Drinking water quality assessment of river Ganga in West Bengal, India through integrated statistical and GIS techniques

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ABSTRACT

An attempt has been made to assess the water quality status of the lower stretch of river Ganga flowing through West Bengal for drinking using integrated techniques. For this study, 11 parameters at 10 locations from Beharampur to Diamond Harbour over nine years (2011-2019) were considered. The eastern stretch of Ganga showed a variation of Water Quality Index (WQI) from 55 to 416 and Synthetic Pollution Index (SPI) from 0.59 to 3.68 in nine years. The result was endorsed through a fair correlation between WQI and SPI ($r^2 > 0.95$). The map interpolated through GIS revealed that the entire river stretch in the year 2011, 2012, and 2019 and location near to ocean during the entire period of nine years were severely polluted (WQI $> 100$ or SPI $> 1$). Turbidity and boron concentration mainly contribute to the high scores of indices. Further, the origin of these ions was estimated through multivariate statistical techniques. It was affirmed that the origin of boron is mainly attributed to seawater influx, that of fluoride to anthropogenic sources, and other parameters originated through geogenic as well as human activities. Based on the research, a few possible water treatment mechanisms are suggested to render the water fit for drinking.

Key words: IDW Geostatistics, river Ganga water quality, spatial interpolation, synthetic pollution index (SPI), water quality index (WQI), weighted arithmetic mean method

HIGHLIGHTS

- The study provides a base line assessment of the water quality of river Ganga for drinking.
- Water quality was marked as polluted and unfit for drinking.
- The seawater influx, geogenic and anthropogenic activities were assessed as the major sources of pollution.
- Water treatment technologies were suggested to render the water fit for drinking.
- It will be helpful to formulate appropriate management strategies.

INTRODUCTION

River Ganga, internationally known as The Ganges, is one of the major rivers in India and plays a pivotal role in sustaining the lives of millions of people both physically as well as spiritually. It was declared as the ‘National River of India’ and drains approximately one-fourth of the Indian territory. It flows through Uttarakhand, Uttar Pradesh, Bihar, Jharkhand and West Bengal, covering a length of 2,525 km, and further drains into the Bay of Bengal. The towns on the river banks support about 37% of the urban population.

Over a period of time, the quality of water of the river has deteriorated due to pollution from various point and non-point sources resulting from increasing population density, rapid industrialization, unplanned urbanization, and rising living standards. Untreated industrial effluents, enormous amounts of municipal sewage, agricultural runoff, open defecation, and other waste, including polythennes and dead bodies, are being released into the river indiscriminately, irrespective of its carrying capacity. Despite the alarming level of pollution, untreated water is still used for various purposes, which may impact the aquatic life and human health.

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human health. Therefore, water quality assessment is essential as the initial step towards generating public awareness and aiding the planners and government authorities to conserve and manage the water bodies.

Water quality assessment through quantification of various physico-chemical parameters is very difficult to understand in its primary form and barely represents the actual scenario. Therefore, an assessment tool is required to integrate all the parameters scientifically to represent water quality through a single numerical value. Among many assessment tools used for water quality analysis, the Water Quality Index (WQI) is the most popular indexing tool that integrates all the parameters while comparing with the standards recommended by the government authorities to safeguard human health (Ewaid et al. 2020; Nong et al. 2020). It was developed by Horton (1965), in which arithmetic weighting was used with multiplicative variables (Horton 1965; Avvannavar & Shrihari 2008; Kumar & Dua 2009; Lkr et al. 2020). Further, many modifications were done according to requirement, and many new indices were developed, such as the National Sanitation Foundation-WQI (NSFWQI), Oregon Water Quality Index, Canadian Council of Ministers of the Environment-WQI (CCME-WQI), British Columbia Water Quality Index (BCWQI), Overall Index of Pollution (OIP), WQI by Bhargava, etc. (Poonam et al. 2013). These indices were also applied to assess the water quality of the river systems in India, including various stretches of river Ganga (Samantray et al. 2009; Sharma & Kansal 2011; Saha et al. 2012; Shah & Joshi 2017; Shukla et al. 2017; Mitra et al. 2018; Ghosh et al. 2019; Kamboj & Kamboj 2019; Lkr et al. 2020).

Another promising tool, the Synthetic Pollution Index (SPI), was also evaluated in this study to validate the pollution level assessed by WQI. It was developed by Ma et al. (2009) to assess the impact of pollutants on the water quality and was later adopted in various studies due to its simplicity (Solangi et al. 2019; Hui et al. 2020; Sunar et al. 2020).

Although the indices depict water quality, the numbers do not make the general public visualize the water quality status. Therefore, integration of the data set with a geographic information system (GIS) can help in illustrating the water quality status of river Ganga to the general public, policy makers or stakeholders. This will make the research output more approachable and understandable to the policy makers and general public. Pollution source identification through various statistical techniques such as factor analysis (FA) and cluster analysis (CA) also helps the policy makers and government to control water pollution (Bhatti et al. 2019; Saha & Paul 2019a).

Since river Ganga is listed as the sixth most polluted river in the world (Panigrahi & Pattnaik 2019), a number of studies have been carried out to assess the water quality of river Ganga (Tiwary et al. 2005; Mishra 2010; Bhutiani et al. 2016a, 2016b; Shukla et al. 2017; Kamboj & Kamboj 2019; Matta et al. 2020). However, the use of WQI and SPI together for evaluation of the water quality of Ganga river is limited. Therefore, the present study aims to assess the water quality of river Ganga flowing in the state of West Bengal, India based on the monitoring data of the environmental regulatory board of West Bengal during 2011–2019 by using integrated techniques. The result was validated through a fair correlation between WQI and SPI ($r^2 > 0.95$), which authenticates the extent to which the water is suitable for drinking. This represents a pioneer study to assess the drinking water quality using these integrated techniques in the mentioned stretch of the river. Further, the pollution sources are identified and thereby water treatment techniques to safeguard the human health are proposed. This base line assessment of drinking water quality of lower stretch of river Ganga may assist the policy makers to formulate appropriate management strategies for pollution abatement of the river.

**STUDY AREA**

This study is conducted in the lower stretch of River Ganga, flowing in the state of West Bengal, India, between $87^\circ 55' 24.315''$ E, $24^\circ 48' 20.227''$ N and $87^\circ 46' 10.382''$ E, $21^\circ 41' 28.733''$ N (Figure 1). A total of ten sampling locations were selected for this study, which were strategically decided by Central Pollution Control Board (CPCB) for effective monitoring of the river (Table 1). The river basin experiences subtropical humid climate with three distinct seasons, namely cold, hot dry season, and monsoon, with an average rainfall of about 1,500 mm. The geology comprises newer alluvium (Holocene sediments) as well as older alluvial (Middle-Upper Pleistocene sediments). Extensive pollution resulting from anthropogenic activities such as sewage as well as untreated industrial effluents discharge, large scale idol immersion, mass bathing during religious festivals, disposal of dead bodies etc. has caused massive deterioration in the water quality of the river. This stretch also receives more than 87 MLD (millions of litres per day) waste water from 22 grossly polluting industries, where the chemical industry discharges about 70% of the total waste water, followed by the pulp-paper industry with 20% discharge (CPCB 2013). The remaining percentage includes other industries such as distillery; food, dairy and beverage; sugar; textile and bleaching and dyeing.
Figure 1 | Map showing study area and sampling locations.
In spite of these polluting activities, this stretch always remains as the primary source of drinking water in many cities of Murshidabad, Baharampur, Bardhaman, Nadia, Hooghly, North 24 Parganas, Kolkata, and Howrah districts. Moreover, Kolkata has three water works, namely Palta, Garden Reach and Baranagar, where a total of 1,136 million litres/day of river water is treated and supplied to the habitats (UNU 2000). Similarly, Howrah has two water works, Padhmapukur and Serampore, supplying about 270 million litres of water/day (UNU 2000). Therefore, water quality assessment and documentation of the management practices are required to safeguard human health.

**MATERIALS AND METHODOLOGY**

The West Bengal Pollution Control Board (WBPCB) is responsible for water quality monitoring of the stretch of River Ganga in the Eastern Region of India, in the State of West Bengal. The physio-chemical data of monitoring during 2011–2019 was obtained from the database of WBPCB. The raw data analysed in this study is in the form of monthly data in reference to surface water samples collected every month at ten monitoring stations in West Bengal. These data sets were assessed through WQI and SPI to evaluate the extent of suitability of the river water for drinking. The parameters such as ammoniacal nitrogen (NH3-N), boron (B), chloride (Cl−), fluoride (F−), sodium (Na+), nitrate nitrogen (NO3-N), pH, sulphate (SO42−), total dissolved solids (TDS), hardness and turbidity were selected for calculation of WQI and SPI. This was based on the fact that among all parameters analysed by WBPCB, these particular considerations were responsible for health impact upon drinking as mentioned by the World Health Organization (WHO). Moreover, these two indices depend on the integration of the water quality parameters through weighted average. The unit weightage in this study was considered based on the drinking water quality standard approved by WHO. The parameter having highest impact on drinking water quality has high unit weightage, such as B, F−, NH3-N (Table 2). The unit weightage (Wj) of parameters is mathematically expressed as:

\[ W_j = \frac{w_j}{\sum_{i=1}^{n} w_j} \quad (1) \]

where \( w_j \) is the weightage of the \( i^{th} \) parameter, which is inversely proportional to the recommended standard value (\( S_i \)) of the \( i^{th} \) parameter.

**Table 1** | Details of monitoring station of river Ganga in the West Bengal Stretch (CPCB 2013)

| Sl. No. | Location | Activities                      |
|---------|----------|---------------------------------|
| 1       | Baharampore | Bathing, Washing, Navigation   |
| 2       | Tribeni (Near Burning Ghat) | Bathing, Washing, Cremation, Navigation |
| 3       | Serampore | Bathing, Washing, Navigation   |
| 4       | Dakshineshwar | Bathing, Washing, Navigation |
| 5       | Nabadwip (Ghoshpara near Monipurghat) | Bathing, Washing, Navigation |
| 6       | Howrah-Shivpur | Bathing, Washing, Fishing, Navigation |
| 7       | Garden Reach | Bathing, Washing, Fishing     |
| 8       | Uluberia | Bathing, Washing, Fishing      |
| 9       | Palta | Bathing, Washing, Fishing, Navigation |
| 10      | Diamond Harbour | Bathing, Washing, Fishing, Navigation |

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**WQI model**

The WQI involves the following steps after parameter selection and weightage determination (Sirajudeen et al. 2013; Saha & Paul 2018):
(i) **sub-indices determination**: transformation of different scale data into non-dimensionless quantity through dividing the measured value with respect to the standard value recommended by WHO (Table 2), as shown:

\[ Q_i = 100 \frac{V_i}{S_i} \]  

(2)

where \( Q_i \) is the sub-index, \( V_i \) represents the analytical value of the water quality parameters, \( S_i \) stands for the standard value of the water quality parameters recommended by WHO.

(ii) **integration of sub-indices through weighted average**: integration of the sub-index value with the respective unit weightage as:

\[ WQI = \sum_{i=1}^{n} W_i Q_i \]  

(3)

Finally, the WQI has been categorized into five classes as mentioned in Table 3.

**SPI model**

The SPI is determined by the following equation after the selection of parameters and unit weightage of each parameter (Ma et al. 2009):

\[ SPI = \sum_{i=1}^{n} \frac{V_o}{V_s} \times W_i \]  

(4)

### Table 2 | Standards recommended by WHO and unit weightage of the parameters used for WQI and SPI

| Parameter | Standard (S_i) | Unit Weightage (W_i) |
|-----------|---------------|---------------------|
| NH$_3$-N  | 1.5           | 0.17987             |
| B         | 0.5           | 0.53962             |
| Cl        | 250           | 0.00108             |
| F         | 1.5           | 0.17987             |
| TH        | 200           | 0.00135             |
| NO$_2$-N  | 50            | 0.00540             |
| pH        | 7.5           | 0.05597             |
| Na        | 200           | 0.00135             |
| SO$_4$    | 250           | 0.00108             |
| TDS       | 600           | 0.00045             |
| Turbidity | 5             | 0.05396             |

All parameters are units in mg/L except pH, TH (mg/L as CaCO$_3$). TH: total hardness.

### Table 3 | Categorization of WQI and SPI for estimation of water quality

| WQI   | SPI   | Water Quality     | Explanation                                                                 |
|-------|-------|-------------------|-----------------------------------------------------------------------------|
| 0–25  | 0–0.25| Excellent         | The water can be used for drinking without any treatment                     |
| 25–50 | 0.25–0.50| Good            | The water can be used for drinking after disinfection only                    |
| 50–70 | 0.50–0.70| Poor            | The water can be used for drinking after primary treatment followed by disinfection |
| 75–100| 0.75–1| Very poor        | The water can be used for drinking after primary as well as secondary treatment |
| >100  | >1    | Worst            | The water in absence of other source can be used for drinking with proper primary, secondary as well as tertiary and advanced water treatment |
where $V_o$ represents the analytical value of the water quality parameters and $V_s$ stands for the standard value of the water quality parameters recommended by WHO as mentioned in Table 2.

The critical value of SPI was evaluated by assigning $V_o$ of the water quality parameter as the recommended standard, beyond which the water is unsuitable for drinking. By integrating all the water quality polluting parameters selected in the study with the unit weightage through Equation (4), the critical value estimated was 1. Further, the categorization was done based on four equal quartiles (Table 3).

Geospatial assessment

The integration of the WQI or SPI data set with GIS can help in illustrating the water quality status of river Ganga in West Bengal, India to the policy makers or to the stakeholders (Tiwari et al. 2015) in a comprehensible manner. The spatial interpolation is done through the Inverse Distance Weighted (IDW) interpolation technique of the spatial analyst tool provided in ArcGIS 10.2. IDW uses the weight of the distance of the measured locations to predict the value of the unknown locations. The weights are considered as inversely proportional to the measured distance to the power value, $p$. In this study $p$ is considered as 2, as a default value of ArcGIS platform. The mathematical formula to predict the unknown value by IDW (Childs 2004):

$$Z_p = \frac{\sum_{i=1}^{n} \frac{z_i}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}}$$

(5)

where $Z_p$ is the value of unknown point, $d_i$ is the distance to the known point, $z_i$ is the value of the measured location and $p$ is the selected exponent.

Source identification

The source was identified through various multivariate statistical tools, such as FA, supported through CA and bivariate statistics as Pearson correlation for documentation of effective water quality management plan (Saha & Paul 2019b). The data set before processing was linearized through z-scale transformation. These environmentrics provide the most meaningful information through reduction of a complex data set to a smaller and simple data set without loss of original information. FA, a linear statistical model, reduces the complex data set into a small set of correlated values, known as principal components (PC) using the following statistical equation (Shrestha & Kazama 2007):

$$y_{ij} = a_{i1}x_{1j} + a_{i2}x_{2j} + a_{i3}x_{3j} + \ldots + a_{im}x_{mj}$$

(6)

where $y$ is component score, $a$ represents component loading (eigenvectors), $x$ is the measured value of the variable, $i$ is the component number, $j$ is the sample number and $m$ represents total number of variables.

The Kaiser Normalization (PC with eigen values $>1$) along with varimax rotation was followed in this study for better interpretability of results. Moreover, Bartlett’s test of sphericity and Kaiser–Meyer–Olkin (KMO) test were also performed to test the significance of these multivariate statistics. PC $> 0.5$ showed most significant correlated variables, which helps in identification of anthropogenic or geogenic sources.

The CA is another form of environmentrics, which associates the related parameters in the form of a cluster (Bhat et al. 2014). This cluster is displayed as a tree-like structure known as a dendrogram, which is prepared through Euclidian distance measure (Equation (7)) and wards clustering algorithm (Romesburg 2004):

$$d_{ij} = \sqrt{\sum_{l=1}^{q} (x_{il} - x_{lj})^2}$$

(7)

where $d_{ij}$ is the Euclidean distance for two individuals $i$ and $j$, each measured on $q$ variables, $x$, $x_{ij} = 1, 2, \ldots, q$.

All statistical analyses were performed using software SPSS 21.0 version.
RESULTS AND DISCUSSION

Physico-chemical analysis

In the present study, a detailed analysis of physico-chemical parameters is conducted for assessment of water quality of the mentioned stretch of river Ganga comprising ten locations as illustrated in box plot (Figure 2) displaying the six-number summary (minimum, first quartile, mean, third quartile, and maximum) of the data set from the years 2011–2019. Apart from this, one way analysis of variance (ANOVA) was performed using Tukey test, with 95% level of confidence ($\alpha=0.05$) (Table 4) to confirm the significant difference between the sampling sites. The descriptive statistics of all the parameters considered in this study for the year 2011–2019 are presented in Table 5.

The pH of the river ranged from 7.31 to 8.15 (Figure 2(d)), which follows the drinking water quality standard recommended by WHO (7.0–8.5). The ANOVA (Table 4) showed that there is no significant statistical difference of pH between the sampling locations, which may be due to low annual variation in free CO$_2$ (Gupta et al. 2017). Moreover, the alkaline nature is due to the influx of domestic and industrial waste water into the river and photosynthetic algae activities that consume CO$_2$ dissolved in water (Driiche et al. 2008). This result is similar to the study of Sarkar et al. (2007) for Hoogly River (lower trench of Ganga River), which showed the pH variation from 7.2 to 8.9. The (TDS) in the study area ranged from 158 to 3,066 mg/L (Figure 2(j)), wherein the majority of sampling locations fit in the prescribed limit of WHO (600 mg/L) except Diamond Harbour. The high amount of TDS at Diamond Harbour is due to sea water intrusion during high tide, as it is located 70 km upstream from the sea. Similar result was reported by Sarkar et al. (2007), where the maximum TDS concentration at Diamond Harbour was given as 2.55 ppt. The turbidity of the river varied from 43.6 to 350.82 Nephelometric Turbidity Units (NTU) (Figure 2(l)) and the highest value was found in Diamond Harbour, which showed a significant difference ($p<0.05$) from the other locations. Turbidity results from the presence of suspended particles such as clay, silt, organic matter, plankton and other microscopic organisms in the water (Grobbelaar 2009). The clarity of water decreases due to the presence of these suspended particles that get deposited in the water.

The total hardness (TH) ranged from 88 to 950 mg CaCO$_3$/L (Figure 2(k)), where all the locations were within the drinking water standard limits of 200 mg CaCO$_3$/L as recommended by WHO (WHO 2017), except Diamond Harbour (950 mg CaCO$_3$/L). Sodium concentration in the river water was significantly high ($p<0.05$) in Diamond Harbour, with a mean range from 310 to 992 mg/L (Figure 2(h)), whereas in other sampling locations it was within the drinking water standard limit of 200 mg/L, recommended by WHO (WHO 2017). Hypertension and cardio-metabolic diseases may result from the intake of excessive sodium in drinking water along with normal dietary sodium consumption (Nwankwo et al. 2020), although no prominent relation of the level of sodium to hypertension can be affirmed conclusively and therefore no health-based guideline is available in this regard (WHO 2003). Moreover, major anions such as chloride and sulfate were also significantly high ($p<0.05$) in Diamond Harbour due to its vicinity to the estuary, with maximum concentration of 1,511.47 mg/L (Figure 2(c)) and 211.13 mg/L, respectively (Figure 2(i)). The occurrence of the major ions in river water is mainly from geogenic sources such as weathering of minerals (Asare-Donkor et al. 2018). However, the mean ammonia-cal nitrogen (NH$_3$-N) showed a significantly high level at Serampore as compared to the other locations. It ranged from 0 to 0.53 mg/L (Figure 2(a)), which was below the permissible limit for drinking water standard recommended by WHO (1.5 mg/L). Ammonia enters into the aquatic environment via direct means such as municipal effluent discharge and excretion of nitrogenous waste from animals and indirect means such as nitrogen fixation, air deposition and runoff from agricultural lands (EPA 2013). In addition, the nitrate in Ganges river mainly comes from domestic sewage, industrial wastewater, agriculture fertilizer and aquaculture (Sarkar et al. 2007). Low values of nitrate nitrogen (mean ranging from 0.25 to 1.11 mg/L) were also observed in all the sites (Figure 2(f)), which may be due to utilization by phytoplankton and other primary producers. Boron concentration in the study area ranged from 0 to 0.39 mg/L (Figure 2(b)). The ANOVA reflected no significant difference ($p>0.05$) between the locations. However, maximum boron concentration was found in Dakhineswar followed by Garden Reach and Diamond Harbour. The significant increase in the boron content of surface water can be attributed to the input of waste water with washing agents containing borate compounds or leaching from sediment or rock containing borates or borosilicates (WHO 1998). The fluoride concentration (mean ranged from 0.17 to 0.74 mg/L (Figure 2(e)) showed no significant difference ($p>0.05$) among all the sampling locations. Although small concentrations of these ions are necessary for the human system, when present at high concentration in drinking water they may cause various acute or chronic diseases.
Figure 2 | Box plot of (a) ammonia (mg/L), (b) boron (mg/L), (c) chloride (mg/L), (d) pH, (e) fluoride (mg/L), (f) nitrate (mg/L), (g) Temperature (°C), (h) sodium (mg/L), (i) sulfate (mg/L), (j) TDS (mg/L), (k) total hardness (mg CaCO₃/L), (l) Turbidity (NTU). (continued.)
The values of these parameters cannot discretely conclude the extent of deviation of the river water quality from drinking standard. Therefore, this study was conducted to assess the status of the river water quality applying WQI and SPI, and the pollution sources were identified through multivariate statistical tools, thereby suggesting appropriate treatment measures required to render the water suitable for drinking.

Figure 2 | Continued.
Water quality assessment through WQI and SPI

WQI was evaluated for nine consecutive years (2011-2019) for the mentioned stretch of river Ganga in Eastern India. The results of WQI (Figure 3) and SPI (Figure 4) were interpolated through IDW geostatistics using ArcGIS for better interpretability of results. The WQI of the eastern stretch of Ganga from Beharampur to Diamond Harbour ranged from 107 to 416 in 2011, 117 to 289 in 2012, 85 to 346 in 2013, 115 to 259 in 2014, 80 to 258 in 2015, 55 to 378 in 2016, 67 to 182 in 2017, 57 to 427 in 2018 and 104 to 272 in 2019. The water quality over the mentioned time period was not at all found to be suitable for...
drinking without advanced treatment. A similar result was obtained for SPI, which ranged from 0.93 to 3.47 in 2011, 1.17 to 2.64 in 2012, 0.85 to 3.50 in 2013, 1.15 to 2.62 in 2014, 0.80 to 2.50 in 2015, 0.94 to 3.68 in 2016, 0.67 to 1.73 in 2017, 0.59 to 4.27 in 2018 and 1.04 to 2.62 in 2019. Figures 3 and 4 indicated that the entire river stretch was severely polluted (WQI > 100 or SPI > 1) in the years 2011, 2012 and 2019. However, the water quality improved in the stretches surrounding the sampling...
Table 4: Test of ANOVA for the parameters within the years (2011–2019) and sampling locations

| Parameter | Source   | DF  | Sum of squares | Mean squares | F         | pr > F |
|-----------|----------|-----|----------------|--------------|-----------|---------|
| pH        | Within group | 9   | 0.357          | 0.040        | 1.494     | 0.165   |
|           | Between group | 80  | 2.126          | 0.027        |           |         |
| NH₃       | Within group | 9   | 0.176          | 0.020        | 2.442     | 0.016   |
|           | Between group | 80  | 0.641          | 0.008        |           |         |
| B         | Within group | 9   | 0.108          | 0.012        | 1.854     | 0.071   |
|           | Between group | 80  | 0.520          | 0.007        |           |         |
| Cl        | Within group | 9   | 4,874,953      | 541,661.5    | 48.85084  | <0.0001 |
|           | Between group | 80  | 887,045.6      | 11,088.07   |           |         |
| F         | Within group | 9   | 0.053          | 0.006        | 1.348     | 0.226   |
|           | Between group | 80  | 0.348          | 0.004        |           |         |
| NO₃       | Within group | 9   | 0.333          | 0.039        | 1.117     | 0.361   |
|           | Between group | 80  | 2.813          | 0.035        |           |         |
| Na        | Within group | 9   | 2,193,348      | 243,705.4    | 39.67198  | <0.0001 |
|           | Between group | 80  | 491,440.8      | 6,143.01    |           |         |
| SO₄       | Within group | 9   | 81,682.51      | 9,075.834   | 46.25495  | <0.0001 |
|           | Between group | 80  | 15,697.06      | 196.2132    |           |         |
| TDS       | Within group | 9   | 18,482,147     | 2,053,572   | 56.63335  | <0.0001 |
|           | Between group | 80  | 2,900,866      | 36,260.82   |           |         |
| TH        | Within group | 9   | 977,610.5      | 108,623.4   | 23.93993  | <0.0001 |
|           | Between group | 80  | 362,986.5      | 4,537.332   |           |         |
| Turbidity | Within group | 9   | 166,585.8      | 18,509.53   | 8.38157   | <0.0001 |
|           | Between group | 80  | 176,677.6      | 2,208.47    |           |         |

Digits in bold represent statistical significance.

Locations: S3 (Triveni) in 2013, S5 (Sreerampur); S6 (Dakhineswar) and S9 (Uluberia) in 2015, S2 (Nawadip); S3 (Triveni); S4 (Palta) and S5 (Sreerampur) in 2016, S2 (Nawadip); S5 (Sreerampur) and S7 (Shivpur) in 2017, S5 (Sreerampur) and S7 (Shivpur) in 2018, although it continued to remain polluted (WQI: 75–100 or SPI: 0.75–1), which signified that the usage can only be achieved with primary as well as secondary treatment. Moreover, the water quality improved in a few sampling locations across the stretches around S1 (Beharampur) in 2016, S6 (Dakhineswar) and S8 (Garden Reach) in 2017, S1 (Beharampur); S6 (Dakhineswar); S8 (Garden Reach) and S9 (Uluberia) in 2018, indicating the usage of water for drinking by primary treatment followed by disinfection. However, the water quality again deteriorated in 2019. The sampling site S10 (Diamond Harbour) showed the worst water quality throughout the entire period of nine years due to intrusion of sea water.
from Bay of Bengal during high tides. Since the river flows further downstream through numerous towns and cities to enter the state of West Bengal, it seemingly acquires more pollution load before draining into Bay of Bengal, as obtained in this study. Sharma et al. (2014) in their study demonstrated through the application of WQI that Ganges river at various locations in Allahabad stretch showed inferior water quality for drinking purpose. The higher values of WQI or SPI in these stretches of Ganga were attributed to turbidity and boron concentration. Further, the relation between WQI and SPI was evaluated through regression model (Table 6). The result confirmed the significant good relation between these two indexing tools, with $r^2 > 0.9$ in all the years.

**Pollution source identification**

The WQI and SPI both affirmed the water quality of river Ganga as polluted, which requires treatment for drinking. However, the application of the treatment methodology is not feasible until the pollution sources are identified. Therefore, identification of pollution sources was done through multivariate statistics, FA supported by CA. The FA in this study follows Kaiser Normalization, where PCs greater than 1 were retained. It reduces the data set to four PCs, with a cumulative variance of 87.12 and KMO value of 0.792, affirming its statistical significance (Table 7). The result of Principal Component Analysis (PCA) is presented as a component loading plot in Figure 5. The components are indicated by colour code (Figure 5). The first component (PC1) comprised Cl$^-$, SO$_4^{2-}$, TDS, TH, Na$^+$ and turbidity, with an eigen value of 5.07 and maximum variance of 50.74. Around 35.5% of the samples have Na/Cl$^-$ > 1, indicating silicate weathering from the alluvium deposits of Gangatic

| Sampling Location | Temp | pH  | TDS  | Turbidity | TH  | Na  | Cl  | SO$_4^{2-}$ | NH$_3$ | NO$_3$ | BF  | B   | F   |
|-------------------|------|-----|------|-----------|-----|-----|-----|------------|-------|-------|-----|-----|-----|
| Baharampur        | 27.30| 7.89| 193.27| 122.29    | 139.49| 10.33| 10.87| 13.83      | 0.11  | 0.66  | 0.02| 0.25| 2.59|
| Min               | 26.25| 7.39| 158.57| 43.60     | 118.59| 8.50 | 9.55 | 7.71       | 0.03  | 0.42  | 0.00| 0.17| 0.00|
| Max               | 29.10| 8.15| 251.67| 165.33    | 146.33| 14.59| 12.53| 16.62      | 0.18  | 0.76  | 0.08| 0.29| 0.25|
| Min               | 26.42| 7.54| 162.48| 78.94     | 119.95| 7.67 | 9.93 | 8.05       | 0.02  | 0.38  | 0.00| 0.19| 0.00|

The concentrations of all parameters are in mg/L, except pH: unitless, turbidity: NTU, TH (total hardness): mg CaCO$_3$/L.
plains (Frings et al. 2015), around 22.2% of samples have Na/Cl between 0.86 and 1, indicating seawater intrusion (Shammi et al. 2017), while the rest originates from anthropogenic sources. The sulphates originate from the sedimentary sulphur containing minerals such as dolomite and gypsum as geogenic sources apart from other industrial and sewage effluents (Sarin et al. 1989; Chakrapani & Veizer 2006; Dwivedi et al. 2018). TH comprises \( \text{Ca}^{2+} \), \( \text{Mg}^{2+} \), \( \text{CO}_3^{2-} \) and \( \text{HCO}_3^- \), which dilutes in the water from the silicate, calcite and dolomite weathering as well as from the mass bathing and washing with detergents.
discharge of industrial effluents and domestic sewage (Sarin et al. 1989; Nath et al. 2017). The second component, PC2, is attributed to NH$_3$-N and F$^-$, with a variance of 13.66. The agricultural runoff, untreated industrial effluents, and domestic and municipal fresh sewage increase the level of fluoride and nitrate in the river water (Khullar 2004; Mandal et al. 2010; Dubey & Ujjania 2013; Sankhla & Kumar 2018). The third component (PC3) comprised only boron (B), with a variance of 11.56. The origin of B may be attributed to the sea water intrusion during the tides, which can also be acknowledged by its high concentration in the location S10 (Diamond Harbour). The content of boron decreases in the stretch of river

Figure 4 | Synthetic pollution index (SPI) of the river Ganga in eastern India to validate the suitability for drinking in subsequent years (2011–2019).
with increase in distance from the Bay of Bengal. Moreover, the content of boron is also evident in different parts of Bay of Bengal, which intrude in to fresh water during high tides (Saxena et al. 2004; Gupta & Gupta 2015; Shammi et al. 2017; Danish et al. 2019). The fourth component (PC4) comprised NO₃⁻/C₀-N only, with approximately the same variance as PC3, 11.15 and eigen value of 1.11. The nitrate is derived from the oxidation of ammonia in sewage, agricultural runoff, industrial effluents, etc. by autotrophic bacteria (Indirani 2010; Deshmukh 2013; Dubey & Ujjania 2013; Mitra et al. 2018). Therefore, the presence of nitrate in water reveals that the water got polluted a long time ago. The result of PCA is also shown as a component loading plot, where the same colour indicates same component(s) (Figure 5). This result is supported by cluster analysis, which was performed by wards linkage and euclidian distance measure (Figure 6). The dendrogram shows close linkage between SO₄²⁻, TDS, Cl⁻, Na⁺, TH and turbidity as the first group, which is attributed to geogenic and anthropogenic sources. On the other hand, NH₃-N and F⁻ are present in the second group, which might be attributed to anthropogenic activities. NO₃⁻-N, which might be derived from ammoniacal sources, forms the third linkage, and boron as fourth linkage is attributed to sea water intrusion from Bay of Bengal.

Table 6 | Regression relation between WQI and SPI for the years 2011–2019

| Year | Regression equation | Regression coefficient |
|------|---------------------|-----------------------|
| 2011 | SPI = 0.0081 WQI + 0.1618 | 0.9951 |
| 2012 | SPI = 0.0087 WQI + 0.2012 | 0.9671 |
| 2013 | SPI = 0.0096 WQI + 0.0582 | 0.998 |
| 2014 | SPI = 0.0098 WQI + 0.0191 | 0.9234 |
| 2015 | SPI = 0.0096 WQI + 0.0495 | 0.9991 |
| 2016 | SPI = 0.0097 WQI + 0.0364 | 0.9998 |
| 2017 | SPI = 0.0092 WQI + 0.0556 | 0.9345 |
| 2018 | SPI = 0.01 WQI – 0.0061 | 0.9985 |
| 2019 | SPI = 0.0095 WQI + 0.0746 | 0.9986 |

Table 7 | Components of factor analysis to estimate the pollution sources

| Parameter | Principal Component (PC) |
|-----------|--------------------------|
|           | 1      | 2      | 3      | 4      |
| NH₃       | -.128  | .684   | -.298  | .392   |
| B         | .114   | -.018  | .962   | -.010  |
| Cl        | .983   | -.008  | .062   | -.042  |
| F         | .080   | .871   | .122   | -.147  |
| NO₃       | -.037  | -.001  | .006   | .960   |
| Na        | .950   | .099   | -.027  | -.058  |
| SO₄        | .981   | .032   | .019   | -.086  |
| TDS       | .990   | .044   | .009   | -.043  |
| TH        | .847   | -.079  | .268   | .007   |
| Turbidity | .713   | -.346  | .222   | .055   |
| Eigen Value | 5.074 | 1.366  | 1.156  | 1.115  |
| Variance (%) | 50.740 | 13.664 | 11.563 | 11.152 |

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Rotation converged in five iterations; digits in bold represent strong component loading.
Proposed water quality management practice

The water needs proper treatment such as screening/straining followed by primary sedimentation. Since the water showed high level of turbidity, coagulation-flocculation can be incorporated after primary sedimentation in the treatment plant as a vital practice. Here, aluminium-sulphate (alum), a cost effective and widely available coagulant, can be used to lower the turbidity. Higher amounts of boron can be treated using polymer coagulants such as polyvinyl alcohol, glucoheptanamide derivatives of poly(amidoamine) and poly(ethyleneimine), poly(glycidyl methacrylate) and poly-N,N’-diallyl morpholinium bromide modified with hydroxyethyaminoglycerol, hydroxyethyaminoglycerol functionalized to poly(glycidyl methacrylate) and poly(4-vinyl-1,3-dioxalan-2-one-co-vinyl acetate), alkyl monol, diol or triol containing polyethylenimines (Wolska & Bryjak 2013). Apart from this, defluoridation of water can be done using most effective and conventional treatment with

Figure 5 | Component loading plots of factor analysis (FA) to estimate the origin of pollutants.

Figure 6 | Dendrogram for physio-chemical parameters of river Ganga (2011–2019).
lime and alum (Nalgonda technique). This step should be followed by secondary sedimentation with optimum sedimentation time. Finally, before using the water for drinking, disinfection should be done through chlorination and filtration.

Apart from this, direct disposal of sewage in Ganga should be checked. The wastewater should at first be treated in Sewage Treatment Plants through necessary steps before discharging it into the river. Solid waste dumping should be prevented in the river to improve the water quality. Cremation as well as devotional activities such as idol immersion etc. should be checked in the river banks. The use of river water for domestic activities such as washing clothes, utensils etc. with detergents should be limited. The main source of pollution of river Ganga is the industries, which should be regularly monitored for zero discharge of wastewater and the efficiency of the effluent treatment plants. These measures can contribute towards ameliorating water pollution and restoring the water quality of the divine river Ganga.

This study may lead the way towards future research for validation of these treatment technologies for rendering Ganga river water potable. Apart from this, quantitative assessment of a few important parameters such as heavy metals, pesticides, etc. might be evaluated on a monthly basis for better assessment of the river water. This information can also be focused for further assessment of drinking water quality in the lower stretch of the river.

CONCLUSIONS

This constitutes a pioneer study for water quality assessment of the eastern stretch of one of the most polluted rivers in India, the Ganga (flowing through the State of West Bengal) by the application of WQI and SPI, and the data set is integrated with GIS for depicting the status of pollution in a better manner. The water quality assessed through these integrated techniques affirmed that the mentioned stretch of River Ganga is polluted and not suitable for drinking without appropriate treatment. A few parameters such as boron and turbidity were identified as critical polluting parameters responsible for deterioration in the water quality. The multivariate statistical techniques (FA and PCA) indicated that the presence of boron is attributed to sea water intrusion; whereas turbidity originates from silicate weathering from the alluvium deposits of Gangetic plains as well as anthropogenic activities (such as mass bathing and washing with detergents, discharge of industrial effluents and domestic sewage). Based on the water quality status and origin of the polluting factors, this study also suggested various treatment techniques. The outcome of this study and the suggested techniques can be used by the regulatory authority for documentation of management strategies and framing of effective water quality management plans to combat the pollution of the mighty river Ganga.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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