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# Assessing the water quality of River Ganga in Varanasi, India, through WQI, NPI, and multivariate techniques: a comprehensive study

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## ABSTRACT

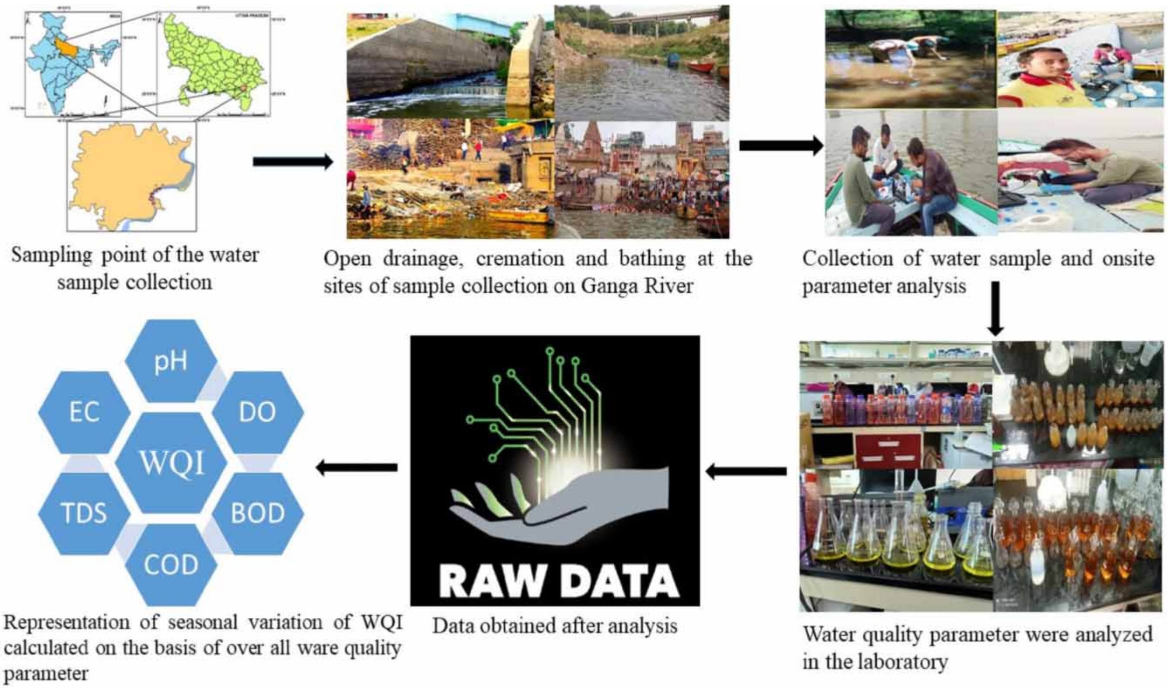
In the present research water quality from nine different sampling points (S1–S9) from the River Ganga at Varanasi was examined for different water quality parameters, and multivariate statistical analyses were carried out. Subsequently, several indices, such as water quality index and Nemerow pollution index (NPI), were calculated. The results indicated that the Ganga River at Varanasi had high levels of coliform concentrations, altered pH, and elevated dissolved oxygen/biochemical oxygen demand and chemical oxygen demand values. The weighted arithmetic water quality index values revealed that sites S8, S9, and S2 were the most polluted and unfit for bathing and drinking. Most of the sampling sites have NPI values greater than 1 for several parameters, indicating high levels of pollution. The study revealed that the water quality is poor for bathing and drinking at most of the sites throughout the year. In addition, the upstream water quality assessment revealed that water quality was good compared with the heavily contaminated downstream region. This knowledge can be useful for environmentalists, policymakers, and water resource managers to develop strategic plans to preserve the cultural and aesthetic worth of the Ganga River in the future.

**Key words:** contaminants, Ganga River, Nemerow pollution index, sites, weighted arithmetic water quality index

## HIGHLIGHTS

- Water sample of River Ganga was alkaline in nature at Varanasi.
- Water quality index ranged from poor to unsuitable for bathing and drinking purposes.
- Nemerow pollution index values indicated that different parameters caused pollution.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Indian rivers are facing a threat because the discharge of various contaminants through various industries, agricultural runoff, untreated sewage, and improper disposal of solid waste has led to deterioration in the quality of river water (Gupta *et al.* 2020a 2020b; Ali *et al.* 2021). River Ganga at Varanasi is equally threatened by these pollution sources such as partially treated sewage, cremation of dead bodies, and various religious and commercial activities (Girija *et al.* 2007; Narain 2014; Marathe *et al.* 2017). Despite the high levels of contamination in the river water, it is still used for various purposes, which could potentially harm human health. Therefore, determining the quality of the water is crucial in raising public awareness. Water-borne diseases affect 80% of Indians, and deaths from diarrhoea and other water-borne diseases are increasing (Conaway 2015).

Reports from the Central Pollution Control Board of India showed that almost half of the sewage generated in cities along the banks of the Ganga is discharged into the river without proper treatment, leading to adverse impacts on the river (CPCB 2021). Varanasi, one of the major cities situated along the River Ganga, has been reported to have the worst water quality among all the cities situated along the Ganga. The city generates an estimated 230–410 million litres per day of municipal sewage, which is discharged into the River Ganga after the treatment, along with other sources such as industrial effluents, household waste, and remains from cremated bodies (Chaudhary *et al.* 2017). These discharges have a negative impact on the physicochemical and biological qualities of the river, and the problem is expected to worsen in the future (Sarkar *et al.* 2012; Chaudhary *et al.* 2017).

Despite having some information about the water quality of the Ganga River in Varanasi, there is still a lack of comprehensive and long-term studies. Therefore, there is a pressing need for a detailed evaluation of the water quality of the Ganga River at Varanasi (Das & Tamminga 2012). Measuring water quality by quantifying numerous physicochemical parameters is a highly challenging task, which nevertheless only provides a loose approximation of the overall situation. Therefore, an effective evaluation tool is needed that can integrate all the relevant parameters to represent the water quality as a single numerical value (Gupta *et al.* 2019). Among various evaluation tools, the water quality index (WQI) is the most commonly used tool for water quality assessment. It considers all the relevant parameters, provides appropriate importance to each parameter, and compares them to the standards set by government authorities to protect public health (Ewaid *et al.* 2020; Nong *et al.* 2020). WQI is a comprehensive scientific technique for determining the overall state of water quality to determine appropriate treatment strategies to address current concerns (Tyagi *et al.* 2013; Jain 2020). WQI is one of the most recent approaches to study the water quality as a whole (Kamboj & Kamboj 2019; Dimri *et al.* 2020; Gupta *et al.* 2020a, 2020b). The Nemerow pollution index (NPI) serves as a crucial tool in evaluating and quantifying environmental pollution levels, offering a comprehensive assessment of the impact of various pollutants on ecosystems. Developed by Leonard Nemerow, this index amalgamates multiple parameters into a single metric, to gauge the extent of pollution, encompassing diverse factors such as air, water, and soil quality. Its versatility and ability to encapsulate complex environmental data make the NPI a valuable instrument in environmental research, guiding efforts aimed at mitigating pollution and preserving ecological balance.

Multivariate methods such as cluster analysis (CA) and principal component analysis (PCA) are utilized in different studies to recognize potential pollutants (Misaghi *et al.* 2017). PCA is a multivariate technique, and in situations where colossal measure of information is accessible, it is a reasonable way to reduce the data (Gupta *et al.* 2020b). Moreover, CA is additionally one of the multivariate techniques used to evaluate relative similarity in the homogeneity of estimated parameters (Shrestha & Kazama 2007). Multiple researches on the water quality of the Ganga and its tributaries have been published using WQI and multivariate statistical methods (Kamboj & Kamboj 2019; Dimri *et al.* 2020; Jain 2020; Matta *et al.* 2022; Nandi *et al.* 2022). The earlier published work on water quality assessment of headwater stream (Bhagirathi) and the Ganga in the Himalayan region has been reported only on some and limited study sites (Sarin *et al.* 1992; Singh & Hasnain 1998; Chakrapani 2005; Sood *et al.* 2008; Chakrapani & Saini 2009; Matta *et al.* 2015), which does not indicate a pattern of impact on water quality at a specific location within the entire stretch from Varanasi upstream to downstream. The city of Varanasi, nestled along the banks of the sacred Ganges River, grapples with the intricate challenges of water quality. Despite its spiritual significance and cultural prominence, Varanasi faces acute issues regarding the Ganga's water pollution. The river here encounters a myriad of pollutants stemming from urban waste, industrial discharge, untreated sewage, and religious rituals performed directly at its *ghats* (Dimri *et al.* 2020). Consequently, the water quality of the River Ganga at Varanasi is a significant concern, affecting the health of both the river ecosystem and the millions who rely on its waters for various purposes. Efforts to address this issue have been initiated, encompassing local initiatives, government interventions, and public awareness campaigns. However, the persistence of water quality challenges in Varanasi underscores the urgency for sustained, comprehensive strategies to restore and maintain the Ganges's health in this historically and spiritually significant city.

The goals of the present study were to evaluate the water quality of the Ganga River in Varanasi, using physicochemical analysis, WQI, NPI, and multivariate statistics, and identify the most significant factors, i.e., (i) identifying association or disparity among study sites and different seasons, (ii) identifying water quality parameter variations in river water quality, and (iii) identifying the impact of possible pollution sources (natural or anthropogenic).

## 2. MATERIALS AND METHODS

### 2.1. Study area

River Ganga is one of the most important rivers of India. It flows through five states and several large and small cities. Varanasi is one of the major cities situated along the River Ganga and one of the most important religious and tourist cities (Chakrapani & Saini 2009; NMCG 2019). For a detailed investigation of the water quality, a total of nine sampling points (designated as S1, S2, S3, S4, S5, S6, S7, S8, and S9) were fixed along the city sites of River Ganga. The locations for the sampling were chosen based on the presence of drains, pollution sources, population density, probable anthropogenic activity, and socioeconomic significance of the area (Table S1 and Figure 1).

### 2.2. Sample collection and analysis

The current investigation was carried out for a period of 2 years in the monsoon, pre-, and post-monsoon seasons from nine different locations from the entry point to downstream up to the limits of Varanasi city, stretched across a length of around 12 km. All the samples were collected at a fixed date every month between 08.00 AM and 10.00 AM. Samples were collected, preserved, transported, and analysed per standard methods prescribed in APHA (2017). The samples were analysed for a total of 20 different (physicochemical, biological) parameters. Unstable factors such as pH, temperature, total dissolved solids (TDS), and dissolved oxygen (DO) were

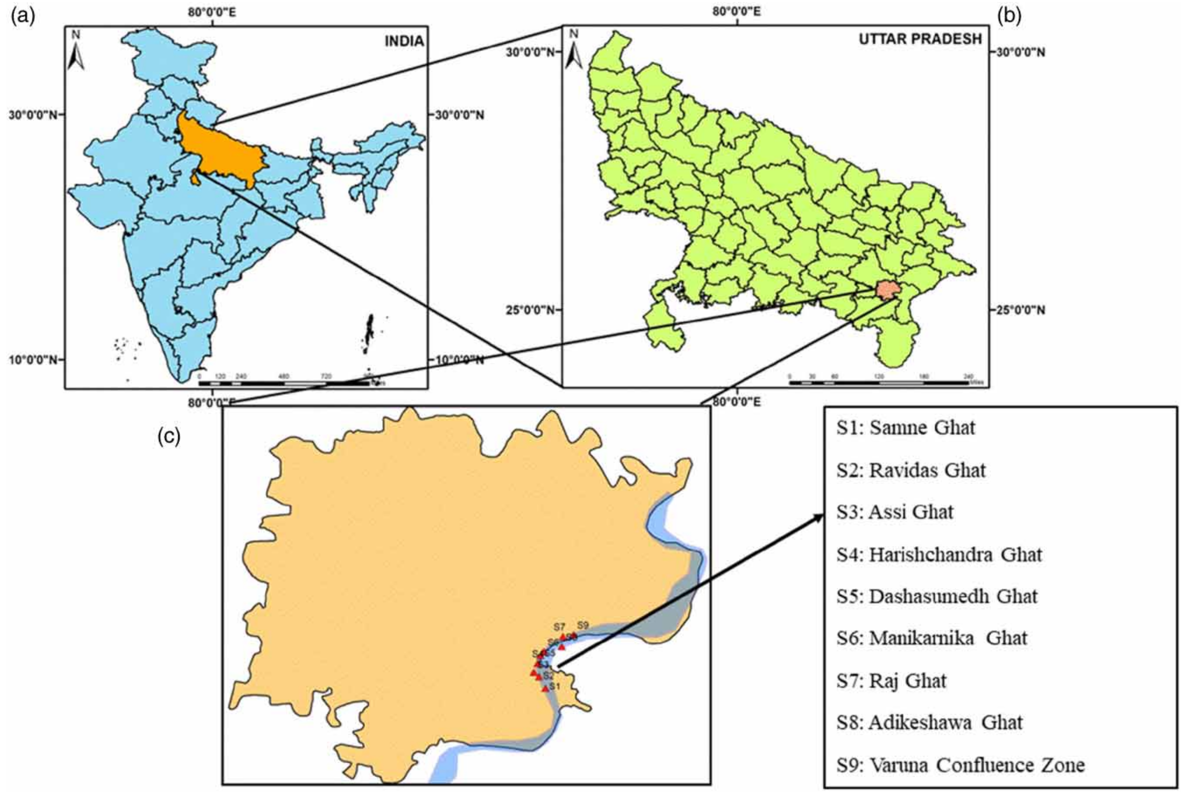


**Figure 1** | (a–c) Location of sampling sites along the stretch of the River Ganga at Varanasi.

evaluated by using a portable multiparameter water quality analysis kit (Hanna HI98194) immediately after sampling. The results of the qualitatively analysed samples are presented in Table S1.

All of the apparatus used for the experiments had been pre-calibrated using a standard solution or in accordance with the standard guideline to guarantee the accuracy and precision of the observations. Standard operating procedures for all the equipment and chemical analyses were adhered to throughout the study period with the necessary safety precautions. All the chemical analyses were carried out using 'A' grade glassware with chemicals from Borosil, Merck, and Fisher Scientific to ensure accurate results.

## 2.3. Statistical analyses

The descriptive statistics (minima, maxima, mean, and standard deviation) were computed for all the parameters using Excel 2019. A violin plot was created with box plots of the biological data for each site using Origin Pro 2023. The data distribution was examined by using the Kolmogorov–Smirnov test. A correlation matrix plot of the variables was produced using the Spearman correlation test because most of the data did not follow a normal distribution. Correlation matrix plots, PCA, and heat maps with dendrogram analysis were carried out using R 4.2.2.

### 2.3.1. Principal component analysis

To evaluate the potential impact of different parameters on the hydrochemistry of the river and to identify implicit linear connections from a variety of variables, PCA was used (Simeonov *et al.* 2003). The correlation matrix between a parameter and the data matrix was used to standardize the data matrix prior to statistical analysis to make certain that all parameters were handled similarly and that no parameter with higher actual values dominates the PCA (Simeonov *et al.* 2004). The principal components were created in a sequential order, with decreasing contributions to variance, for example, the first principal component (PC1) significantly contributes to variations in the initial results, and subsequent component (PC2) accounts for decreasing proportions of variance (Vieira *et al.* 2012).

### 2.3.2. Cluster analysis

CA (also known as clustering) has been used to arrange the large datasets into clusters according to a predetermined set of shared criteria. The fundamental goal of clustering was to categorize groups or clusters of monitoring stations that were comparably similar based on their similarities and differences. In this study, the CA based on the hierarchical approach for standardized datasets was used. A visual representation of the grouping process, the dendrogram, shows the clusters and their surroundings while significantly reducing the complexity of the original data (Simeonov *et al.* 2003).

### 2.3.3. Spearman rank correlation

Spearman correlation is a non-parametric test that is used to determine the relationship between two variables. The Spearman correlation test makes no assumptions about the data distribution. The formula used to calculate the Spearman correlation is as follows:

$$\rho = 1 - \frac{\sum d_i^2}{n(n^2 - 1)}$$

where $\rho$ is Spearman rank correlation, $d_i$ is the difference between the ranks of corresponding variables, and $n$ is the number of observations.

Spearman's correlations were utilized to investigate the correlation structures between the variables that showed non-normal distribution of the parameters affecting water quality (Shrestha & Kazama 2007). By examining Spearman's correlation coefficient (Spearman's R), these non-parametric correlations might be used to further examine the temporal fluctuations of the river water quality metrics (Varol & Sen 2009; Wang *et al.* 2013).

### 2.3.4. Violin plots

A violin plot is a type of data visualization that shows the distribution of data across different categories. It is similar to a box plot in a way that it not only displays the median, quartiles, and range of the data but also shows the probability density of the data at different values, providing a more complete picture of the data's distribution. The shape of the violin plot is generally symmetrical around the median, with wide sections indicating high density of the data and narrow sections indicating lower density. The plot can be used to compare the distribution of data across multiple groups or categories and can provide insights into the skewness, kurtosis, and other characteristics of the data.

## 2.4. Nemerow pollution index

NPI is an important pollution index for the assessment of water quality. Nemerow and Sumitomo created this index in 1971 for the United States Environmental Protection Agency. It is a widely used, incredibly straightforward approach to assess water quality (Reta *et al.* 2019; Haque *et al.* 2020). With the aid of the following equation, NPI is determined as follows:

$$\mathrm{NPI} = \frac{C_i}{S_i}$$

where $C_i$ is the observed concentration of the $i$th parameter and $S_i$ is the permissible limit of the $i$th parameter.

## 2.5. Weighted arithmetic water quality index

The weighted arithmetic WQI (WAWQI), which gives each criterion a weight that represents how essential it is in determining the quality of the water, was first proposed by Horton in 1965. This WQI was developed using the Indian criteria and World Health Organization (WHO) standards (WQI).

The WAWQI is determined as follows:

$$\mathrm{WWQI} = \sum W_i Q_i$$

where $W_i$ is the weightage of each parameter used in water quality estimation:

$$Q_i = 100\left(\frac{V_i - V_0}{S_i - V_0}\right)$$

where $Q_i$ is the sub-index of the $i$th parameter for all the $n$ water quality parameters, $S_i$ is the recommended standard for the $i$th parameter, $V_i$ is the monitored value of the $i$th parameter, and $V_0$ is the ideal value of the parameter in pure water (i.e., $V_0 = 0$, except pH = 7.0, DO = 14.6).

The unit weight of each parameter was calculated as the ratio of the assigned weight to each parameter by summation of the weight assigned to all parameters as follows:

$$W_i = \frac{\sum w_i}{\sum_{i=1}^{n} w_i}$$

where $W_i$ is the unit weight, $w_i$ is the weighting for each variable, and $n$ is the number of parameters.

Subsequently, a quality rating ($q_i$) was calculated for each parameter using the following equation:

$w_i \; \alpha \; 1/S_i$
$w_i = k/S_i$
$k$ = Proportionality constant and $w_i$ = Unit weightage
$k = 1/\sum (1/S_i)$.

The order of the water quality parameters measured in this study, based on the impact on human health, is likely to be as follows: BOD > DO > pH > $NO_3^-$ > EC > TC/TDS > Hardness > COD/$Cl^-$ > $SO_4^{2-}$/Alkalinity. For the WQI computation, weight was determined based on the standard value of each parameter. The guidelines of BIS IS 10500:2012 and water quality criteria B from CPCB were followed in the current study's standard values for each parameter (http://www.uppcb.com/river quality.htm). The relative parameter weights are presented in Table 1, and the categorization of WQI for drinking water quality suitability is presented in Table 2.

**Table 1** | Relative parameter weights

| Sl. No. | Parameters | Standard value ($S_i$) (BIS/CPCB) | Unit weight ($W_i$) |
|---|---|---|---|
| 1 | pH | 8.5 | 0.17 |
| 2 | EC | 1,000 | 0.01 |
| 3 | TDS | 500 | 0.002 |
| 4 | TH | 300 | 0.004 |
| 5 | TA | 200 | 0.007 |
| 6 | DO | 5 | 0.29 |
| 7 | BOD | 3 | 0.48 |
| 8 | COD | 250 | 0.005 |
| 9 | $Cl^-$ | 250 | 0.005 |
| 10 | $NO_3^-$ | 50 | 0.02 |
| 11 | $SO_4^{2-}$ | 200 | 0.007 |
| 12 | TC | 500 | 0.002 |

## 3. RESULTS AND DISCUSSION

### 3.1. Water quality of River Ganga

The spatial and temporal variations of different water quality parameters on a monthly interval at selected study sites are depicted in Figure 2, and their average values along with standard deviations are presented in Table 3.

**Table 2** | Categorization of water quality index for drinking water quality suitability

| WQI rating | Classification |
|---|---|
| 0–25 | Outstanding |
| 25–50 | Good |
| 50–75 | Poor |
| 75–100 | Very poor |
| >100 | Extremely polluted |

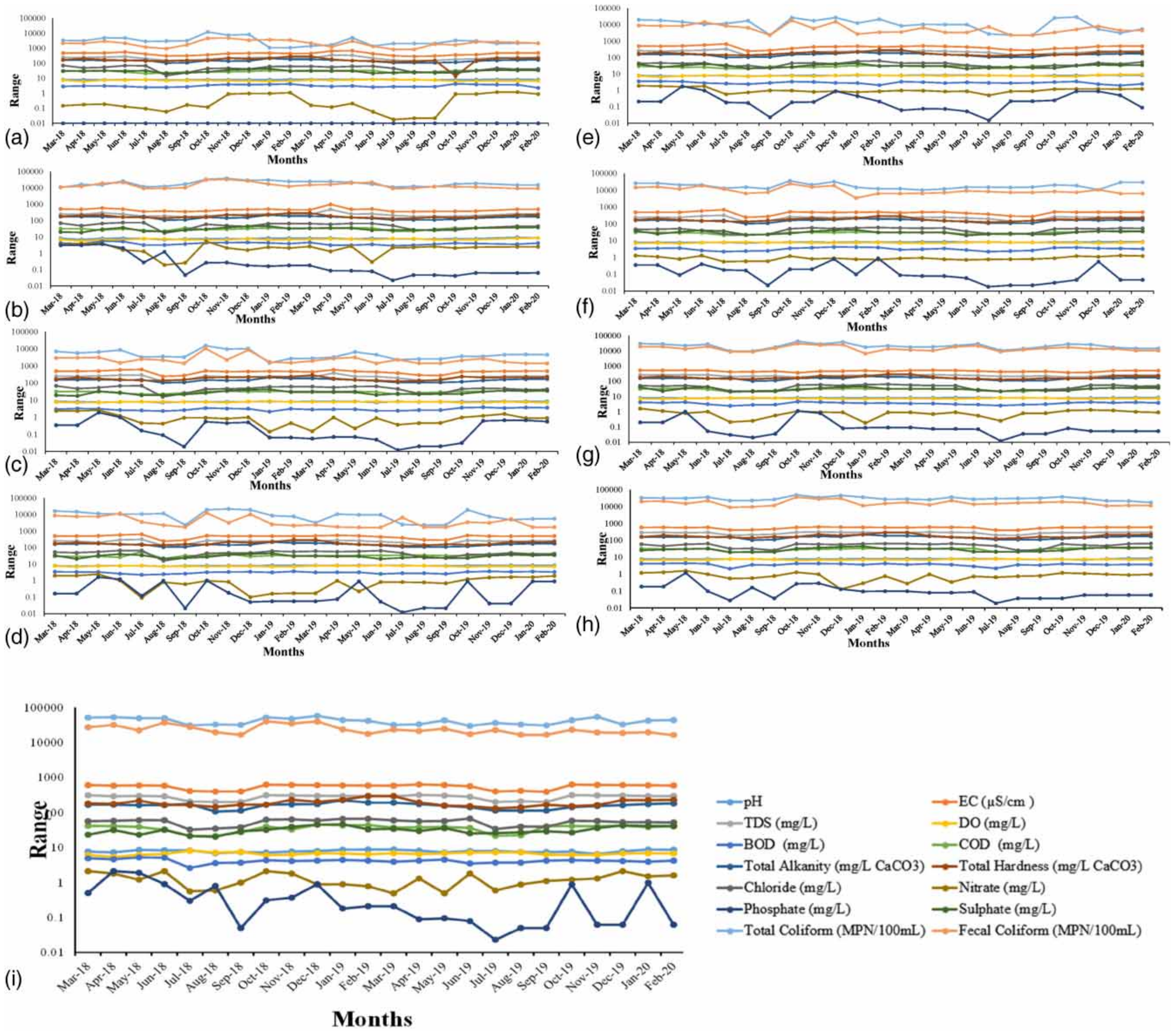


**Figure 2** | Physicochemical parameters of water quality of the River Ganga at Varanasi during 2018–2020: (a) sampling sites 1 (S1), (b) S2, (c) S3, (d) S4, (e) S5, (f) S6, (g) S7, (h) S8, and (i) S9.

Average temperatures of the pre-monsoon, monsoon, and post-monsoon river water were 22.61 ± 0.90, 24.69 ± 1.03, and 19.92 ± 0.82 °C, respectively. A change in temperature with the season has been encountered, which shows the impact of seasonality on water temperature. The depth, turbulence, time of day, and heat input from the outside environment were all observed to influence water temperature. Temperature plays a key role in various natural processes of the aquatic environment. A change in the temperature may trigger a change in various parameters.

The average pH value was observed as 8.11 ± 0.16, 7.87 ± 0.13, and 8.17 ± 0.11 during the pre-monsoon, monsoon, and post-monsoon seasons, respectively, indicating that the water was slightly alkaline (Figure 2).

**Table 3** | Values of water quality for different physicochemical parameters at study sites along the stretch of the River Ganga at Varanasi

| Sr. No. | Seasons parameters | Pre-monsoon | | | Monsoon | | | Post-monsoon | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Min** | **Max** | **Mean ± SD** | **Min** | **Max** | **Mean ± SD** | **Min** | **Max** | **Mean ± SD** |
| 1 | Colour | 10 | 20 | 12.73 ± 4.10 | 10 | 15.63 | 11.67 ± 2.40 | 14.5 | 20 | 16.11 ± 2.25 |
| 2 | Temperature, °C | 21.6 | 24.3 | 22.61 ± 0.90 | 23.31 | 26.41 | 24.69 ± 1.03 | 18.81 | 21.14 | 19.92 ± 0.82 |
| 3 | pH | 7.90 | 8.5 | 8.11 ± 0.16 | 7.68 | 8.07 | 7.87 ± 0.13 | 7.92 | 8.26 | 8.17 ± 0.11 |
| 4 | EC (μS/cm) | 492 | 597.67 | 537.17 ± 43.66 | 372.87 | 473.5 | 411.69 ± 33.45 | 441.63 | 602.6 | 495.74 ± 62.09 |
| 5 | TDS (mg/L) | 245.33 | 300.5 | 270.37 ± 21.97 | 186.81 | 236.88 | 208.25 ± 15.63 | 223.5 | 301 | 248.92 ± 29.75 |
| 6 | DO (mg/L) | 6.32 | 7.58 | 7.18 ± 0.41 | 7.18 | 8 | 7.70 ± 0.29 | 6.54 | 8.176 | 7.27 ± 0.50 |
| 7 | BOD (mg/L) | 2.97 | 4.55 | 3.59 ± 0.53 | 2.46 | 3.76 | 2.93 ± 0.47 | 2.81 | 4.19 | 3.69 ± 0.45 |
| 8 | COD (mg/L) | 29.97 | 38.87 | 32.61 ± 2.53 | 23.43 | 33.29 | 26.51 ± 2.94 | 31.47 | 40.38 | 33.85 ± 2.62 |
| 9 | Total alkalinity (mg/L as $CaCO_3$) | 163.25 | 174.17 | 167.14 ± 3.13 | 116.54 | 129.88 | 124.35 ± 3.98 | 159.695 | 177.9 | 166.91 ± 6.29 |
| 10 | Total hardness (mg/L as $CaCO_3$) | 195.98 | 208.78 | 199.30 ± 4.07 | 144.59 | 152.74 | 146.76 ± 2.99 | 190.81 | 220.49 | 207.28 ± 8.28 |
| 11 | Chloride (mg/L) | 45.43 | 62.92 | 55.66 ± 4.95 | 25.64 | 46.05 | 37.51 ± 7.40 | 45.07 | 59.37 | 51.22 ± 5.46 |
| 12 | Nitrate (mg/L) | 0.95 | 3.03 | 1.46 ± 0.65 | 0.55 | 1.34 | 0.89 ± 0.29 | 0.82 | 2.55 | 1.17 ± 0.05 |
| 13 | Phosphate (mg/L) | 0.17 | 1.69 | 0.53 ± 0.48 | 0.04 | 0.48 | 0.19 ± 0.14 | 0.12 | 0.92 | 0.38 ± 0.24 |
| 14 | Sulphate (mg/L) | 26.31 | 31.88 | 30.01 ± 1.81 | 22.05 | 27.54 | 25.59 ± 1.96 | 33.52 | 38.08 | 35.06 ± 1.59 |
| 15 | Faecal coliform (MPN/100 mL) | 2,291.67 | 24,906.67 | 11,235.0 ± 7,778.81 | 1,377.5 | 21,650 | 9,445.56 ± 6,796.20 | 3,220 | 25,169.9 | 11,916.77 ± 7,935.75 |
| 16 | Total coliform (MPN/100 mL) | 3,310 | 43,233.33 | 18,601.11 ± 12,810.09 | 2,746.25 | 34,000 | 14,500.97 ± 10,877.19 | 4,352 | 45,552 | 21,002.51 ± 12982.14 |
| 17 | Salinity (PSU) | 0.20 | 0.32 | 0.26 ± 0.06 | 0.19 | 0.26 | 0.23 ± 0.04 | 0.21 | 0.42 | 0.32 ± 0.11 |

*Note*: Values are in mg/L unless specified, temperature is in °C, EC in μs/cm; faecal and total coliform in MPN/100 mL, and salinity in PSU.

During the pre-monsoon and monsoon season, the maximum pH was as 8.23 (S1) and the minimum was 7.90 (S9). The same order was found in the monsoon and post-monsoon seasons, i.e., the maximum value was 8.07 at S1 and the minimum was 7.68 at S9. In the post-monsoon season, the maximum value was 8.25 (S1) and the minimum value was 7.92 (S9). According to BIS (2012) guidelines, the standard range of the pH value is 6.5–8.5, which was followed in the samples. However, the water was found to be alkaline in nature. The influence of domestic and industrial effluents entering the rivers and the activities of photosynthetic algae, which consume dissolved $CO_2$, are the causes of the alkaline nature of the river water.

Electrical conductivity (EC) varies considerably in different sites. The EC of the water samples on different sites was recorded as 537.17 ± 43.66, 411.69 ± 33.45, and 495.74 ± 62.09 μS/cm during the pre-monsoon, monsoon, and post-monsoon seasons, respectively (Figure 2), and comparatively higher values were obtained in the pre-monsoon season at S9 because of the wastewater from Varuna Nala and some domestic sewage from Shahi Nala. During the pre-monsoon season, EC was 597.67 μS/cm (S9) and the minimum value was 492 μs/cm (S6). In the post-monsoon season, the maximum value was 602.60 μS/cm (S9) and the minimum value was 441.63 μS/cm (S5). Higher values of EC were found in the post-monsoon season followed by the pre-monsoon and monsoon seasons owing to the increase of ionic concentration because of the religious human activities, industrial wastes, and draining of contaminated water through drains and other sources into the River Ganga (Dimri *et al.* 2020).

The average value of the TDS under the present study was observed as 270.37 ± 21.97, 208.25 ± 15.63, and 248.92 ± 29.75 mg/L for the pre-monsoon, monsoon, and post-monsoon seasons (Figure 2). The highest value of TDS during the pre-monsoon season was 300.50 mg/L (S9) followed by 294.75 (S2), 293.0 (S8), and 278.75 mg/L (S1), respectively. During the post-monsoon season, the maximum TDS was 236.88 mg/L (S8) while the minimum value was 186.81 mg/L (S1). Higher TDS values were observed at locations S9, S8, and S2 because of the discharge of sewage and cremation remains from the surroundings. During the monsoon season, TDS remained in the favourable condition because of water dilution. The higher value of TDS in the post-monsoon season than in pre-monsoon and monsoon seasons of the Ganga River can be attributed to a combination of factors including reduced flow rate, evaporation, resuspension of bottom sediments, groundwater inputs, and anthropogenic activities (agricultural runoff, industrial effluents, and untreated sewage).

Salinity values were 0.24 ± 0.01, 0.21 ± 0.02, and 0.32 ± 0.11 PSU during pre-monsoon, monsoon, and post-monsoon seasons, respectively. Saltiness depends upon the path flow and the contacting environment of the water along with the solubility of minerals from aquifers and surrounding rocks. Soluble salts in the surface water originate primarily from the solution of rock materials and domestic waste. Hence, salinity usually increases with the increasing depth. In the pre-monsoon season, the maximum salinity was 0.32 PSU (S9) and the minimum value was 0.20 PSU (S1), while in the monsoon, the maximum salinity was 0.26 PSU (S9) and the minimum value was 0.19 PSU (S3). During the post-monsoon, the maximum salinity was 0.42 PSU (S9) and the minimum value was 0.21 PSU (S1). The combination of reduced freshwater inflow, increased evaporation, tidal influence, anthropogenic activities, and groundwater inputs leads to higher salinity in the River Ganga during the post-monsoon season compared with the pre-monsoon and monsoon seasons.

The average alkalinity values were 167.14 ± 3.13, 124.35 ± 3.98, 166.91 ± 6.29 mg/L during the pre-monsoon, monsoon, and post-monsoon seasons, respectively. In the pre-monsoon season, the maximum alkalinity was 174.12 mg/L (S2) and the minimum value was 164.58 mg/L (S7), while in the monsoon season, the maximum alkalinity value was 129.88 mg/L (S2) and the minimum value was 116.54 mg/L (S4). In the post-monsoon season, the maximum alkalinity was 173.12 mg/L (S9) and the minimum value was 159.70 mg/L (S3). Bicarbonate was the main species causing alkalinity in about 80–90% of the sample because of the bicarbonate dissolved in the water, which reacts with the water to form carbonic acid ($H_2CO_3$), which then dissociates to form a bicarbonate ion. This is likely due to the fact that bicarbonate is a very common component of natural waters and can be present in significant concentrations. In addition, bicarbonate is relatively stable in water and does not undergo rapid changes in concentration or reactivity. Overall, the presence of bicarbonate and its contribution to alkalinity can have important implications for water quality and treatment. For example, alkalinity can affect the pH of water and the effectiveness of certain disinfection methods. According to BIS (2012), the limit of alkalinity in consumable water is 200 mg/L. Under the present study, all the values were under permissible limits. The average values of hardness were observed as 199.30 ± 4.07, 146.76 ± 2.99, and 207.28 ± 8.28 mg/L in the pre-monsoon, monsoon, and post-monsoon seasons, respectively. During the pre-monsoon season, the maximum value was 202.55 mg/L (S9) and the minimum value was 195.98 mg/L (S4), while in the monsoon period, the maximum value was 152.74 mg/L (S9) and the minimum value was 144.59 mg/L (S6). In the post-monsoon season, the maximum value was 211.88 mg/L (S9) and the minimum value was 202.58 mg/L (S4). The main contributors to water hardness are anions such as carbonates, bicarbonates, and chloride, as well as cations such as calcium and magnesium. Numerous human health issues, including kidney, heart, and stone problems, are brought on by the hardness of water (Kamboj & Kamboj 2019). According to BIS (2012), the permissible level of hardness in drinking water is 300 mg/L. Under this study, all the values were under permissible limits. The flowrate of the River Ganga decreases significantly, leading to a higher concentration of dissolved ions. This concentration increase is particularly pronounced for ions that contribute to alkalinity and hardness, such as calcium, magnesium, and bicarbonates. The extensive contact between water and rocks/sediments increases the dissolution of minerals that contribute to alkalinity and hardness, such as limestone and dolomite. Evaporation can further concentrate dissolved ions in the river water, leading to higher alkalinity and hardness values. The combined effects of these factors result in higher alkalinity and hardness values in the River Ganga during the post-monsoon season compared with that during the pre-monsoon and monsoon seasons (Kumar *et al.* 2015; Dimri *et al.* 2020; Trombadore *et al.* 2020; Nandi *et al.* 2022).

A high value of chloride in water is an indicator of the water pollution contributed by organic waste with either industrial or animal origins. The average values of chloride were observed as 55.66 ± 4.95, 37.51 ± 7.40, and 51.22 ± 5.46 mg/L in the pre-monsoon, monsoon, and post-monsoon seasons, respectively. During the pre-monsoon season, the maximum chloride was 58.28 mg/L (S8) and the minimum level was 45.43 mg/L (S5), while in the monsoon period, the maximum level was 42.89 mg/L (S9) and the minimum level was 25.64 mg/L (S7). In the post-monsoon season, the maximum level was 59.37 mg/L (S9) and the minimum chloride value was 45.07 mg/L (S1). The permissible limit of chloride in consumable water is 250 mg/L (BIS 2012). All the values for chloride observed in the present study were under the permissible limit (BIS 2012). Pre-monsoon has a higher chloride concentration than post-monsoon, and this might be due to the high temperature, reduced flow, and reduced discharges into the river. A high value of chloride was observed at sites S8, S9, and S2, which might be because of the discharge of household waste, sewage, and industrial discharge (Kumar *et al.* 2006).

Dissolved oxygen is a key characteristic in determining the quality of the water because it reflects the underlying physical as well as biological processes in water bodies. Under the present investigation, the average DO values were 7.18 ± 0.41, 7.70 ± 0.29, and 7.27 ± 0.50 mg/L in the pre-monsoon, monsoon, and post-monsoon seasons, respectively. Due to the increased oxygen solubility in water at lower temperatures, DO levels were high in the monsoon season. In addition, greater photosynthetic activity brought on by ample sunlight and the visibility of clear water is what causes oxygen to be released into water (Ravindra & Kaushik 2003). The lower value of DO in the pre-monsoon season may be because of the high rate of evaporation and sedimentation processes and high turbidity, leading to lesser saturation of light in the water.

The biochemical oxygen demand (BOD) values observed in the water samples collected throughout different seasons were found to be higher than the permissible limit of 3 mg/L (BIS 2012), with the pre-monsoon, monsoon, and post-monsoon average values being 3.59 ± 0.53, 2.93 ± 0.47, and 3.69 ± 0.45 mg/L, respectively. In the present study, the highest BOD value was observed at S9 (Varuna Confluence Zone) in all the three seasons owing to the direct discharge of sewage, open drainage household discharge into the river from Varuna, Shahi Nala, and agricultural runoff. The findings of the study revealed that the BOD values were comparatively higher than those reported in a few earlier studies (Gupta *et al.* 2017).

Chemical oxygen demand (COD) gives an overall assessment of the organic matter present in water. COD is very useful for determining the contamination level of sewage and industrial waste. The average COD values were 32.61 ± 2.53, 26.51 ± 2.94, and 33.85 ± 2.62 mg/L during the pre-monsoon, monsoon, and post-monsoon seasons, respectively. The highest value of COD in the pre-monsoon season was 38.78 mg/L (S9) and the minimum level was 29.97 mg/L (S5), while in the monsoon season, the maximum level was 28.03 mg/L (S2) and the minimum level was 23.43 mg/L (S7). During the post-monsoon season, the maximum level was 40.38 mg/L (S9) and the minimum level was 31.47 mg/L (S1). The higher concentration was observed in the post-monsoon than in pre-monsoon and monsoon seasons. The COD values were found to be higher in downstream sites, possibly because of partially treated sewage and industrial effluents. The previous reports recorded COD value of 27.81 mg/L in the Ganga River at Varanasi (Kumari *et al.* 2013). Our reported values are slightly higher than some of the previously reported values for River Ganga at Varanasi. The higher values of BOD and COD in the post-monsoon season compared with the pre-monsoon and monsoon seasons of Ganga water can be attributed to several factors such as anthropogenic activities (untreated waste discharge, agricultural runoff, urbanization, and industrial and hospital wastewater), reduced flow rate, increased organic matter input, and reduced self-purification capacity. Average nitrate concentrations in the present study were 1.46 ± 0.65, 0.89 ± 0.29, and 1.17 ± 0.05 mg/L in the pre-monsoon, monsoon, and post-monsoon seasons, respectively. The end products of the metabolic oxidation of ammonia are represented by the geographical and temporal fluctuation in nitrates (Mahananda *et al.* 2010).

The average phosphate concentrations were 0.53 ± 0.48, 0.19 ± 0.14, and 0.38 ± 0.24 mg/L during the pre-monsoon, monsoon, and post-monsoon seasons, respectively. During the pre-monsoon season, the maximum level was 1.60 mg/L (S2) and the minimum level was 0.17 mg/L (S1 and S6), while in the monsoon period, the maximum level was 0.48 mg/L (S2) and the minimum level was 0.04 mg/L (S7). In the post-monsoon period, the maximum concentration was 0.93 mg/L (S1). In soluble and organic forms, phosphate can be found in natural water systems (Hasan *et al.* 2009). The use of detergents is known to notably escalate the phosphate content in water. The quality of river water is significantly impacted by the addition of man-made phosphorus to surface water, primarily originating from domestic sewage. The variation in phosphate levels across seasons in the river could be influenced by several factors, including agricultural runoff, sediment release, and varying human activities, contributing to fluctuations in phosphate concentrations observed during different seasons.

The average concentrations of sulphate were 30.01 ± 1.81, 25.59 ± 1.96, and 35.06 ± 1.59 mg/L in the pre-monsoon, monsoon, and post-monsoon seasons, respectively. During the pre-monsoon period, the maximum level was 31.88 mg/L (S8) and the minimum level was 26.31 mg/L (S3), while in the monsoon season, the maximum level was 27.54 mg/L (S6) and the minimum level was 22.05 mg/L (S3). In the post-monsoon period, the maximum level was 38.08 mg/L (S9) and the minimum level was 33.52 mg/L (S3). The permissible limit of sulphate in water is 200 mg/L (BIS 2012). All the values for sulphate in the present study were under the permissible limit (BIS 2012). The lower value of sulphate observed may be due to its tendency to easily precipitate and settle to the bottom of the river (Abdul-Razak *et al.* 2010).

The average values of faecal coliform (FC) were 11,235.0 ± 7,778.81, 9,445.56 ± 6,796.20, and 11,916.77 ± 7,935.75 MPN/100 mL and that of total coliform (TC) were 18,601.11 ± 12,810.09, 14,500.97 ± 10,877.19, and 21,002.51 ± 12,982.14 MPN/100 mL in the pre-monsoon, monsoon, and post-monsoon seasons, respectively. The presence of coliform bacteria in water indicates pollution from faeces excreted from living organisms (Figure 3). During the pre-monsoon and monsoon seasons, downstream sample locations have a larger quantity of total coliform bacteria that exceed the allowed level of CPCB and BIS recommendations. During the peak tourism season, the number of total coliforms was greater in places known for religious tourism activities. In this study, we found that the quality of water is favourable in monsoon season in comparison with the pre- and post-monsoon seasons because of the dilution of water and the weak interaction of water with the contaminants (Mahananda *et al.* 2010; Kumar *et al.* 2015; Kamboj & Kamboj 2019; Dimri *et al.* 2020; Trombadore *et al.* 2020; Nandi *et al.* 2022). Overall, the study can attribute to the water quality parameters values that were higher in the post-monsoon than the pre- and monsoon seasons of River Ganga at Varanasi owing to the reduced freshwater inflow, increased evaporation, tidal influence, anthropogenic activities (agricultural runoff, open drain, untreated domestic waste, hospital waste, and urbanization), and groundwater inputs leads. The maximum water quality parameter values were low in monsoon compared with the other seasons due to increased freshwater dilution, enhanced self-purification capacity, higher flow rate, and reduced anthropogenic activities (heavy rainfall can reduce the input of pollutants) (Mahananda *et al.* 2010; Kumar *et al.* 2015; Kamboj & Kamboj 2019; Dimri *et al.* 2020; Gupta *et al.* 2020a, 2020b; Trombadore *et al.* 2020; Nandi *et al.* 2022).

The 0–0.5 (0 to −0.5) correlation coefficient shows negligible correlation to moderate positive (negative) correlation, and the 0.5–1 (−0.5 to −1) correlation coefficient shows moderately positive (negative) to very high positive (negative) correlation (Mukaka 2012). The temperature was negative correlated with total hardness (−0.64) and weak negative correlated with DO (−0.32). The pH moderately correlated with DO (0.57) and alkalinity (0.52), and weakly negatively correlated with temperature (−0.31). EC correlated very highly correlated with TDS (0.99) and moderately with alkalinity (0.69), chloride (0.67), and sulphate (0.55). TDS indicated a moderate correlation with alkalinity (0.68), chloride (0.66), and sulphate (0.66). Alkalinity had a strong positive correlation with hardness (0.79) and a moderately positive correlation with chloride (0.56) and faecal coliform

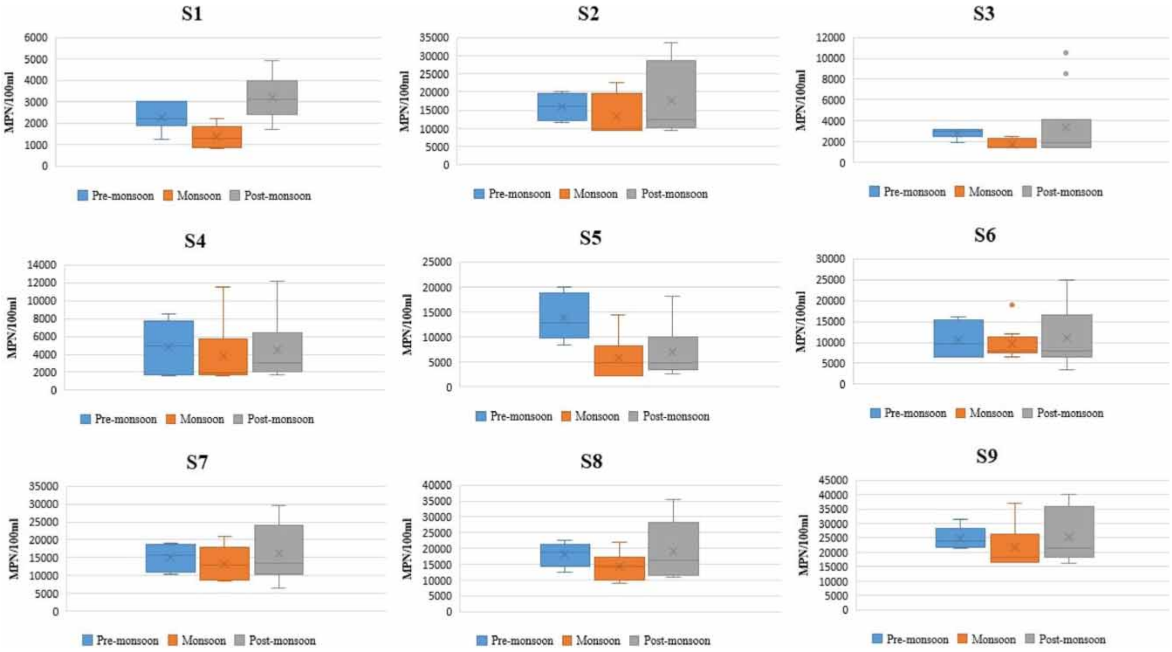
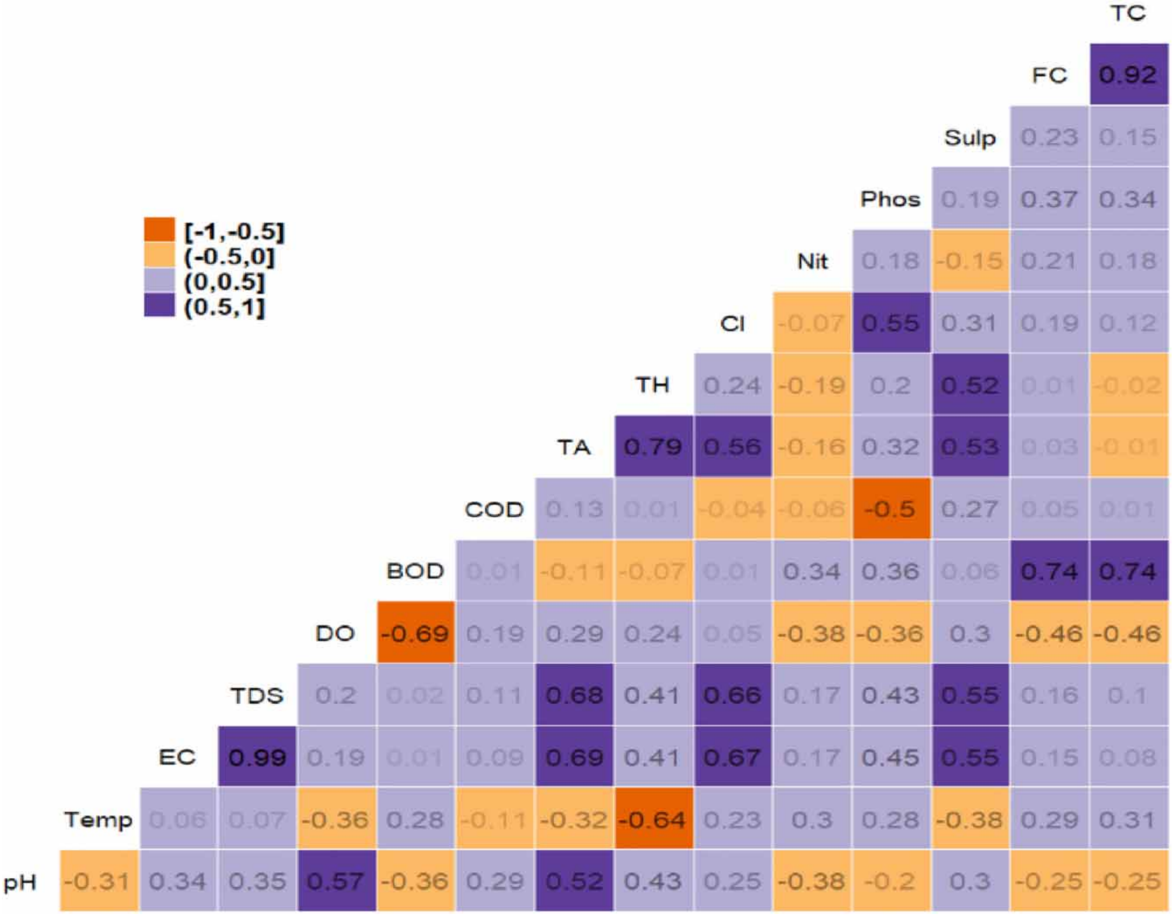


**Figure 3** | Box plot of faecal coliform at all sampling sites (S1–S9) during 2018–2020.



🟧 [-1,-0.5]
🟨 (-0.5,0]
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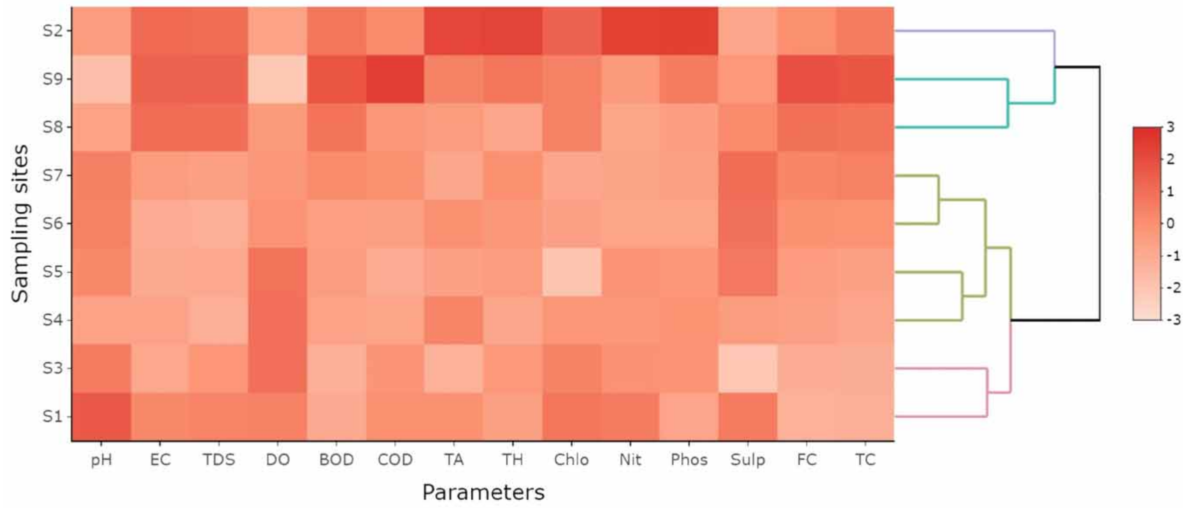
🟪 (0.5,1]

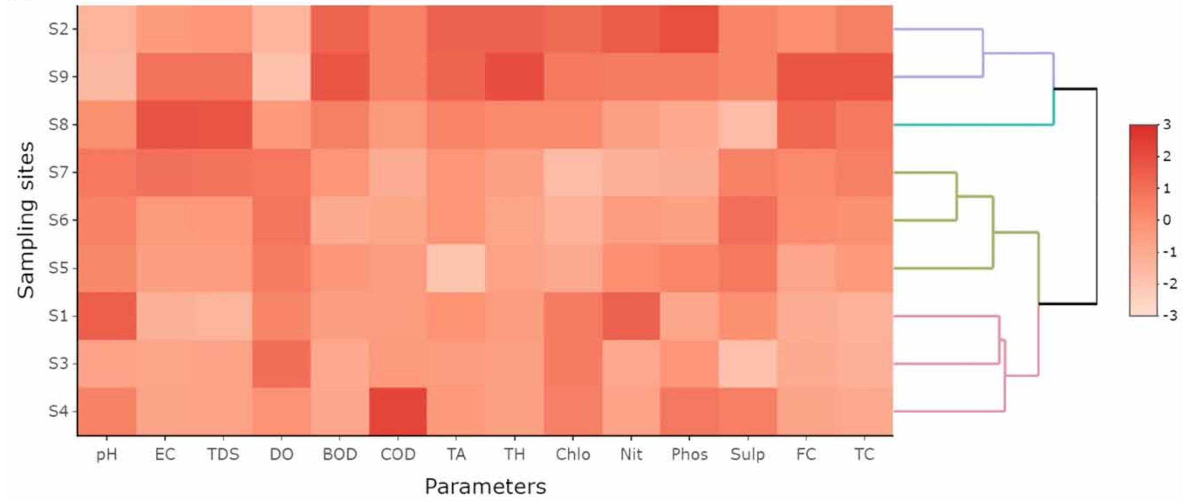
| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | TC |
| | | | | | | | | | | | | | FC | 0.92 |
| | | | | | | | | | | | | Sulp | 0.23 | 0.15 |
| | | | | | | | | | | | Phos | 0.19 | 0.37 | 0.34 |
| | | | | | | | | | | Nit | 0.18 | -0.15 | 0.21 | 0.18 |
| | | | | | | | | | Cl | -0.07 | 0.55 | 0.31 | 0.19 | 0.12 |
| | | | | | | | | TH | 0.24 | -0.19 | 0.2 | 0.52 | 0.01 | -0.02 |
| | | | | | | | TA | 0.79 | 0.56 | -0.16 | 0.32 | 0.53 | 0.03 | -0.01 |
| | | | | | | COD | 0.13 | 0.01 | -0.04 | -0.06 | -0.5 | 0.27 | 0.05 | 0.01 |
| | | | | | BOD | 0.01 | -0.11 | -0.07 | 0.01 | 0.34 | 0.36 | 0.06 | 0.74 | 0.74 |
| | | | | DO | -0.69 | 0.19 | 0.29 | 0.24 | 0.05 | -0.38 | -0.36 | 0.3 | -0.46 | -0.46 |
| | | | TDS | 0.2 | 0.02 | 0.11 | 0.68 | 0.41 | 0.66 | 0.17 | 0.43 | 0.55 | 0.16 | 0.1 |
| | | EC | 0.99 | 0.19 | 0.01 | 0.09 | 0.69 | 0.41 | 0.67 | 0.17 | 0.45 | 0.55 | 0.15 | 0.08 |
| | Temp | 0.06 | 0.07 | -0.36 | 0.28 | -0.11 | -0.32 | -0.64 | 0.23 | 0.3 | 0.28 | -0.38 | 0.29 | 0.31 |
| pH | -0.31 | 0.34 | 0.35 | 0.57 | -0.36 | 0.29 | 0.52 | 0.43 | 0.25 | -0.38 | -0.2 | 0.3 | -0.25 | -0.25 |

**Figure 4** | Spearman correlation matrix plot for the analysed variables (physiochemical and biological parameters), and significant values are darkened ($p < 0.05$, correlations with $p$-values greater than 0.05 are considered insignificant).

(a) Pre-Monsoon



(b) Monsoon



(c) Post-Monsoon

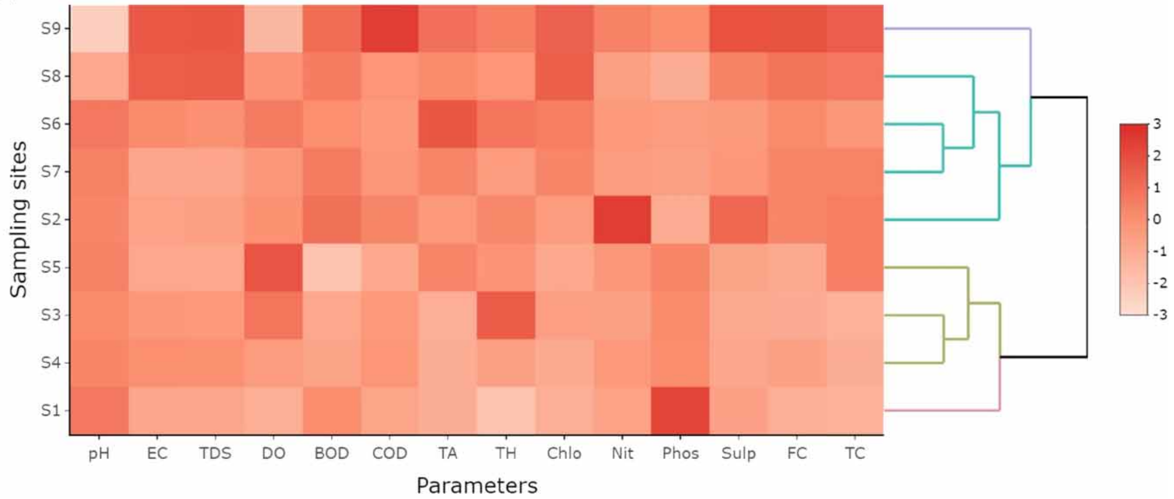


**Figure 5** | Heatmaps of the water quality of the River Ganga at Varanasi from different seasons: (a) pre-monsoon, (b) monsoon, and (c) post-monsoon.

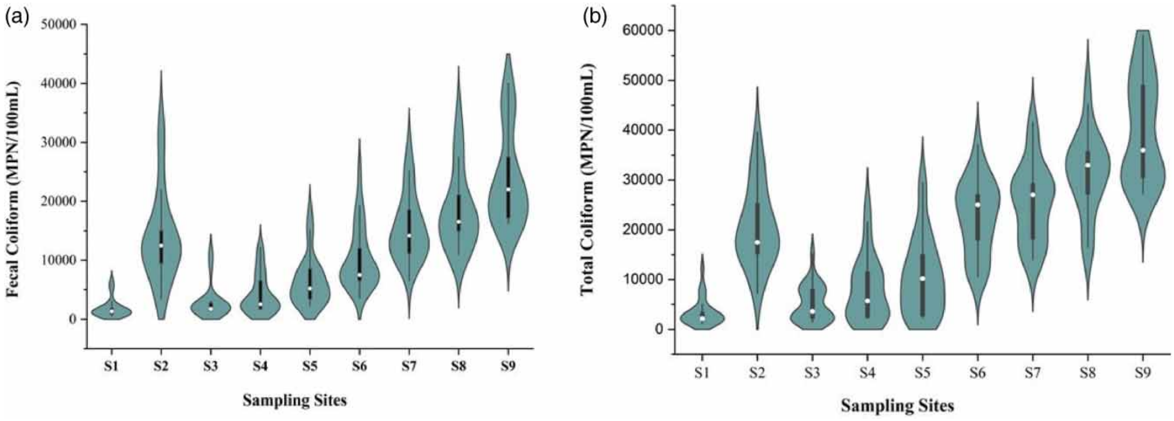


**Figure 6** | (a) and (b) Violin plot for faecal and total coliforms, respectively.

**Table 4** | PCA for the physicochemical parameter of the Ganga River water

| Parameters | PC1 (35.8%) | PC2 (20.6%) | PC3 (9.6%) | PC4 (8.6%) |
|---|---|---|---|---|
| pH | −0.3101 | | | |
| EC | −0.4056 | | | |
| TDS | −0.4040 | | | |
| DO | | −0.4620 | | |
| BOD | | 0.5526 | | |
| COD | | | 0.6568 | −0.3786 |
| TA | −0.4208 | | −0.3120 | |
| TH | | | −0.5869 | |
| Chlo | −0.3708 | | | |
| Nit | | | | 0.6478 |
| Sulp | −0.3105 | | | −0.4198 |
| TC | | 0.5125 | | |
| Standard deviation | 2.0725 | 1.5720 | 1.0727 | 1.0139 |
| Proportion of variance | 0.3579 | 0.2059 | 0.0959 | 0.0857 |
| Cumulative proportion | 0.3579 | 0.5639 | 0.6598 | 0.7455 |

(0.53), respectively. Total hardness moderately correlated with sulphate (0.52). Chloride correlated moderately with phosphate (0.55), weakly correlated with sulphate (0.31), and negatively correlated with nitrate (−0.07). DO correlated negatively moderately with BOD (−0.69), and it also negatively correlated with FC (−0.46) and TC (−0.46). There was a significant high positive correlation observed between BOD and both FC (0.74) and TC (0.74). FC correlated very highly with TC (0.92) (Figure 4).

The heatmap of the surface water quality parameters at each sampling site (S1–S9) has been constructed. Cell colour represents the concentration of water quality parameters. The heatmap of the pre-monsoon season (Figure 5(a)) indicated that sites S1, S3, S4, S5, S6, and S7 had almost the same concentration of physicochemical parameters except for a few parameters (DO concentration was high at S3, S4, and S5), while sites S2, S8, and S9 were having almost the same concentration, i.e., EC, TDS, BOD, and Cl. During the monsoon period (Figure 5(a)), sites S1, S3, S4, S5, S6, and S7 were having almost the same concentration except high COD at S4 and high pH at S1, and sites S2, S8, and S9 were having almost the same concentration of BOD, COD, TA, Cl, pH, EC, and TDS. In the post-monsoon period (Figure 5(c)), sites S1, S3, S4, S5, S6, and S7 were having the same concentration except for high BOD at S5, high alkalinity at S6, high TH at S3, and high phosphorus at S1, and sites S8 and S9 for all the parameters had the same concentrations of EC, TDS, Cl, TC, FC, and TA.

Dendrograms were also constructed to explain the relationship between all the data points in the system. Under this study, the dendrogram represented three groups of monitoring sites, and in each group, all sampling locations followed this trend without any exception. In the pre-monsoon period (Figure 5(a)), cluster I is generated by sites S1, S3, S4, S5, S6, and S7, cluster II by sites S8 and S9, and cluster III by S2. In the monsoon period (Figure 5(b)), cluster I is generated by S1, S3, S4, and S5, cluster II by sites S6, S7, and S8, and cluster III by S2 and S9. In the post-monsoon (Figure 5(c)) season, cluster I is generated by S1, S3, S4, S5, S6, and S7, cluster II by sites S8 and S9, and cluster III by S2. These clusters received open drainage waste, domestic and hospital sewage, cremation remains, automobile and small industrial waste, and agricultural runoff (Sharma *et al.* 2021). Dendrograms of the pre- and post-monsoon having almost the same trends compared with the monsoon season.

Figures 6(a) and 6(b) represent the violin plots for faecal and total coliform at different sites. In this study, we observed that S1 site has a lower value (flat shape in graphs) than other sites. Sites S2, S8, and S9 were observed as higher concentration (wide shape) at different sites of the River Ganga because of the direct discharge of open drains, untreated sewage, industrial influent, and hospital and domestic sewage on these sites. The occurrence of coliform bacteria in water is a signal of contamination from human or animal faecal waste. It has been found that downstream sampling sites have a higher number of the total coliform bacteria that are in excess of the permissible limit of CPCB and BIS guidelines during pre-monsoon and monsoon seasons (Dimri *et al.* 2020; Trombadore *et al.* 2020; Nandi *et al.* 2022).

PCA is a mathematical approach that does not rely on assumptions and is used to minimize the number of samples while maintaining the original sample information (Gupta *et al.* 2020b).

To find changes in water quality, PCA was applied to 12 variables for rivers from nine sampling sites. According to Shrestha & Kazama (2007) and Gupta *et al.* (2020b), an eigenvalue greater than 1 was taken into consideration as a criterion for the extraction of the principal component necessary to explain the variance in the data. Therefore, PC1, PC2, PC3, and PC4 were selected for elucidation for PCA. Table 4 provides the variable loading and

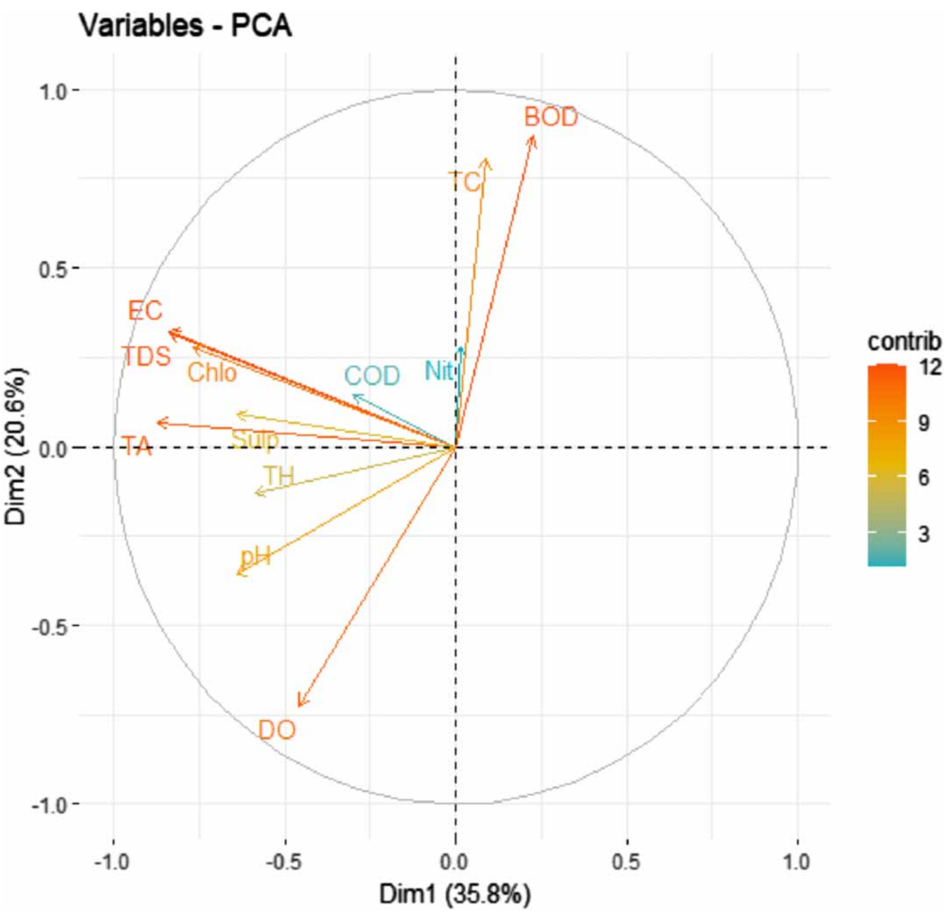


**Figure 7** | Biplot for PCA.

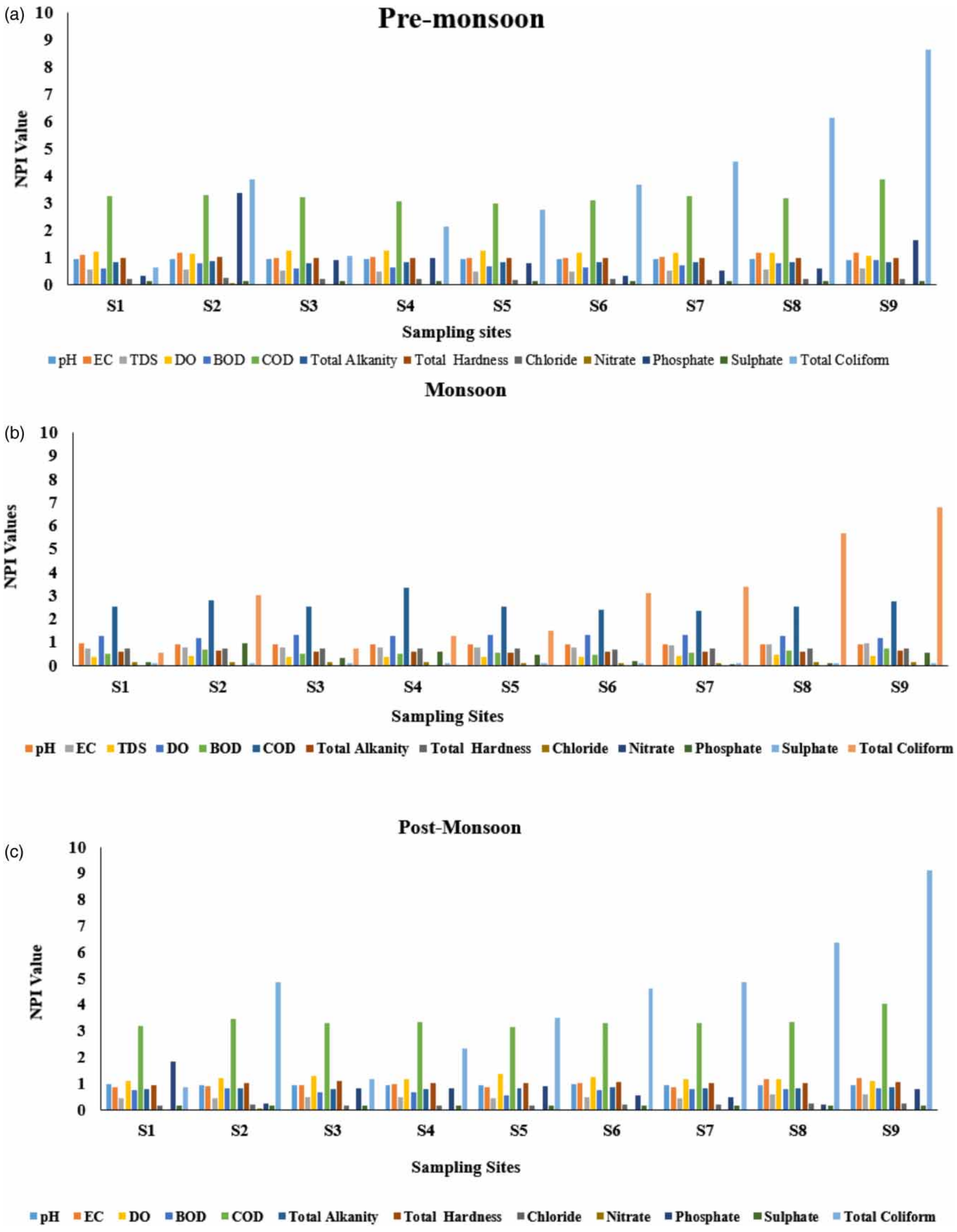


**Figure 8** | NPI values of water quality of the River Ganga at Varanasi during different seasons: (a) pre-monsoon, (b) monsoon, and (c) post-monsoon.

variance (%) for the components generated from PCA, and Figure 7 depicts a biplot, which shows the factor loadings in the component. In the biplots of PC1 and PC2, each vector represents a variable, and the correlation of two variables is reflected by the angle between the two corresponding vectors. The colour scale and the length of each vector are related to the contribution to the total variance. This analysis explained the variance of 74.55%. The factor matrix's loadings are typically categorized as strong, moderate, and weak based on their absolute values, which are, respectively, greater than 0.75, between 0.75 and 0.50, and between 0.50 and 0.30 (Liu *et al.* 2003). PC1 shows weak loadings with EC, TDS, TA, chloride, sulphate, and pH and explains 35.8% of the overall variance. PC2 relates to moderate BOD and TC loadings and accounts for 20.6% of the total variation. PC3 is connected to moderate loadings of COD and TH and accounts for 9.6% of the total variation. PC4 is associated with modest Nit loadings and accounts for 8.6% of the overall variance.

### 3.2. Nemerow pollution index

Each NPI value, less than or equal to 1, represents the relative pollution that each parameter has produced.

On the basis of the NPI, we found that different parameters caused pollution in the Ganga River at Varanasi. In the pre-monsoon season, EC, hardness, COD, phosphate, and total coliform having NPI values greater than 1 and in the monsoon period COD and total coliform where as in post-monsoon season EC, hardness, COD, and total coliform. NPI values above 1.0 imply the presence of water impurities of that parameter (Rathod *et al.* 2011). Comparing the NPI values in different seasons, we found that S2 and S9 sites were more polluted (Figure 8).

### 3.3. Water quality index

To understand the pollution levels in the river, a WQI was calculated using 12 major physicochemical parameters, i.e., pH, EC, TDS, DO, BOD, COD, TA, TH, chloride, nitrate, sulphur, and TC. WQI values of different sites in different seasons have been calculated and given in Figure 9. Comparing WQI values with the classification of water quality, the quality of water at the sites except S3, S4, and S5 in the post-monsoon period and at sites S2, S7, S8, and S9 in the pre-monsoon period were found unfit for bathing and drinking (Figure 9). However, in the monsoon period, the quality is better than in the pre-monsoon and post-monsoon seasons. WQI and water quality in this study were observed as favourable conditions in the monsoon season in comparison with the pre- and post-monsoon due to dilution of water and weak interaction of water to contaminants (Mahananda *et al.* 2010; Kamboj & Kamboj 2019; Dimri *et al.* 2020; Nandi *et al.* 2022).

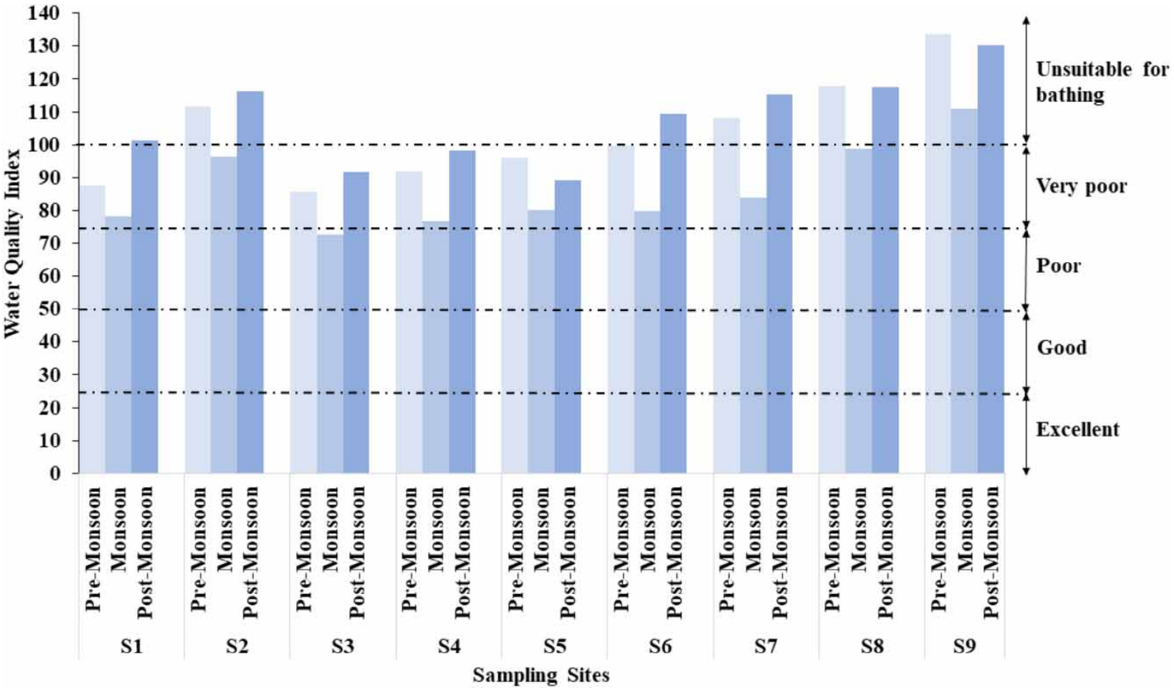


**Figure 9** | Comparison of WQI of different seasons, i.e., pre-monsoon, monsoon, and post-monsoon.

The order of the water quality parameters measured in this study, by their impact on human health, is likely to be as follows: BOD > DO > pH > $NO_3^-$ > EC > TC/TDS > Hardness > COD/$Cl^-$ > $SO_4^{2-}$/Alkalinity. For the WQI computation, weight was determined based on the standard value of each parameter. The guidelines of BIS IS 10500:2012 and water quality criteria B from CPCB were followed in the current study's standard values for each parameter (http://www.uppcb.com/riverquality.htm). Different sources of pollution in the study sites are direct discharge from open drains, untreated sewage, industrial influent, hospital and domestic sewage, agricultural runoff, and cremation remains.

## 4. CONCLUSION

The findings of the present study revealed that the concentration of physicochemical parameters in the water of the River Ganga was higher downstream than it was upstream, indicating that River Ganga at Varanasi is negatively impacted by activities such as discharge of domestic sewage, open drain, and agricultural and industrial effluents because of extensive urbanization. Various sources have resulted in higher coliform, high pH, low DO, high BOD, and COD. The observed WQI values subsequently indicated that the water quality of the Ganga was degraded to the level that it was unsafe for bathing. The WQI values played a crucial role in identifying untreated sewage discharge points as major pollution sources for the Ganga River at Varanasi, serving as a powerful tool for pollution source identification. The study highlights the significance of augmenting water resources to mitigate pollution problems, as evidenced by the fluctuations in WQI values during the pre-monsoon, monsoon, and post-monsoon periods, with the sites S2, S8, and S9 identified as the most contaminated. The Ganga River in Varanasi is severely polluted because of the discharge of polluted water through various sources, resulting in poor water quality that is unsuitable for human consumption, including drinking and bathing at most of the ghats. The recommended approach for calculating an optimum WAWQI score is to consider TC, BOD/DO, and COD along with other relevant parameters. Overall, the water quality of the Ganga River is substandard and requires treatment prior to usage. The findings from this study can aid decision-makers in effectively managing and preserving the Ganga River in Varanasi.

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## AUTHOR CONTRIBUTIONS

Sample and data collection and analysis were carried out by Gurudatta Singh; Supriya Chaudhary and other authors contributed to writing; and Virendra Kumar Mishra contributed toward editing of the MS.

## DATA AVAILABILITY STATEMENT

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

## CONFLICT OF INTEREST

The authors declare there is no conflict.

## REFERENCES

Abdul-Razak, A., Asiedu, A. B., Entsua-Mensah, R. E. M. & deGraft-Johnson, K. A. A. 2010 Assessment of the water quality of the Oti River in Ghana. *West African Journal of Applied Ecology* **16**(1), 1–12.

Ali, S. Y., Sunar, S., Saha, P., Mukherjee, P., Saha, S. & Dutta, S. 2021 Drinking water quality assessment of river Ganga in West Bengal, India through integrated statistical and GIS techniques. *Water Science and Technology* **84**(10–11), 2997–3017.

APHA (American Public Health Association) 2017 *Standard Methods for the Examination of Water and Wastewater*, 23rd edn. American Public Health Association, Washington, DC.

BIS 2012 Drinking water specifications 2nd revision. Bureau of Indian Standards (IS 10500: 2012). New Delhi. http://cgwb.gov.in/documents/wq-standards.pdf.

Chakrapani, G. J. 2005 Major and trace element geochemistry in upper Ganga river in the Himalayas, India. *Environmental Geology* **48**, 189–201.

Chakrapani, G. J. & Saini, R. K. 2009 Temporal and spatial variations in water discharge and sediment load in the Alaknanda and Bhagirathi Rivers in Himalaya, India. *Journal of Asian Earth Sciences* **35**(6), 545–553.

Chaudhary, M., Mishra, S. & Kumar, A. 2017 Estimation of water pollution and probability of health risk due to imbalanced nutrients in River Ganga, India. *International Journal of River Basin Management* **15**(1), 53–60.

Conaway, C. 2015 *The Ganga River Is Dying Under the Weight of Modern India. Newsweek*. Available from: https://www.newsweek. com/2015/10/02/ganges-riverdying-under-weight-modern-india-375347. html.

CPCB 2021 (Central Pollution Control Board) Pollution Assessment: River Ganga. Parivesh Bhawan, East Arjun Nagar, Delhi, India.

Das, P. & Tamminga, K. R. 2012 The Ganges and the GAP: An assessment of efforts to clean a sacred river. *Sustainability* **4**(8), 1647–1668.

Dimri, D., Daverey, A., Kumar, A. & Sharma, A. 2020 Monitoring water quality of River Ganga using multivariate techniques and WQI in upper Ganga basin of Uttarakhand, India. *Environmental Nanotechnology Monitoring & Management* **15**, 100375.

Ewaid, S. H., Abed, S. A., Al-Ansari, N. & Salih, R. M. 2020 Development and evaluation of a water quality index for the Iraqi rivers. *Hydrology* **7**(3), 67.

Girija, T. R., Mahanta, C. & Chandramouli, V. 2007 Water quality assessment of an untreated effluent impacted urban stream: The Bharalu tributary of the Brahmaputra River, India. *Environmental Monitoring and Assessment* **130**, 221–236.

Gupta, N., Pandey, P. & Hussain, J. 2017 Effect of physicochemical and biological parameters on the quality of river water of Narmada, Madhya Pradesh, India. *Water Science* **31**(1), 11–23.

Gupta, D., Singh, G., Patel, A. K., Shukla, R., Mishra, U. & Mishra, V. K. 2019 An assessment of groundwater quality of Varanasi District using water quality index and multivariate statistical techniques. *Environmental We International Journal of Science and Technology* **14**, 143–157.

Gupta, D., Shukla, R., Barya, M. P., Singh, G. & Mishra, V. K. 2020a Appraisal of river water quality based on field observations: A case study on Narmada River. *Indian Journal of Ecology* **47**(4), 897–901.

Gupta, D., Shukla, R., Barya, M. P., Singh, G. & Mishra, V. K. 2020b Water quality assessment of Narmada River along the different topographical regions of the central India. *Water Science* **34**(1), 202–212.

Haque, M. M., Niloy, N. M., Nayna, O. K., Fatema, K. J., Quraishi, S. B., Park, J. H., Kim, K. W. & Tareq, S. M. 2020 Variability of water quality and metal pollution index in the Ganges River, Bangladesh. *Environmental Science and Pollution Research* **27**, 42582–42599.

Hasan, I., Rajia, S., Kabir, K. A. & Latifa, G. A. 2009 Comparative study on the water quality parameters in two rural and urban rivers emphasizing on the pollution level. *Global Journal of Environmental Research* **3**(3), 218–222.

Jain, S. 2020 Analysis of different water quality parameters of Ganga River by multivariate tools. *Journal of Science and Technology* **5**(04), 268–275.

Kamboj, N. & Kamboj, V. 2019 Water quality assessment using overall index of pollution in riverbed-mining area of Ganga-River Haridwar, India. *Water Science* **33**(1), 65–74.

Kumar, A., Qureshi, T. A., Parashar, A. & Patiyal, R. S. 2006 Seasonal variation in physico-chemical characteristics of Ranjit Sagar reservoir, Jammu & Kashmir. *Journal of Ecophysiology and Occupational Health* **6**(3), 159–163.

Kumari, M., Tripathi, S., Pathak, V. & Tripathi, B. D. 2013 Chemometric characterization of river water quality. *Environmental Monitoring and Assessment* **185**(4), 3081–3092.

Kumar, P., Singh, A. N., Shrivastava, R. & Mohan, D. 2015 Assessment of seasonal variation in water quality dynamics in river Varuna—A major tributary of River Ganga. *International Journal of Advanced Research* **3**(3), 1176–1193.

Liu, W. X., Coveney, R. M. & Chen, J. L. 2003 Environmental quality assessment on a river system polluted by mining activities. *Applied Geochemistry* **18**(5), 749–764.

Mahananda, M. R., Mohanty, B. P. & Behera, N. R. 2010 Physico-chemical analysis of surface and ground water of Bargarh District, Orissa, India. *International Journal of Research and Reviews in Applied Sciences* **2**(3), 284–295.

Marathe, N. P., Pal, C., Gaikwad, S. S., Jonsson, V., Kristiansson, E. & Larsson, D. J. 2017 Untreated urban waste contaminates Indian river sediments with resistance genes to last resort antibiotics. *Water Research* **124**, 388–397.

Matta, G., Kumar, A., Srivastava, S., Singh, V. & Dhingra, G. K. 2015 Impact assessment on water quality of Ganga Canal System in Himalayan Region. *International Journal of Scientific & Engineering Research* **6**(5), 1524–1531.

Matta, G., Kumar, A., Nayak, A., Kumar, P. & Pant, G. 2022 Pollution complexity quantification using NPI and HPI of River Ganga system in Himalayan Region. *Proceedings of the Indian National Science Academy* **88**(4), 651–663.

Misaghi, F., Delgosha, F., Razzaghmanesh, M. & Myers, B. 2017 Introducing a water quality index for assessing water for irrigation purposes: A case study of the Ghezel Ozan River. *Science of the Total Environment* **589**, 107–116.

Mukaka, M. M. 2012 A guide to appropriate use of correlation coefficient in medical research. *Malawi Medical Journal* **24**(3), 69–71.

Nandi, I., Pokharia, C., Chaturvedi, V. & Shah, K. 2022 Developing a robust tool for quality health assessment of rivers using optimized weighted arithmetic water quality index method: A study on River Ganges at Varanasi in India: Health assessment of River Ganga using WAWQI method. *International Journal for Research in Applied Sciences and Biotechnology* **9**(3), 7–20.

Narain, S. 2014 Ganga: The river, its pollution and what we can do to clean it. *Centre for Science and Environment* 1–32.

NMCG (National Mission for Clean Ganga) 2019 *GRBMP Reports. Ganga Basin Plan Report 1. River Ganga at A Glance: Identification of Issues and Priority Actions for Restoration*. Available from: https://nmcg.nic.in/writereaddata/fileupload/33_43_001_GEN_DAT_01.pdf.

Nong, X., Shao, D., Zhong, H. & Liang, J. 2020 Evaluation of water quality in the South-to-North water diversion project of China using the water quality index (WQI) method. *Water Research* **178**, 115781.

Rathod, S. D., Mohsin, M. & Farooqui, M. 2011 Water quality index in & around Waluj–Shendra industrial area Aurangabad (MS). *Asian Journal of Biochemical and Pharmaceutical Research* **1**(2), 368–372.

Ravindra, K. & Kaushik, A. 2003 Seasonal variations in physico-chemical characteristics of River Yamuna in Haryana and its ecological best-designated use. *Journal of Environmental Monitoring* **5**(3), 419–426.

Reta, G., Dong, X., Li, Z., Bo, H., Yu, D., Wan, H. & Su, B. 2019 Application of single factor and multi-factor pollution indices assessment for human-impacted river basins: Water quality classification and pollution indicators. *Nature Environment & Pollution Technology* **18**(3), 1063–1072.

Sarin, M. M., Krishnaswami, S., Trivedi, J. R. & Sharma, K. K. 1992 Major ion chemistry of the Ganga source waters: weathering in the high altitude Himalaya. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences* **101**, 89–98.

Sarkar, U. K., Pathak, A. K., Sinha, R. K., Sivakumar, K., Pandian, A. K., Pandey, A., Dubey, V. K. & Lakra, W. S. 2012 Freshwater fish biodiversity in the River Ganga (India): Changing pattern, threats and conservation perspectives. *Reviews in Fish Biology and Fisheries* **22**, 251–272.

Sharma, G., Lata, R., Thakur, N., Bajala, V., Kuniyal, J. C. & Kumar, K. 2021 Application of multivariate statistical analysis and water quality index for quality characterization of Parbati River, Northwestern Himalaya, India. *Discover Water* **1**, 1–20.

Shrestha, S. & Kazama, F. 2007 Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan. *Environmental Modelling & Software* **22**(4), 464–475.

Simeonov, V., Stratis, J. A., Samara, C., Zachariadis, G., Voutsa, D., Anthemidis, A., Sofoniou, M. & Kouimtzis, T. 2003 Assessment of the surface water quality in Northern Greece. *Water Research* **37**(17), 4119–4124.

Simeonov, V., Simeonova, P. & Tzimou-Tsitouridou, R. 2004 Chemometric quality assessment of surface waters: Two case studies. *Chemia I Inżynieria Ekologiczna* **11**(6), 449–469.

Singh, A. K. & Hasnain, S. I. 1998 Major ion chemistry and weathering control in a high altitude basin: Alaknanda River, Garhwal Himalaya, India. *Hydrological Sciences Journal* **43**(6), 825–843.

Sood, A., Singh, K. D., Pandey, P. & Sharma, S. 2008 Assessment of bacterial indicators and physicochemical parameters to investigate pollution status of Gangetic river system of Uttarakhand (India). *Ecological Indicators* **8**(5), 709–717.

Trombadore, O., Nandi, I. & Shah, K. 2020 Effective data convergence, mapping, and pollution categorization of ghats at Ganga River Front in Varanasi. *Environmental Science and Pollution Research* **27**, 15912–15924.

Tyagi, S., Sharma, B., Singh, P. & Dobhal, R. 2013 Water quality assessment in terms of water quality index. *American Journal of Water Resources* **1**(3), 34–38.

Varol, M. & Şen, B. 2009 Assessment of surface water quality using multivariate statistical techniques: A case study of Behrimaz Stream, Turkey. *Environmental Monitoring and Assessment* **159**(1–4), 543.

Vieira, J. S., Pires, J. C., Martins, F. G., Vilar, V. J., Boaventura, R. A. & Botelho, C. M. 2012 Surface water quality assessment of Lis River using multivariate statistical methods. *Water, Air, & Soil Pollution* **223**, 5549–5561.

Wang, Y., Wang, P., Bai, Y., Tian, Z., Li, J., Shao, X., Mustavich, L. F. & Li, B. L. 2013 Assessment of surface water quality via multivariate statistical techniques: A case study of the Songhua River Harbin region, China. *Journal of Hydro-Environment Research* **7**(1), 30–40.

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