30	< 50	36.93–65
Free ammonia (as N)	–	1.2 or less	–	–

BIS Bureau of Indian Standards, CPCB Central Pollution Control Board, India, EPA US Environmental Protection Agency

anthropogenic interferences such as pollution, coastal development, destructive fishing, ferrying, overexploitation, etc., resulted in unique information that may provide mitigating measures to conserve biodiversity. Water quality criteria for wildlife propagation and fisheries need to be addressed for the sustenance of endemic biota inhabiting in the Sundarban Biosphere Reserve, which is also opined by many previous workers. Although the creek waters (Sundarbans) are impacted by various human-induced activities (such as fishing, irrigation, ferry service, boating and tourism), some water quality parameters are still well within the permissible limits, where it is suitable for bathing, aquatic biodiversity, fisheries and recreation purpose.

Acknowledgements The authors are grateful to the Director, School of Environmental Studies, Jadavpur University, Kolkata -700032, India for laboratory support to carry out the research work. The authors also acknowledge Mr. K. Lohith Kumar, Scientist, ICAR-Central Inland Fisheries Research Institute, Kolkata for the preparation of the map citing the sampling stations.

Author contributions SB: conceptualization, sample collection, interpretation of data, and manuscript preparation. PG: statistical analysis, interpretation of data, and manuscript preparation. SB: guidance, review and manuscript corrections. SD: statistical analysis, and manuscript preparation. SKD: manuscript preparation and corrections.

Funding No financial support received from any organization, as the work was under a part of Ph.D. research work.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Ethical approval The authors declare that they have strictly followed all the rules and principles of ethical and professional conduct while completing the research work. No specific permission was required to collect the water samples at the study sites. Under this research no involvement of human and/or animals.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- APHA (2005) In: Rice EW, Baird RB, Eaton AD, Clesceri LS (eds) Standard methods for the examination of water and Wastewater, 21st edn. American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF), Washington, DC, USA
- Ansari KGMT, Bhadury P (2017) Occurrence of epibionts associated with meiofaunal basibionts from the world's largest mangrove ecosystem, the Sundarbans. *Mar Biodivers* 47(2):539–548
- Arumugam S, Sigamani S, Samikannu M, Perumal M (2016) Assemblages of phytoplankton diversity in different zonation of Muthupet mangroves. *Reg Stud Mar Sci* 3:234–241
- Bagchi KG (1972) The Bhagirathi–Hooghly Basin. Calcutta University Publication, Calcutta
- Barakat A, Baghdadia ME, Raisa J, Aghezzaf B, Slassib M (2016) Assessment of spatial and seasonal water quality variation of Oum Er Rbia River (Morocco) using multivariate statistical techniques. *Int Soil Water Conserv Res* 4:284–292
- Barletta M, Lima AR, Costa MF (2019) Distribution, sources and consequences of nutrients, persistent organic pollutants, metals and microplastics in South American estuaries. *Sci Total Environ* 651:1199–1218. <https://doi.org/10.1016/j.scitotenv.2018.09.276>
- Bhattacharya BD, Hwang JS, Sarkar SK, Rakhsit D, Murugan K, Tseng LC (2015) Community structure of mesozooplankton in coastal waters of Sundarban mangrove wetland, India: a multivariate approach. *J Mar Sys* 141:112–121
- Bostanmaneshrad F, Partani S, Noori R, Hans-Peter N, Berndtsson R, Adamowski JF (2018) Relationship between water quality and macro-scale parameters (land use, erosion, geology, and population density) in the Siminehrood River Basin. *Sci Total Environ* 639:1588–1600

- Brzezinski MA (1958) The Si:C:N ratio of marine diatoms: inter-specific variability and the effect of some environmental variables. *J Phycol* 2:347–357
- Chakraborti P (1995) Evolutionary history of the coastal quaternaries of the Bengal plain India. *Proc INSA* 61:343–354
- Chang H (2008) Spatial analysis of water quality trends in the Han River basin, South Korea. *Water Res* 42:3285–3304
- Chaudhuri K, Manna S, Sarma SK, Naskar P, Bhattacharyya S, Bhattacharyya M (2012) Physicochemical factors controlling water column metabolism in Sundarban estuary India. *Aquat Biosyst* 8:26
- Chimwaza B, Mumba PP, Moyo BHZ, Kadewa W (2014) The impact of farming on river banks on water quality of the rivers. *Int J Environ Sci Technol* 2(4):353–358
- Choudhury A, Bhadury P (2015) Relationship between N:P:Si ratio and phytoplankton community composition in a tropical estuarine mangrove ecosystem. *Biogeosciences* 12:2307–2355
- Das GK (2012) Impact of water quality on the changing environmental scenario of Sunderbans. *Reason* 11:57–66
- Debels P, Figueroa R, Urrutia R, Barra R, Niell X (2005) Evaluation of water quality in the Chillán River (Central Chile) using physicochemical parameters and a modified water quality index. *Environ Monit Assess* 110(1–3):301–322
- Forina M, Armanino C, Raggio V (2002) Clustering with dendrograms on interpretation variables. *Anal Chim Acta* 454:13–19
- Ghahremanzadeh H, Noori R, Baghvand A, Nasrabadi T (2018) Evaluating the main sources of groundwater pollution in the southern Tehran aquifer using principal component factor analysis. *Environ Geochem Health* 40:1317–1328
- Gogoi P, Sinha A, Das Sarkar S, Chanu TN, Yadav AK, Koushlesh SK, Borah S, Das SK, Das BK (2019) Seasonal influence of physico-chemical parameters on phytoplankton diversity and assemblage pattern in Kailash Khal, a tropical wetland, Sundarbans India. *Appl Water Sci* 9:156
- Gogoi P, Das SK, Das Sarkar S, Chanu TN, Manna RK, Sengupta A, Raman RK, Samanta S, Das BK (2020) Environmental factors driving phytoplankton assemblage pattern and diversity: insights from Sundarban eco-region. *Ecohydrol Hydrobiol*. <https://doi.org/10.1016/j.ecohyd.2020.09.005>
- Gopal B, Chauhan M (2006) Biodiversity and its conservation in the Sundarban mangrove ecosystem. *Aquat Sci* 68(3):338–354
- Hazra S, Ghosh T, Dasgupta R, Sen G (2002) Sea level and associated changes in the Sundarbans. *Sci Cult* 68(9–12):309–321
- Helena B, Pardo R, Vega M, Barrado E, Fernandez JM, Fernandez L (2000) Temporal evolution of groundwater composition in an alluvial aquifer (Pisuerga River, Spain) by principal component analysis. *Water Res* 34:807–816
- Hernández-Romero AH, Tovilla-Hernández C, Malo EA, Bello-Mendoza R. (2004) Water quality and presence of pesticides in a tropical coastal wetland in southern Mexico. *Mar Pollut Bull* 48(11–12):1130–1141
- Karuppasamy PK, Perumal P (2000) Biodiversity of zooplankton in Pichavaram mangroves, South India. *Adv Biosci* 19:23–32
- Khan MYA, Gani KM, Chakrapani GJ (2016) Assessment of surface water quality and its spatial variation. A case study of Ramganga River, Ganga Basin India. *Arab J Geosci* 9(1):1–9
- Kumar M, Ramanathan A, Rao MS, Kumar B (2006) Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi India. *Environ Geol* 50:1025–1039
- Kumarasamy P, James RA, Dahms HU, Byeon CW, Ramesh R (2014) Multivariate water quality assessment from the Tamiraparani river basin Southern India. *Environ Earth Sci* 71(5):2441–2451
- Levinton JS (2001) Marine biology. Oxford Univer Press, New York, p 560
- Liu Y, Theller LO, Pijanowski BC, Engel BA (2016) Optimal selection and placement of green infrastructure to reduce impacts of land use change and climate change on hydrology and water quality: an application to the Trail Creek Watershed Indiana. *Sci Total Environ* 553:149–163
- López-López JA, Mendiguchían C, García-Vargas M, Morenón C (2014) Multi-way analysis for decadal pollution trends assessment: the Guadalquivir River estuary as a case study. *Chemosphere* 111:47–54
- Majumdar RK, Mukherjee AL, Roy NG, Sarkar K, Das S (2002) Groundwater studies on south Sagar Island region, South 24-Parganas, West Bengal. In: *Proceedings of the International Conference on Water Related Disasters*, New Age International Publishers, Calcutta, India, pp 175–183
- Mallin MA, Lewitus AJ (2004) The importance of tidal creek ecosystems. *J Exp Mar Biol Ecol* 2(298):145–149
- Manna S, Chaudhuri K, Bhattacharyya S, Bhattacharyya M (2010) Dynamics of Sundarban estuarine ecosystem: eutrophication induced threat to mangroves. *Saline Syst* 6:8
- Mitra A, Gangopadhyay A, Dube A, Schmidt ACK, Banerjee K (2009) Observed changes in water mass properties in the Indian Sundarbans (northwestern Bay of Bengal) during 1980–2007. *Curr Sci* 97:1145–1152
- Mondal I, Bandyopadhyay J, Dhara S (2017) Detecting shoreline changing trends using principle component analysis in Sagar Island, West Bengal India. *Spatial Inform Res* 25(1):67–73
- Murugan A, Ayyakkannu K (1991) Ecology of uppanar backwaters, Cuddalore: 1 physico-chemical parameters. *Mahasagar* 24(1):31–38
- Noori R, Sabahi MS, Karbassi AR, Baghvand A, Taati Zadeh H (2010) Multivariate statistical analysis of surface water quality based on correlations and variations in the data set. *Desalination* 260:129–136
- Noori R, Karbassi AR, Ashrafi Kh, Ardestani M, Mehrdadi N (2011) Development and application of reduced-order neural network model based on proper orthogonal decomposition for BOD5 monitoring: active and online prediction. *Environ Progress Sustain Energy*. <https://doi.org/10.1002/ep.10611>
- Noori R, Karbassi A, Khakpour A, Shahbazbegian M, Khalf Badam HM, Vesali-Naseh M (2012) Chemometric analysis of surface water quality data: case study of the Gorganrud River Basin Iran. *Environ Model Assess* 17:411–420
- Noori R, Safavi S, Nateghi Shahrokni SA (2013) A reduced-order adaptive neuro-fuzzy inference system model as a software sensor for rapid estimation of five-day biochemical oxygen demand. *J Hydrol* 495:175–185
- Osibanjo O, Daso AP, Gbadebo AM (2011) Gbadebo AM (2011) The impact of industries on surface water quality of River Ona and River Alaro in Oluyole Industrial Estate, Ibadan Nigeria. *Afr J Biotechnol* 10(4):696–702
- Otto M (1998) Multivariate methods. In: Kellner R, Mermet JM, Otto M, Widmer HM (eds) *Analytical chemistry*. Wiley-VCH, Weinheim, p 916
- Paul AK, Bhandyopadhyay MK (1987) Morphology of Sagar Island, a part of Ganga delta. *J Geol Soc India* 29:412–423
- Rahaman SMB, Golder J, Rahaman MS, Hasanuzzaman AFM, Huq KA, Begum S, Islam SS, Bir J (2013) Spatial and temporal variations in phytoplankton abundance and species diversity in the Sundarbans mangrove forest of Bangladesh. *J Mar Sci Res Dev* 3(2):1–9
- Rahaman SMB, Rahaman MS, Ghosh AK, Gain D, Biswas SK, Sarder L, Islam SS, Sayeed AB (2015) A spatial and seasonal pattern of water quality in the Sundarbans river systems of Bangladesh. *J Coast Res*. <https://doi.org/10.2112/jcoastres-D-13-00115.1> (Coconut Creek (Florida), ISSN 0749-0208)
- Rajasegar M (2003) Physico-chemical characteristics of the Vellar estuary in relation to shrimp farming. *J Environ Biol* 24:95–101

- Rakshit D, Sarkar SK, Bhattacharya BD, Jonathan MP, Biswas JK, Mondal P, Mitra S (2015) Human-induced ecological changes in western part of Indian Sundarban Megadelta: a threat to ecosystem stability. *Maine Pollut Bull* 99:186–194
- Ramakrishnan R, Perumal P, Santhanam P (1999) Spatio-temporal variations of hydrographical features in the Pichavaram mangroves and Mohi aqua farm, Southeast coast of India. In: *Proceeding of international seminar on application with hydrogeochemistry*. Annamalai University, Dept. of Geology, Annamalai University, Annamalai Nagar, Tamil Nadu, India, pp 197–203
- Redfield AC (1958) The biological control of the chemical factors in the environment. *Am Sci* 46:205–222
- Reghunath R, Murthy TR, Raghavan BR (2002) The utility of multivariate statistical techniques in hydro geochemical studies: an example from Karnataka, India. *Water Res* 36:2437–2442
- Saliu JK, Ekpo MP (2006) Preliminary chemical and biological assessment of Ogbe Creek, Lagos, Nigeria, West Africa. *App Ecol* 9:12
- Saravanakumar A, Rajkumar M, Thivakaran GA, Serebiah J (2008) Abundance and seasonal variations of phytoplankton in the creek waters of western mangrove of Kachchh-Gujarat. *J Environ Biol* 29(2):271–274
- Sarkar SK and Bhattacharya BD (2010) Water quality analysis of the coastal regions of Sundarban Mangrove Wetland, India using multivariate statistical techniques. In: Sarkar SK (ed) *Environmental management*, p 258. ISBN 978-953-307-133-6
- Sarkar SK, Singh BN, Choudhury A (1986) Compositions and variations in the abundance of zooplankton in the Hooghly estuary, West Bengal India. *Proc Indian Acad Sci (Anim Sci)* 95(2):125–134
- Satpathy KK, Sahu G, Mohanty AK, Prasad MVR, Panigrahi RC (2009) Phytoplankton community structure and its variability during southeast monsoon transition in the coastal waters of Kalpakkam, East Coast of India. *Int J Oceans Oceanogr* 3(1):43–74
- Şener Ş, Şener E, Davraz A (2017) Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). *Sci Total Environ* 584–585(131–662):144
- Sharma S (1996) *Applied multivariate techniques*. Wiley, New York
- Sharma M, Kansal A, Jain S, Sharma P (2015) Application of multivariate statistical techniques in determining the spatial temporal water quality variation of Ganga and Yamuna Rivers present in Uttarakhand State, India. *Water Qual Expo Health* 7(4):567–581
- Shrestha S, Kazama F (2007) Assessment of surface water quality using multivariate statistical techniques: a case study of the Fuji river basin Japan. *Environ Modell Softw* 22(4):464–475
- Simeonova P, Simeonov V, Andreev G (2003) Water quality study of the Struma River Basin, Bulgaria. *Cent Eur J Chem* 2:121–136
- Singh KP, Malik A, Mohan D, Sinha S (2004) Multivariate statistical techniques for the evaluation of spatial and temporal variations in water quality of Gomti river (India)—a case study. *Water Res* 38:3980–3992
- Sreelekshmi S, Nandan SB, Kaimal SV, Radhakrishnan CK, Suresh VR (2020) Mangrove species diversity, stand structure and zonation pattern in relation to environmental factors—A case study at Sundarban delta, east coast of India. *Reg Stud Mar Sci* 1:35:101111
- Vajravelu M, Martin Y, Ayyappan S, Mayakrishnan M (2018) Seasonal influence of physico-chemical parameters on phytoplankton diversity, community structure and abundance at Parangipettai coastal waters, Bay of Bengal, South East Coast of India. *Oceanologia*. <https://doi.org/10.1016/j.oceano.2017.08.003>
- Vega M, Pardo R, Barrado E, Deban L (1998) Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. *Water Res* 32(12):3581–3592
- Vernberg FJ, Vernberg WB (2001) *The Coastal Zone*. University of South Carolina Press, Columbia, p 191
- Wang XL, Lu YL, Han JY, He GZ, Wang TY (2007) Identification of anthropogenic influence on water quality of rivers in Taihu watershed. *J Environ Sci* 19:475–481
- Wang X, Cai Q, Ye L, Qu X (2012) Evaluation of spatial and temporal variation in stream water by multivariate statistical techniques: a case study of the Xiangxi River basin China. *Q Int* 1:1–8
- Wang YB, Liu CW, Liao PY, Lee JJ (2014) Spatial pattern assessment of river water quality: Implications of reducing the number of monitoring stations and chemical parameters. *Environ Monit Assess* 186(3):1781–1792
- Willet P (1987) *Similarity and clustering in chemical information systems*. Research Studies Press Wiley, New York
- Wunderlin DA, Diaz MP, Ame MV, Pesce SF, Hued AC, Bistoni MA (2001) Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality. A case study: Suquia river basin (Cordoba, Argentina). *Water Res* 35:2881–2894
- Zhao J, Fu G, Lei K, Li Y (2011) Multivariate analysis of surface water quality in the Three Gorges area of China and implications for water management. *J Environ Sci* 23(9):1460–1471

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.