



Spatio-temporal dynamics of ecological, bacteriological, and overall water quality of the Damodar River, India

Md. Mofizul Hoque¹ · Aznarul Islam¹

Received: 31 May 2023 / Accepted: 21 January 2024 / Published online: 12 February 2024
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2024

Abstract

Assessing river water quality is crucial for human and ecological needs because of the deterioration of the river and escalated water pollution under the threats of anthropogenic activities. In order to assess river water quality, the Damodar River water was evaluated from the perspectives of spatio-temporal dynamics of ecological (organic pollution index or OPI and eutrophication index or EI), bacteriological (coliform count and comprehensive bathing water quality index or CBWQI), and overall water quality assessments (water quality index or WQI and comprehensive pollution index or CPI). The OPI reveals that 44.66% of water samples have heavy organic pollution; however, EI depicts that almost all water samples of Damodar River have severe eutrophication, especially in the pre- and post-monsoon seasons. Moreover, the fecal coliform count and CBWQI indicate the unsuitability of river water for bathing. The overall WQI portrays that 21.56%, 33.59%, and 22.47% of water samples have heavy pollution in pre-monsoon, monsoon, and post-monsoon, respectively. Moreover, 73.39% of water samples have low CPI indicating slight comprehensive pollution. This study also reveals that the pollution level in the Damodar River downstream of the Durgapur barrage is high among the other stations. The major reasons behind the severe contamination of Damodar River water are urban-industrial and agricultural effluents mixing into the river that lead to higher concentrations of BOD, DO, fecal coliform, COD, fluoride TSS, and turbidity in the river water. Thus, this study carries appreciated information on policy recommendations for the different stakeholders of the Damodar River basin including regional planners, agri-engineers, and ecological river engineers for sustainable river management.

Keywords Bacteriological water quality · Damodar River · Eutrophication · Organic pollution · Spatio-temporal dynamics

Introduction

Water pollution and water-related problems are major issues all over the world (Aboyeji 2013). Water is a crucial natural resource as all organisms rely on it (Karataş and Karataş 2016) and is used for several purposes including drinking, bathing, food processing, domestic and industrial supply, irrigation, etc. (Hoque et al. 2022b). Recently, people have become much more concerned about surface and ground freshwater pollution as they use it for various purposes and

environmental contexts (Inyinbor Adejumoke et al. 2018; Jayaswal et al. 2018). Humans in underdeveloped and developing countries, especially rural people, use river water for numerous purposes such as irrigation, drinking, bathing, etc. (Perret 2002; Ghosh et al. 2022b). The freshwater ecosystem depends on the quantity and quality of water and seasonality (Baron et al. 2002; Hoque et al. 2022a). The river water quantity and quality depend upon numerous natural and anthropogenic factors like surface and sub-surface runoff, rock weathering, precipitation, temperature, mining activities (Bhateria and Jain 2016), urban-industrial and agricultural effluents (Al-Hadithi et al. 2019), and structural intervention (e.g., dam, barrage weir, rail, and road bridge) (Hoque et al. 2022b). Besides, the diversion and interruption of river water (Hoque et al. 2022c) with over-exploitation for irrigation, industrial, and domestic purposes accelerate the pollution level in river water (Falowo et al. 2017) leading to environmental degradation and loss of riverine ecosystem and biota (Hoque et al. 2022a).

Responsible Editor: Xianliang Yi

✉ Aznarul Islam
aznarulislam@gmail.com

Md. Mofizul Hoque
mofizul.10@gmail.com

¹ Department of Geography, Aliah University, 17 Gorachand Road, Kolkata 700 014, West Bengal, India

Increasing pollution levels, measured in higher BOD and lower DO concentration, due to the mixing of urban-industrial effluents and agricultural run-off with river water lead to growing alga, moss, freshwater sponges, crustaceans, insects, and gastropods that deteriorate habitat productivity of river (Leal et al. 2021). The use of polluted river water through irrigation in crop fields affects crop productivity (Sarkar and Islam 2019). Moreover, using the polluted river water for various purposes of human needs like bathing and drinking leads to numerous diseases such as Blackfoot disease, kidney stones, methemoglobinemia, diarrhea, high blood pressure, blue-baby syndrome, etc., and even cancer (Sunitha et al. 2021). The magnitude of human health issues varies spatially and seasonally because of the varying levels of water pollution and sewage disposal. For example, Hoque et al. (2023) depicted escalated non-carcinogenic risk health issues from fluoride in the Jalangi River (India) during the monsoon period compared to other seasons. Similarly, Hoque et al. (2022b) found higher health problems in the lower stretch of the Damodar River. Hence, the spatio-temporal quality assessment of river water is required for various purposes. To this end, the Vietnam Environmental Agency (VEA) developed a water quality index (WQI) to evaluate overall water quality suitably (Son et al. 2020; Ha et al. 2021). Furthermore, comprehensive and organic pollution, eutrophication, and bacteriological water quality are evaluated to measure the river water pollution level.

Damodar River water is polluted due to anthropogenic interventions and is considered one of the most polluted rivers in India (Banerjee et al. 2003). It is a controlled river as its flow is diverted and interrupted by the Damodar Valley Corporation (DVC) dams and barrage (Hoque et al. 2022a). In this context, the Damodar River water quality has been evaluated in various contexts. For example, irrigation water quality assessment (e.g., Banerjee and Gupta 2010; Hoque et al. 2022c), drinking water quality analysis (e.g., Hoque et al. 2022b; Das and Das 2023), industrial quality evaluation (e.g., Singh et al. 2008), detection of point and non-point sources of pollution (e.g., George et al. 2010; Ghosh and Banerjee 2012; Singh et al. 2019), ecological health assessment in the context of dams (e.g., Hoque et al. 2022a), and eco-geomorphological analysis of the Daomardar River (e.g., Ghosh et al. 2022a). Reviewing these works, it appears that drinking water quality is very poor while irrigation water quality ranges from moderate (upper reach) to poor (lower reach) and industrial water is still suitable. However, the escalated level of effluents discharged into river water is depleting the industrial water quality in a loop manner. Moreover, habitat destruction and ecological health issues are increasingly reported in the post-dams period. However, post-dam water stagnation and the problem of eutrophication are not explored in the previous works. Moreover, bacteriological water quality in terms of

coliform count is also unknown. Similarly, comprehensive water quality taking all the major aspects of the water quality is not assessed for holistic water quality analysis. Most importantly, although this river is spatially long (592 km) extending through diverse topographic units like plateaus and plains with diverse land use and land cover, most of the previous attempts are limited in this regard. Moreover, as this river belongs to the monsoon regime, seasonal variations are also not taken into consideration regarding bacteriological and ecological analysis.

Therefore, the major research question for the present investigation is framed as, how spatial and temporal dimensions of river water pollution are linked to the ecological and bacteriological water quality of Damodar River? Therefore, the major objectives of the present study are (1) to examine the nature of ecological, bacteriological, and overall water quality of the Damodar River; (2) to find out the spatial and temporal variation in river water quality; (3) to find out the association among the water quality indices and factors governing the water quality. The present study will be helpful for the various stakeholders concerned with water quality monitoring and sustainable water resource management of the Damodar River basin and other similar areas of the world.

Materials and methods

Study area

Damodar River, located in eastern India (Fig. 1), with a total length of 592 km covers a basin area of 23,370.98 km². The three-fourth area of the basin lies in the upper part, i.e., part of the Chotanagpur plateau, while the lower part is the Ganga-Damodar depositional plain which is also known as the para-deltaic surface (Hoque et al. 2022c). The river basin is monsoon climate dominated, i.e., hot humid summer with cool, dry winter (Islam et al. 2023). Hence, the river regime fluctuates in tune with the vagaries of the monsoon (Hoque et al. 2023). The average discharge measured at Rhondia Weir is 296 m³s⁻¹ (Hoque et al. 2022b). The river is one of the most contaminated rivers as per the findings of Rainwaterharvesting (2022). Moreover, it is the first river controlled by the multi-purpose dams constructed by the DVC which came into existence on July 7, 1948 (Ghosh et al. 2022b; Islam et al. 2023). Once, it was called the “river of sorrow” as numerous destructive floods occurred in the basin area, especially the lower part. Anthropogenic interventions in the form of the construction of dams and discharge of urban-industrial effluents have exerted pressure on the river systems turning the river into a “river of agony” (Hoque et al. 2022b). It flows over the big urban and industrial cities like Bardhaman, Durgapur, Asansol, Dhanbad, Bokaro,

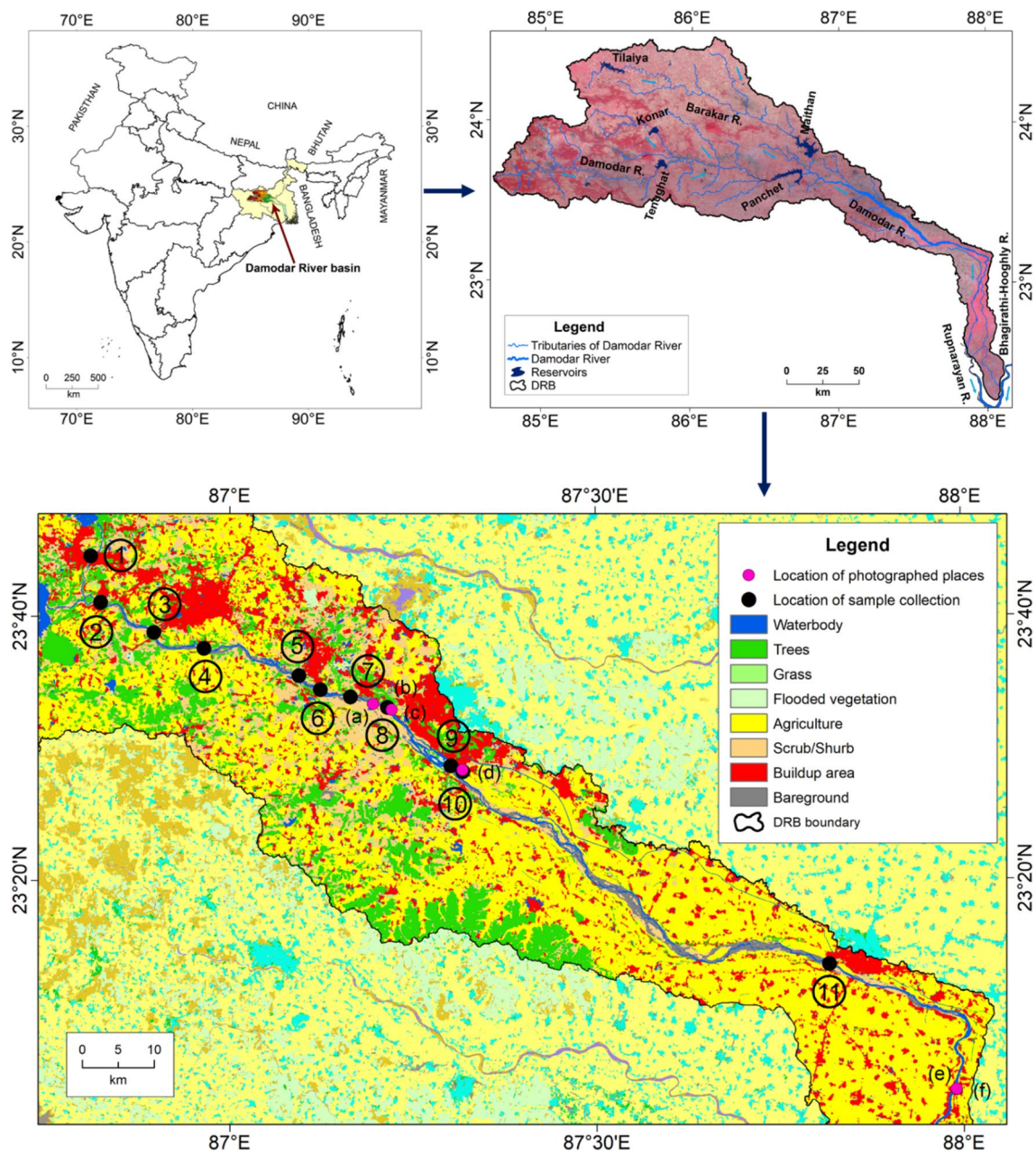


Fig. 1 Location of the study area with water samples collection and LULC map (note: place name of the sample location as mentioned from 1 to 11 are the WBPCB water quality monitoring stations referred to Table 1; location of photographed places marked as a–f are mentioned in Fig. 6)

Ramgarh, etc., during the river course (Hoque et al. 2022c). The sewages with numerous intoxicants mix into the river directly or indirectly from the different point and non-point sources of these urban-industrial and agro-based basin areas (Singh et al. 2014; Hoque et al. 2022c). Moreover, the Damodar River basin is home to heavy industry, mining operations, and a densely populated area (738 persons per km² as per the 2011 census) (Dutta et al. 2021; Hoque et al. 2023). Thus, river water is under severe stress from the perspective of water quality.

Database

The monthly water quality data of 11 monitoring stations on the Damodar River was obtained from the West Bengal Pollution Control Board (WBPCB 2022). The spatio-temporal water quality data of 11 stations were collected from February, 2014, to January, 2023 (Fig. 1; Table 1). Therefore, a total of 35 water sample data were collected for pre-monsoon (February–May), 36 sample data for monsoon (June–September),

Table 1 Details of water quality monitoring stations and seasons-wise (pre-monsoon, monsoon, and post-monsoon) distribution of water samples

Stations Sl. no	Station name	Lat	Long	Year	Seasons		
					Pre-monsoon	Monsoon	Post-monsoon
1	Barakar at Asansol (Water Intake Point)	23°44' 34.52"	86°48' 32.48"	2014–2023	35	36	36
2	Damodar at Dishergarh Village (Near Bihar-West Bengal Border)	23°41' 04.34"	86°49' 21.76"		35	36	36
3	Damodar at Ds of IISCO after 3rd Out-fall at Dhenna Village	23°38' 48.78"	86°53' 44.67"		35	36	36
4	River Damodar at Asansol Us	23°37' 36.02"	86°57' 51.77"		35	36	36
5	Damodar at Narainpur After Confluence of Nunia Nallah	23°35' 32.62"	87°05' 38.77"		35	36	36
6	River Damodar at Raniganj Ds	23°34' 27.79"	87°07' 25.79"		35	36	36
7	River Damodar at Andal Us	23°33' 54.47"	87°09' 53.30"		35	36	36
8	River Damodar at Andal Ds	23°33' 07.75"	87°12' 54.32"		35	36	36
9	River Damodar at Durgapur Us	23°28' 41.10"	87°18' 06.66"		35	36	36
10	Damodar Near Mujher Mana Village after Confluence of Tamla Nallah,	23°28' 12.14"	87°19' 05.74"		35	36	36
11	Water Intake Point for Burdwan Town	23°13' 35.90"	87°49' 04.21"		35	36	36

Nallah is a watercourse discharging urban-industrial effluents into the main river; Us for Upstream and Ds for Downstream

and another 36 samples for post-monsoon (October–January) period from 11 monitoring stations on the river (Table 1).

Water quality standardization was maintained following the American Public Health Association (APHA) standard methods (Table 2) as it examines a wide range of water quality and recognizes each element in a single section for all types of water. Moreover, parameters like temperature and pH are measured onsite, i.e., at monitoring stations using a probe and a meter. Other hydro-chemical parameters used in this study are tested in the Durgapur regional laboratory maintained by WBPCB. For quality control of test parameters like DO, BOD, and COD, water samples are carried in ice bags and preserved at 4 °C, and tests are done mostly within 72 h (WBPCB 2022). Further, the analytical techniques' accuracy was measured using charge ion balance error (CBE) computed using Eq. (1) following Mouhoumed et al. (2020).

$$\% \text{ CBE} = \frac{TC - TA}{TC + TA} \times 100 \quad (1)$$

where TC and TA stand for the considered total cation and anion concentrations (mg/l).

It was observed that 93.45% of samples ($N=1177$) were below the CBE threshold value of 10% signifying its reliability for further analysis (El Baba et al. 2020).

Methodology

Ecological water quality assessment

The ecological water quality of Damodar River has been assessed through the organic pollution index (OPI) and eutrophication Index (EI). OPI and EI are noble illustrative water quality assessment indicators (Liu et al. 2011). These methods are more appropriate as their estimations are much more comprehensive than a single measurement and exhibit water quality (Chen et al. 2016).

Organic pollution index (OPI) It is used to measure organic pollution levels in aqua or water. The present study has

Table 2 Analytical water testing methods and APHA standard method numbers

Parameter	Method	APHA (1998) number
NO ₃ ⁻ (mg/l)	Automated cadmium reduction method	4500-NO ₃ ⁻ F
NH ₃ (mg/l)	Phenate method	4500-NH ₃ F
Total phosphorus (mg/l)	Flow injection analysis for orthophosphate	4500-P G
Total suspended solids (mg/l)	Total suspended solids dried at 103–105 °C method	2540 D
EC (µS/cm)	APHA standard methods	2510B (2012), 22nd edition
Turbidity (NTU)	APHA standard methods	2130B (2012), 22nd edition

assessed the organic pollution level in the Damodar River water through four chemical parameters as COD, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphate (DIP), and DO concentration by using Eq. (2) following Son et al. (2020). It comprehensively accounts for the multivariate effects of COD, DIN, and DIP on organic pollution in water (Liu et al. 2011).

$$OPI = \frac{COD}{COD_s} + \frac{DIN}{DIN_s} + \frac{DIP}{DIP_s} + \frac{DO}{DO_s} \quad (2)$$

where CODs and DOs denote the limited COD and DO concentrations; DINs denote the total limited NO_3^- -N and NH_3 -N concentration; DIPs denote the limited PO_4^{3-} concentration based on environmental standards following the work of Ochir and Davaa (2011). Based on the OPI score, the water quality is classified into six categories as excellent ($OPI < 0$), good ($0 \leq OPI \leq 1$), begin to be polluted ($1 < OPI \leq 2$), lightly polluted ($2 < OPI \leq 3$), moderately polluted ($3 < OPI \leq 4$), and heavily polluted ($OPI > 4$) water (Liu et al. 2011).

Eutrophication index (EI) It is used to measure the eutrophication level in the water. The eutrophication level of Damodar River water has been calculated based on COD, DIP, and DIN indicators by using Eq. (3) following Liu et al. (2011).

$$EI = \frac{COD \times DIP \times DIN}{4500} \times 10^6 \quad (3)$$

where COD, DIP, and DIN are the observed chemical oxygen demand, dissolved inorganic nitrogen, and dissolved inorganic phosphate concentration. The DIN concentration is measured by the total nitrite, nitrate, and ammonium concentration, while the DIP is measured by the observed phosphate concentration in the river water. The $EI > 1$ indicates an eutrophication situation in water and a higher EI value denotes heavier eutrophication (Liu et al. 2011). It is divided into four levels such as no eutrophication ($0 \leq EI \leq 1$), mild eutrophication ($1 < EI \leq 3$), moderate eutrophication ($3 < EI \leq 9$), and severe eutrophication ($EI > 9$) in water (Chen 2021).

Bacteriological water quality assessment

The spatio-temporal dimensions of the bacteriological quality of Damodar water have been assessed through the total coliforms (TC), fecal coliform (FC), and fecal streptococci (FS). The bacteriological analysis emphasizes the account of the multiple-tube fermentation technique. This technique has been used especially to detect the coliform index of water samples by presumptive, confirmatory, and completed tests

(Some et al. 2021). The index value is given as the most probable number (MPN) and read as MPN/100 ml.

Moreover, to capture the holistic perspective on bathing water quality, a comprehensive bathing water quality index (CBWQI) has been computed following the standard procedure of comprehensive pollution index (CPI) as discussed in the following using Eqs. (6) and (7). In the present context, CBWQI has been computed considering the WBPCB parameters such as pH, DO, COD, FC, and FS with their outdoor bathing standard (WBPCB 2023). CBWQI has been categorized into five classes based on the CPI score (Son et al. 2020) which is mentioned under CPI.

Overall water quality assessment

The overall water quality of Damodar River has been measured using the overall water quality index (WQI) and comprehensive pollution index (CPI).

Overall water quality index (WQI) The VEA suggested WQI has been used in this study to assess the overall Damodar River water quality for different usage purposes. To evaluate the water quality, nine water quality parameters such as pH, ammonium (NH_3 -N), phosphates (PO_4^{3-}), total suspended solids (TSS), turbidity, total coliform (TC), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and dissolved O_2 (DO) have been taken for the computation of WQI based on VEA guidelines. In addition, the water temperature has been used to calculate temperature-dependent DO saturated concentration by Eq. (4) following Thi Minh Hanh et al. (2011).

$$C_s = 14 : 652 - 0 : 41022T + 0 : 0079910T^2 - 0 : 000077774T^3 \quad (4)$$

where C_s represent DO saturated concentration and T represents water temperature ($^{\circ}\text{C}$).

Finally, the water quality has been measured using the water quality score of Table 3 through Eq. (5) following Son et al. (2020).

$$WQI = \frac{WQI_{pH}}{100} \left[\frac{1}{5} \sum_{a=1}^5 WQI_a \times \frac{1}{2} \sum_{b=1}^2 WQI_b \times WQI_c \right]^{1/3} \quad (5)$$

where WQI_a denotes the chemical water quality parameters of BOD, COD, DO, NH_3 -N, and PO_4^{3-} ; WQI_b denotes the physical water quality parameters of TSS and turbidity; WQI_c denotes the biological water quality parameter of coliform; WQI_{pH} denotes the water quality of pH.

Comprehensive pollution index (CPI) The CPI is used to assess the contamination level in water by using physiochemical parameters with their permissible limit. The CPI has been calculated based on permissible limits of

Table 3 Water quality parameters range and their score

Parameters	Unit	Score of water quality parameters				
		100 Level-1	75 Level-2	50 Level-3	25 Level-4	1 Level-5
NH ₃ -N	mg/l	≤0.1	0.2	0.5	1	≥10
BOD	mg/l	≤4	6	15	25	≥50
DO saturation	%	88–112	75–88, 112–125	50–75, 125–150	20–50, 150–200	<20 and >200
pH	-	6–8.5	-	5.5, 9	-	<5.5 and >9
Total coliform	Most probable number (MPN)/100 ml	≤2500	5000	7500	10,000	>10,000
COD	mg/l	≤10	15	30	50	≥80
PO ₄ ³⁻	mg/l	≤0.1	0.2	0.3	0.5	≥4
TSS	mg/l	≤20	30	50	100	≥150
Turbidity	NTU	≤5	20	30	70	≥100

Based on Thi Minh Hanh et al. (2011)

physio-chemical parameters set by the US Environmental Protection Agency (USEPA) for water quality criteria to protect aquatic life or habitats, including fish. In the present study, 23 physio-chemical parameters such as NH₃-N, BOD, EC, DO, fecal coliform (FC), NO₃⁻-N, pH, water temperature, TC, calcium (Ca²⁺), chloride (Cl⁻), COD, fluoride (F⁻), magnesium (Mg²⁺), PO₄³⁻, potassium (K⁺), sodium (Na⁺), sulfate (SO₄²⁻), total alkalinity (TA), total dissolved solids (TDS), total hardness (TH) as CaCO₃, TSS, and turbidity have been used to measure the comprehensive pollution level in Damodar river water by using Eqs. (6) and (7) following Son et al. (2020),

$$CPI = \frac{1}{n} \sum_{i=1}^n PI_i \tag{6}$$

$$PI_i = \frac{Ci}{Si} \tag{7}$$

where *n* represents the used physio-chemical parameters number; PI_{*i*} denotes the pollution index of *i*th parameters; Ci denotes the observed parameter concentration; and Si denotes the permissible limit of observed parameters based on environmental standards (USEPA). Based on the CPI score, water is categorized into five classes such as clean (0–0.20), sub-clean (0.21–0.40), slightly polluted (0.41–1.00), medium polluted (1.01–2.00), and heavily polluted (> 2.01) water (Son et al. 2020).

Statistical techniques

ANOVA for spatial and temporal variations ANOVA is an arithmetic technique used to describe the variance among two or more variables by significance tests (Hoque et al.

2022c). This technique has been performed in the present work to illustrate the significant difference among the spatial and temporal (pre-monsoon, monsoon, and post-monsoon) water quality indices and indicators using one-way ANOVA in Microsoft Office Excel (v. 2016). ANOVA is computed by Eqs. (8)–(12).

$$F = \frac{MST}{MSE} \tag{8}$$

$$MST = \frac{SST}{p - 1} \tag{9}$$

$$SST = \sum n(x - \bar{x})^2 \tag{10}$$

$$MSE = \frac{SSE}{N - p} \tag{11}$$

$$SSE = \sum (n - 1)S^2 \tag{12}$$

where *F* stands for the ANOVA coefficient; MST stands for the mean sum of all the squares owing to the treatment; MSE stands for the mean sum of squares owing to an error; SST for the sum of squares due to treatment, *p* for total number of populations, *n* = the total number of samples in a population, SSE for sum of squares due to error, *S* for standard deviation of the samples, and *N* for total number of observations.

PCA for association among the water quality indices and controlling factors Principal component analysis (PCA) is a multivariate arithmetic technique used to decline the massive amount of multivariate data extension and modify these data into the principal components without losing any information (Mahammad et al. 2022). It is also an important and

functioning statistical technique for investigating the water quality indices to recognize the controlling and leading indices or indicators of water quality. Hence, to detect controlling and leading indices or indicators of water quality, PCA has been performed by Quartimax with Kaiser normalization using IBM SPSS (v.26). PCA is formulated by Eq. (13).

$$Z_j = a_{j1}P_1 + a_{j2}P_2 + \dots + a_{jn}P_n \text{ and } (a_{ji} = \frac{PCA_{jr}}{\sqrt{\lambda_r}}) \tag{13}$$

where $i = 1, 2, \dots, n$ (for “ n ” variable), $j = 1, 2, \dots, m$ (for “ m ” attribute), PCA_r = factor loadings of a particular stage, λ_r = eigenvalue of a particular stage and each of the observed variables were described as linear in terms of the uncorrelated components, P_1, P_2, \dots, P_n .

Spatial interpolation techniques

The interpolation methods like simple kriging (SK), ordinary kriging (OK), and inverse distance weighting (IDW) have been used to represent the spatial distribution of water quality indices and indicator values in the study area. Among them, IDW is used to create a spatial distribution map from water quality indices and indicator values for better representation of variables. In the IDW method, the weight (λ_i) relies on the distance to the prediction location. Based on the weight, the distance is created between the sample location and the estimation point. The power weight controls the weight. For instance, if the power is bigger, the point’s effect on the distance is also bigger than estimated. In the IDW model, the weight value decreases with increasing distance from the estimation point. The total weights (λ_i) are equal to 1 and this model is formulated by Eq. (14) following Sarkar et al. (2021a).

$$\lambda_i = d_{i0}^{-p} / \sum_{i=1}^n d_{i0}^{-p} \tag{14}$$

where d_{i0} is the distance between the sample location and estimation points. The distance occurs smaller when the weight is enlarged exponentially by a power parameter of p .

Results

General hydro-chemistry

The physio-chemical water quality parameters have been evaluated based on environmental standards (USEPA) following Ochir and Davaa (2011), Dkhar et al. (2014), and Sulthonuddin et al. (2019), and found that a higher percentage of BOD, DO, FC, TC, COD, and F^- concentration in water samples exceeded their permissible limit at all the

stations in all the seasons. It also is observed that a higher percentage of TSS and turbidity concentration in monsoon water samples compared to other seasons at all the stations exceeded their permissible limit. Moreover, a higher percentage of water samples of PO_4^{3-} concentration in monsoon and post-monsoon exceeded its standard limit than the pre-monsoon period. Additionally, the NH_3-N concentration in 37.14%, 25%, and 30.36% of water samples in pre-monsoon, monsoon, and post-monsoon periods correspondingly at the station Damodar near the village of Mujher Mana exceeded its permissible limit which is high among the other stations in all the seasons (Tables S1, S2, and S1).

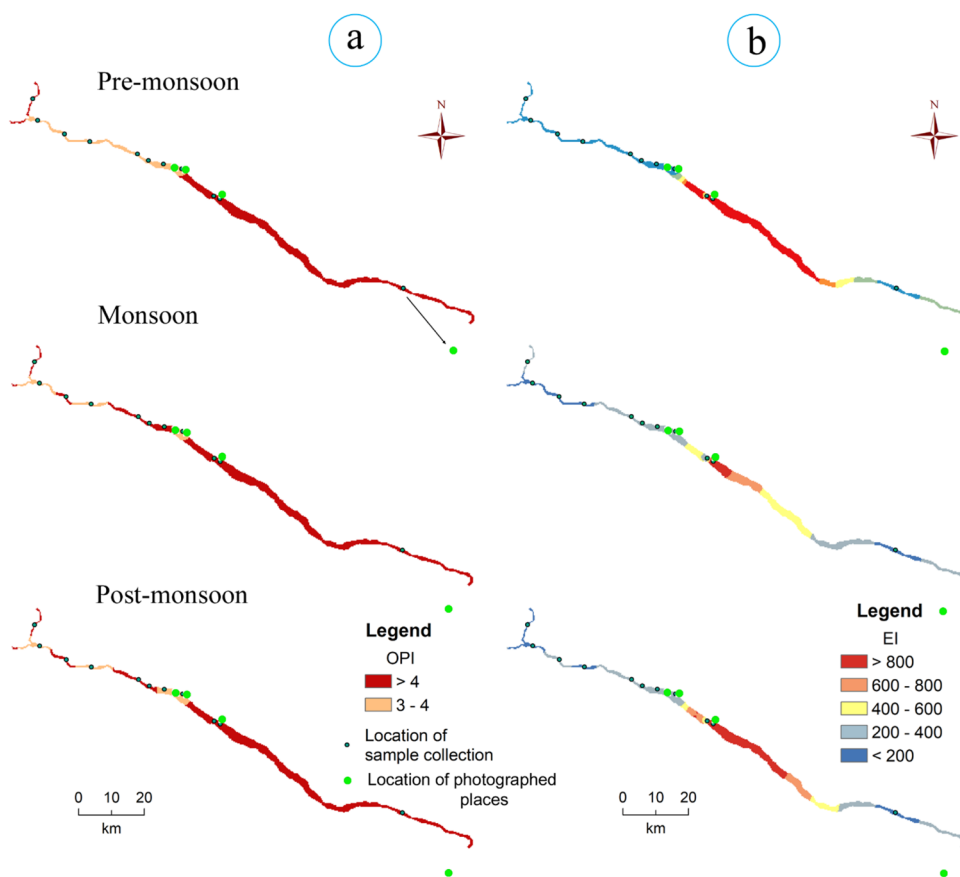
Ecological water quality

Organic pollution index (OPI)

OPI has been used to measure organic pollution levels in various stretches of Damodar River water. This study reveals that the average OPI score ranges from 3.61 to 15.77 with a mean value of 4.96, 3.64 to 6.92 with a mean value of 4.46, and 3.65 to 7.83 with a mean value of 4.34 in pre-monsoon, monsoon, and post-monsoon period correspondingly (Table S4). It is also found that the OPI score of station 10 is high in all the respective seasons among the other stations, but within the station, high in the pre-monsoon. A low OPI score is observed at station 4 in all the seasons. The box plot (Fig. S1a) also shows that the OPI score is high at station 10 in all the seasons while low at 9 in pre-monsoon and 4 in the monsoon and post-monsoon seasons. A very high outlier is observed at station 6 in monsoon. The spatio-temporal map displays the OPI score varies from 3 to 4 in the upper part of this studied river section in the pre-monsoon at stations 2–8, in monsoon at stations 2, 4, and 8, and in post-monsoon at stations 2, 4, 7, and 8, indicating that these sections have moderate organic pollution in respective seasons based on the categorical classification of OPI (Fig. 2a). The OPI score > 4 lies in the middle and lower parts of the studied section in all the seasons while upper part in the pre-monsoon at stations 1, in monsoon at stations 1, 3, 5, 6, and 7, and post-monsoon at stations 1, 3, 5, and 6, indicating heavy organic pollution.

Moreover, based on the categorical classification of the OPI score, it is found that only 2.78% of water samples begin to be contaminated ($1 < OPI \leq 2$ score) in monsoon at station 6 and post-monsoon at station 8. A high percentage of water samples of station 10 lies in > 4 OPI score, i.e., heavy organic pollution category in pre-monsoon (94.29%), monsoon (100.00%), and post-monsoon (100.00%) seasons, while a lower percentage of water samples lies in this group at station 7 (25.71%) in pre-monsoon, station 4 (19.44%) in monsoon, and station 4 (33.33%). In the light organic pollution ($2 < OPI \leq 3$) class category, the highest percentage

Fig. 2 Spatio-temporal variation of ecological water quality. **a** OPI and **b** EI in water; OPI indicates that organic pollution is higher at the middle and lower stretches of the river, while EI portrays an elevated concentration of eutrophication at the middle stretch of the river. The pre-monsoon season has recorded an escalated level of organic pollution and eutrophication. The OPI classes are based on standard categorization; here, two classes are presented because of the presence of the water samples in these two categories only. For EI, all water samples' EI lies above 9; therefore, for spatial variation, we have divided this range into five classes to indicate the spatial magnitude variation (note: the south-east directed black arrow indicates the location of photographed places 5 and 6 which are located 30 km downstream away from the monitoring station 11, i.e., water intake point at Bardhhaman)



of water samples is observed at station 4 (25.71%) in pre-monsoon, 8 (36.11%) in monsoon, and 4 (25.00%) in post-monsoon seasons. However, in this category, the lowest percentage of water samples is observed at station 2 in pre-monsoon (5.71%), 2 and 3 in monsoon (5.56%), and 6 in post-monsoon (8.33%) seasons. However, comparatively, a higher percentage of water samples is found in the moderately organic pollution ($3 < \text{OPI} \leq 4$) classification group among the other classification groups in all the respective seasons. The highest percentage of water samples lies in this group ($3 < \text{OPI} \leq 4$) at station 3 (71.73%) in pre-monsoon, 1 and 3 (61.11%) in monsoon, and 2 (61.11%) in post-monsoon seasons, while the lowest percentage of water samples lies in this group at station 10 in pre-monsoon (5.71%), at station 8 in monsoon (33.33%), and stations 5 and 8 in post-monsoon (36.11%) (Table 4). These results indicate that organic pollution is high in the pre-monsoon while low in the post-monsoon period, and it is high after the Tamla Nallah confluence in all the seasons.

Eutrophication index (EI)

EI score has also been evaluated to measure the eutrophication level in the Damodar River water in a spatio-temporal dynamic. A higher EI score is observed in all the seasons

and also all the stations in the spatio-temporal dimension indicating severe eutrophication. The average EI score of 572.84, 343.14, and 447.12 is found in pre-monsoon, monsoon, and post-monsoon, respectively. The average lowest EI score is found at station 4 (85.61) in pre-monsoon, 2 (101.37) in monsoon, and also 4 (153.08) in the post-monsoon period, while the highest score is found in pre-monsoon (5106.27), monsoon (1298.20), and post-monsoon (2655.13) at station 10. A very high CV and data outlier of EI score is observed for all the stations in all the seasons (Table S5 and Fig. S1b). Figure S1b represents that the EI score is also high at station 10, similar to other index results.

Moreover, the spatio-temporal variation map represents that the EI score > 800 lies in the middle part of Damodar River water, while < 200 lies in the upper part in pre-monsoon and uppermost part in pre- and post-monsoon and some portion of the lower part near at station 11 in all the seasons (Fig. 2b). The EI score ranges from 200 to 400 in the upper and lower parts of the river in monsoon and post-monsoon seasons (Fig. 2b). Furthermore, 93.25%, 90.15%, and 94.04% of water samples in pre-monsoon, monsoon, and post-monsoon, respectively, lie in EI > 9 category which indicates that the Damodar river water has severe eutrophication in all seasons (Table 5). Only a few percentages, i.e., 5.71%, 5.71%, 2.86%, 2.86%, 2.86%,

Table 4 Season-wise classification of water samples (percentage) in different monitoring stations based on OPI score

Seasons	OPI classification	Monitoring stations										
		1	2	3	4	5	6	7	8	9	10	11
Pre-monsoon	1 < OPI ≤ 2	-	-	-	-	-	-	-	-	-	-	-
	2 < OPI ≤ 3	-	5.71	-	25.71	-	8.57	14.29	14.29	22.86	-	-
	3 < OPI ≤ 4	48.57	65.71	71.43	45.71	62.86	60.00	60.00	54.29	48.57	5.71	34.29
	OPI > 4	51.43	28.57	28.57	28.57	37.14	31.43	25.71	31.43	28.57	94.29	65.71
Monsoon	1 < OPI ≤ 2	-	-	-	-	-	2.78	-	-	-	-	-
	2 < OPI ≤ 3	-	5.56	5.56	27.78	-	13.89	25.00	36.11	22.22	-	-
	3 < OPI ≤ 4	61.11	58.33	61.11	52.78	44.44	44.44	36.11	33.33	47.22	-	58.33
	OPI > 4	38.89	36.11	33.33	19.44	55.56	38.89	38.89	30.56	30.56	100.00	41.67
Post-monsoon	1 < OPI ≤ 2	-	-	-	-	-	-	-	2.78	-	-	-
	2 < OPI ≤ 3	-	-	-	25.00	-	8.33	22.22	19.44	13.89	-	-
	3 < OPI ≤ 4	58.33	61.11	47.22	41.67	36.11	44.44	38.89	36.11	41.67	-	44.44
	OPI > 4	41.67	38.89	52.78	33.33	63.89	47.22	38.89	41.67	44.44	100.00	55.56

Any water sample lies in the (OPI < 0) and (0 ≤ OPI ≤ 1) OPI class categories

Table 5 Season-wise classification of water samples (percentage) in different monitoring stations based on EI score

Seasons	EI classification	Monitoring Stations										
		1	2	3	4	5	6	7	8	9	10	11
Pre-monsoon	0 ≤ EI ≤ 1	-	5.71	-	5.71	-	2.86	2.86	2.86	5.71	-	2.86
	1 ≤ EI ≤ 3	-	-	2.86	-	-	2.86	-	-	5.71	-	2.86
	3 < EI ≤ 9	8.57	5.71	2.86	2.86	2.86	-	2.86	-	5.71	-	-
	EI > 9	91.43	88.57	94.29	91.43	97.14	94.29	94.29	97.14	82.86	100.00	94.29
Monsoon	0 ≤ EI ≤ 1	2.78	2.78	2.78	5.56	-	-	2.78	-	2.78	-	8.33
	1 ≤ EI ≤ 3	2.78	5.56	-	5.56	-	-	8.33	11.11	8.33	2.78	-
	3 < EI ≤ 9	-	5.56	8.33	-	2.78	5.56	-	2.78	2.78	2.78	5.56
	EI > 9	94.44	86.11	88.89	88.89	97.22	94.44	88.89	86.11	86.11	94.44	86.11
Post-monsoon	0 ≤ EI ≤ 1	-	2.86	-	-	-	-	5.71	-	-	-	-
	1 ≤ EI ≤ 3	2.78	2.86	2.86	2.86	-	2.86	5.71	11.43	2.86	-	2.86
	3 < EI ≤ 9	2.78	5.71	-	5.71	-	-	2.86	-	2.86	-	-
	EI > 9	94.44	88.57	97.14	91.43	100.00	97.14	85.71	88.57	94.29	100.00	97.14

5.71%, and 2.86% of water samples at stations 2, 4, 6, 7, 8, 9, and 11 in pre-monsoon; 2.78%, 2.78%, 2.78%, 5.56%, 2.78%, 2.78%, and 8.33% of water samples at stations 1, 2, 3, 4, 7, 9, and 11 in monsoon; and 2.86% and 5.71% of water samples at stations 2 and 7 in post-monsoon, respectively, range from 0 ≤ EI ≤ 1, indicating no eutrophication as per categorical classification (Chen 2021). These results indicate that the eutrophication level is high in the pre-monsoon with a mean of 572.84, while low in the monsoon period with a mean of 343.14, and it is also high after the Tamla Nallah confluence, i.e., station 10 (EI = 5106.27 in pre-monsoon, EI = 1298.20 in monsoon, and EI = 2655.13 in post-monsoon), in all the seasons. Additionally, a very high EI score is observed at all the stations in all the seasons, indicating very high or severe eutrophication.

Bacteriological water quality

Total coliform (TC)

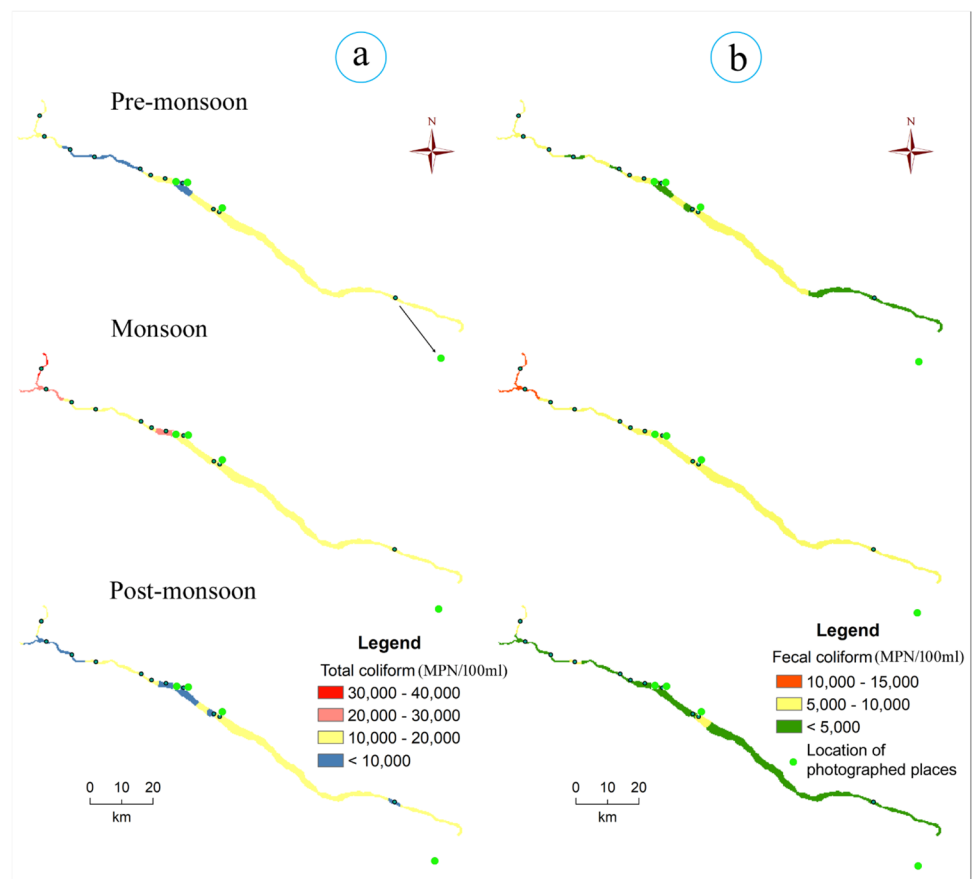
In this study, it is revealed that the average concentration of total coliform organisms or bacteria in Damodar River water ranges from 6942.86 to 17,226.47, 11,313.89 to 33,208.33, and 4588.89 to 14,813.89 with a mean value of 11,315.13, 19,326.52, and 10,270.48 MPN/100 ml in pre-monsoon, monsoon, and post-monsoon period, respectively. The highest average TC concentration in this river water is found in pre-monsoon (17,226.47) at station 10 and in monsoon (33,208.33) and post-monsoon (14,813.89) at station 1, while the lowest TC concentration was found in pre-monsoon (6942.86) at station 4,

monsoon (11,313.89) at station 11, and in post-monsoon (4588.89) at station 3 (Table S6). Moreover, the mean values of TC concentration and spatial variation map show that post-monsoon water quality is good compared to other seasons. The concentration of TC ranges from 20,000 to 40,000 in the upper part of the monsoon at stations 1, 2, and 7. However, TC concentration lies $< 10,000$ in the upper part in the pre- and post-monsoon and also the lower part in the pre-monsoon season at station 11 (Fig. 3a). The box plot shows that most seasons with stations have very high (1.6 lac) data outliers (Fig. S2a). Furthermore, the TC has been classified based on the environmental standard (5000 MPN/100 ml) and found that 68.57%, 60.00%, and 65.00% of samples of stations 1, 6, and 10 in pre-monsoon, 61.11% and 80.56% of water samples of stations 1 and 10 in monsoon, and 55.56% of water samples of station 10 in post-monsoon exceeded its environmental standard (Tables S1, S2, and S3). These results indicate that the TC concentration is high in the monsoon and low in the post-monsoon period. It is also perceived that TC concentration is high at station 1 in monsoon and post-monsoon and also high near Mujher Mana village located downstream of the Durgapur barrage in the pre-monsoon season.

Fecal coliform (FC)

In the analysis of FC concentration, it is observed that the average FC concentration in monsoon season is high followed by pre- and post-monsoon and it ranges from 3494.29 to 9354.29 (mean 5675.58), 5005.56 to 13,863.89 (mean 8510.10), and 2900.00 to 5827.78 (mean 4275.71) MPN/100 ml with a higher CV in pre-monsoon, monsoon, and post-monsoon seasons, respectively. The lowest FC concentration is found at station 9 in pre-monsoon, 11 in monsoon, and 3 in post-monsoon, while the highest FC concentration is found at station 10 in the pre- and post-monsoon seasons and at station 1 in monsoon season (Table S7). The spatial variation map shows that the FC distribution < 5000 lies in the upper and lower stretches in pre-monsoon and most of the stretch except station 10 in post-monsoon. The FC concentration from 5000 to 10,000 lies in the middle and upper stretches in pre-monsoon, most of the stretch, except stations 1 and 2 in monsoon, and at station 10 in the post-monsoon season. The FC concentration ranges from 10,000 to 15,000 in the uppermost part of the upper stretch in monsoon (Fig. 3b). The box plot shows that most of the seasons with stations have very high data outliers (Fig. S2b). Furthermore, the Damodar River water quality

Fig. 3 Spatio-temporal variation of bacteriological water quality. **a** TC and **b** FC concentration in water samples; TC concentration is higher at the middle and lower stretches of the river, while FC concentration portrays an elevated concentration of eutrophication at the middle stretch of the river. Monsoon season has recorded an escalated level of TC and FC concentration (note: the south-east directed black arrow indicates the location of photographed places 5 and 6)



has been classified based on the environmental standard (1000 MPN/100 ml) and found that 91.69%, 96.97%, and 93.18% of water samples in the pre-monsoon, monsoon, and post-monsoon seasons, respectively, exceeded its permissible limit (Tables S1, S2, and S3). Moreover, for the bathing standard limit (2500 MPN/100 ml), it is found that 65.97%, 69.95%, and 51.52% of water samples in pre-monsoon, monsoon, and post-monsoon, respectively, exceed its permissible limit. These results portray that the Damodar River water is unfit for bathing use. Moreover, the FC concentration is high in the monsoon while low in the post-monsoon period. It is also perceived that FC concentration is high near the downstream of Durgapur barrage near the village Mujher Mana in the pre- and post-monsoon, while it is high at station 1 in the monsoon season.

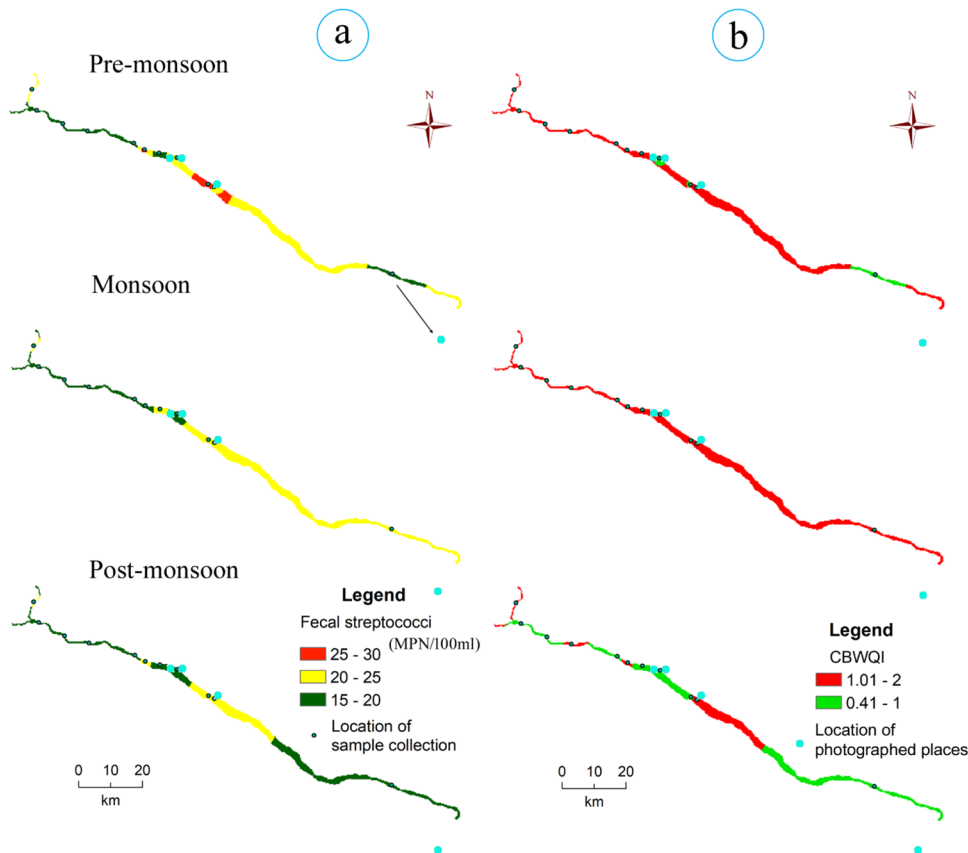
Fecal streptococci (FS)

Streptococci are mainly of human origin and they give some extra evidence of pollution. Some bacteria that are categorized in this assembly can also be observed in animal feces or on plants (Mezbour et al. 2018). Based on the monthly available data, it is observed that the average FS concentration in Damodar River water ranges from 16.14 to 29.57, 16.75 to 25.50, and 15.91 to 23.18 with

a mean value of 20.92, 19.92, and 18.91 in the pre-monsoon, monsoon, and post-monsoon periods, respectively (Table S8). The highest average FS concentration is found at station 9 in pre-monsoon, and at station 10 in monsoon and post-monsoon seasons, while the lowest value is found at stations 3, 4, and 11 in pre-monsoon, monsoon, and post-monsoon periods correspondingly in the study area (Fig. S2c). These results indicate that the FS concentration is high in the pre-monsoon while low in the post-monsoon period. It is also observed that the FS concentration is comparatively high at downstream of the Durgapur barrage near the village Mujher Mana in all the seasons (Fig. 4a). Furthermore, the Damodar River water quality has been classified based on the environmental or bathing standard limit (500 MPN/100 ml), and observed that all the water samples lie below the standard permissible limit indicating suitable for bathing use.

Furthermore, the bathing water quality of the river has also been evaluated and found that it ranges from 0.91 to 1.58 with a mean value of 1.15 in the pre-monsoon, 1.07 to 1.95 with a mean value of 1.43 in monsoon, and 0.82 to 1.22 with a mean value of 0.98 in the post-monsoon season (Table S9). Besides, the spatio-temporal variation map represents that the CBWQI score > 0.41 to 2 lies in the entire stretch of the river water. The middle stretch is more

Fig. 4 Spatio-temporal variation of **a** bacteriological water quality as FS concentration and **b** comprehensive bathing water quality index (CBWQI). It has been observed that FS concentration is higher at the middle stretch of the river and the pre-monsoon season has recorded an elevated concentration of FS. CBWQI reveals that the entire stretch of the river is polluted for bathing as per CPI standards because all stations have CBWQI > 0.41. However, the middle stretch is more polluted than the upper and lower stretches, while monsoon season records the most unacceptable bathing water quality (note: the south-east directed black arrow indicates the location of photographed places 5 and 6)



polluted than the upper and lower stretches and monsoon season water is the most unacceptable for bathing purposes (Fig. 4b).

Overall water quality

Overall water quality index (WQI)

The overall water quality has been assessed through VEA-recommended WQI for various purposes in the study, and it was found that the average WQI values ranged from 49.80 to 79.83, 39.67 to 63.22, and 50.17 to 74.27 with a 69.25, 54.87, and 67.77 mean value in pre-monsoon, monsoon, and post-monsoon seasons, respectively (Table S10). The higher WQI score indicates good water quality and vice versa. The lower WQI values with higher CV were observed at station 10 (i.e., Damodar after Tamla Nallah confluence) in all the seasons while similar results are reported for station 1 only in the monsoon season, indicating poor water quality, i.e., water is suitable for transportation and equivalent purposes only. The remaining stations come under the moderate water quality in all the seasons which indicates that the water of these sections can be used for irrigation and equivalent purposes as per the categorical classification of the WQI score (Table 6).

Moreover, the spatial variation map (Fig. 5a) shows that the WQI score is high at stations 2, 3, 7, and 8 which are located upstream of the Durgapur barrage in the pre-monsoon, indicating good water quality for domestic usage. However, lower WQI values are observed for station 10 in all the seasons while similar results are reported for station 1 only in the monsoon season, indicating poor water quality, i.e., water is suitable for transportation and equivalent purposes only. The remaining stations come under the moderate water quality in all the seasons which indicates that the water of these sections can be used for irrigation and equivalent purposes as per the categorical classification of the WQI score (Table 6).

Further, the WQI score has been classified based on its categorical classification (Table 6) and found that the highest, 37.14% of water samples of station 1 in pre-monsoon, 41.67% of water samples of stations 1, 2, 3, and 10 in monsoon, and 33.33% of water samples of station 3 in post-monsoon, come under heavy water pollution category (WQI score 0–25). While the lowest percentage of water samples at stations 2 and 8 in pre-monsoon (11.43%), at stations 8 and 9 in monsoon (25%), and stations 2 and 7 in post-monsoon (16.67%) comes under the heavy pollution category. A very small or zero percentage of water samples in all the respective seasons

Fig. 5 Spatio-temporal variation of overall water quality: **a** WQI and **b** CPI; overall water quality (WQI and CPI) indicates that water quality is worse at the middle stretch of the river. Monsoon season has recorded an escalated level of pollution (note: the south-east directed black arrow indicates the location of photographed places 5 and 6)

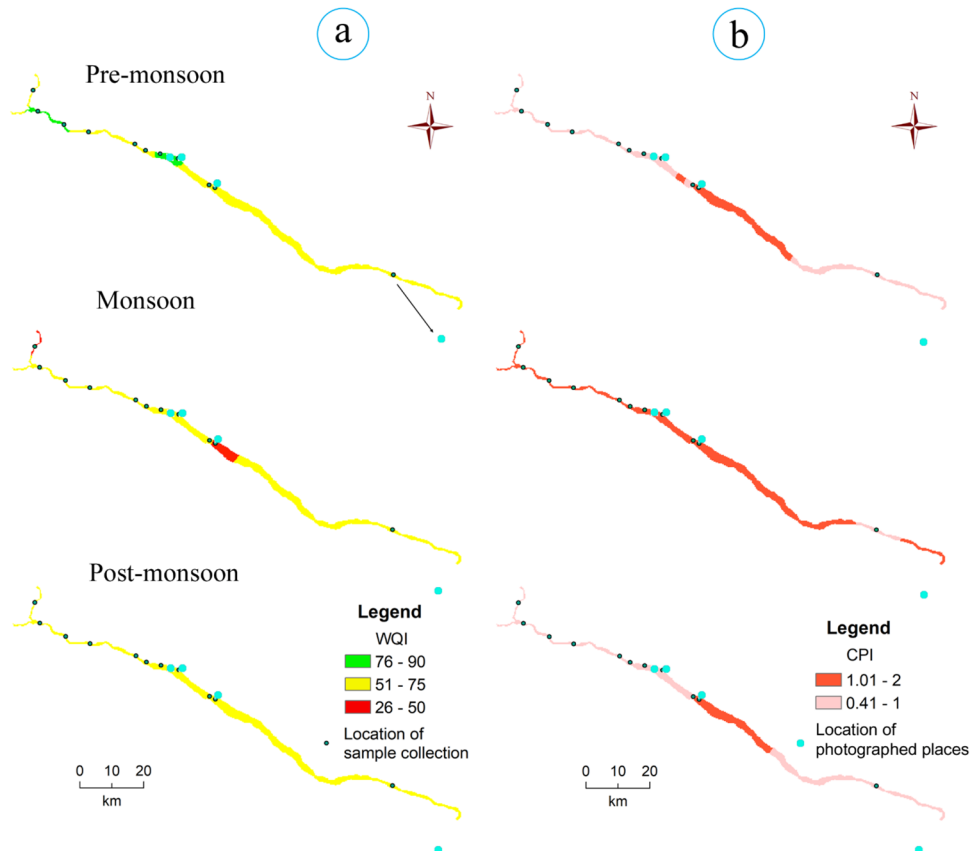


Table 6 Water quality classification according to WQI score

Level	Range of WQI score	Status	Remarks
1	0–25	Heavy pollution	Treatment is required before use
2	26–50	Poor	Can be used for transportation or equivalent purposes
3	51–75	Moderate	Can be used for irrigation or equivalent purposes
4	76–90	Good	Suitable for domestic usage
5	91–100	Very good	Suitable for domestic water supply

Based on Son et al. (2020)

and stations except station 10 lies in the poor water quality category. In the moderate category, the highest 42.86% of the water sample at station 10 in pre-monsoon, 44.44% at station 8 in monsoon, and 30.56% at station 10 in post-monsoon, while the lowest, 5.71% at stations 4 and 7 in pre-monsoon, 13.89% at stations 2 and 3 in monsoon, and 5.56% in post-monsoon at station 3, come under this category. In the good category, the highest 48.57% samples in pre-monsoon at station 2, 33.33% in monsoon at stations 1–4, and 52.78% in post-monsoon at station 5 are found while the lowest 14.29%, 11.11%, and 22.22% of water samples at station 10 in all the seasons, come under this category. In the last or very good water quality category, the lowest percentage of water samples in pre-monsoon (2.86%), monsoon (0.00%), and post-monsoon (0.00%) at station 10 comes under this category, while the highest, 42.86% in pre-monsoon at stations 3 and 7, 13.89% at stations 4, 8, and 9 in monsoon, and 33.33% of water samples at stations 4 and 9 in post-monsoon, come under this very good water quality category (Table 7).

These results indicate that the water quality is most unacceptable in monsoon followed by post-monsoon and

pre-monsoon in the temporal dimension, whereas, in all the seasons, it is comparatively most unacceptable at Damodar River immediately downstream of Durgapur barrage or after the Tamla Nallah confluence among the other stations in the spatial variation based on the average WQI score. The maximum, 28.57%, 41.67%, and 27.78% of water samples in pre-monsoon, monsoon, and post-monsoon, respectively, after the Tamla Nallah confluence and 41.67% of water samples in post-monsoon at Barakar, Dishergarh, and IISCO, were also found heavy pollution in water. Moreover, poor water quality was found at the Tamla Nallah confluence and Barakar in the monsoon seasons. However, good water quality was found at Dishergarh, IISCO, and Andal in pre-monsoon, while moderate water quality was found in the remaining parts in all the seasons based on average WQI score.

Comprehensive pollution index (CPI)

In the spatio-temporal dynamic, the comprehensive pollution has been calculated to assess the contamination level in Damodar river water, and it was found that the pollution

Table 7 Season-wise classification of water samples (percentage) in different monitoring stations based on WQI score

Seasons	WQI classification	Stations										
		1	2	3	4	5	6	7	8	9	10	11
Pre-monsoon	0–25	37.14	11.43	17.14	22.86	22.86	22.86	17.14	11.43	22.86	28.57	22.86
	26–50	-	-	-	-	-	-	-	-	2.86	11.43	2.86
	51–75	11.43	8.57	14.29	5.71	14.29	22.86	5.71	14.29	14.29	42.86	22.86
	76–90	40.00	48.57	25.71	40.00	40.00	37.14	34.29	45.71	37.14	14.29	34.29
	91–100	11.43	31.43	42.86	31.43	22.86	17.14	42.86	28.57	22.86	2.86	17.14
Monsoon	0–25	41.67	41.67	41.67	27.78	38.89	33.33	33.33	25.00	25.00	41.67	19.44
	26–50	-	-	2.78	2.78	2.78	2.78	5.56	2.78	2.78	22.22	8.33
	51–75	25.00	13.89	13.89	22.22	25.00	25.00	27.78	44.44	27.78	25.00	38.89
	76–90	33.33	33.33	33.33	33.33	30.56	30.56	22.22	13.89	30.56	11.11	25.00
	91–100	-	11.11	8.33	13.89	2.78	8.33	11.11	13.89	13.89	-	8.33
Post-monsoon	0–25	30.56	16.67	33.33	22.22	22.22	25.00	16.67	19.44	19.44	27.78	13.89
	26–50	2.78	2.78	2.78	-	-	2.78	-	-	-	19.44	-
	51–75	8.33	16.67	5.56	13.89	11.11	16.67	13.89	19.44	19.44	30.56	25.00
	76–90	41.67	36.11	36.11	30.56	52.78	38.89	44.44	36.11	27.78	22.22	38.89
	91–100	16.67	27.78	22.22	33.33	13.89	16.67	25.00	25.00	33.33	-	22.22

level in monsoon water (average 1.23) was high followed by pre-monsoon (average 0.94) and post-monsoon (average 0.88). The average CPI score ranges from 0.75 to 1.75 in pre-monsoon, 0.98 to 1.67 in monsoon, and 0.71 to 1.69 in the post-monsoon period. The CPI score at station 10 is high among the other stations in all the seasons, while a lower score is observed at station 4 in pre-monsoon, 11 in monsoons, and 3 in post-monsoon season. High CV of 113.60% and 98.43% are observed at station 2 in pre-monsoon and 99.04% in post-monsoon at station 10, while lower at station 5 in pre-monsoon, 11 in monsoon, and 7 in post-monsoon in the spatial dimension. Moreover, in temporal dynamics, an average higher CV is perceived in the monsoon followed by the pre- and post-monsoon season (Table S11). In addition, the box plot (Fig. S3b) shows that the CPI score in monsoon is high at all the stations, and a higher outlier of CPI score is observed for all the stations and seasons.

The spatial variation map also shows that the monsoon season water quality is most unacceptable among the other seasons (Fig. 5b). In almost all the regions or rivers except station 11, the water quality ranges from 1.01 to 2 in the monsoon season and lies in medium pollution based on the categorical classification of CPI score. Moreover, the upper and lower sections except the middle section or the downstream region of Durgapur barrage (station 10) of the studied river water quality lie from 0.41 to 1 in the pre- and post-monsoon periods representing slight pollution (Fig. 5b).

Furthermore, the water quality has been classified based on CPI score and found that 2.86% of water samples range from 0.21 to 0.40, i.e., sub-clean at stations 2 in pre-monsoon, 4 in monsoon, 3 and 7 in post-monsoon season only. However, 80.52%, 59.09%, and 80.56% of water samples in pre-monsoon, monsoon, and post-monsoon seasons, respectively, lie in 0.41 to 1.00, i.e., slightly polluted, high

at stations 8 (94.29%) and 9 (94.29%) in pre-monsoon; 4 (72.22%), 8 (72.22%), and 9 (72.22%) in monsoon; 2 (91.67%), 9 (91.67%), and 11 (91.67%) in the post-monsoon season. A high percentage of water samples of station 10 ranges from 1.01 to 2.00, i.e., medium polluted in pre-monsoon (51.43%), monsoon (59.44%), and post-monsoon (55.56%) seasons only. Moreover, 17.14% and 13.89% of water samples of station 10 in pre-monsoon and post-monsoon and 16.67% of water samples of station 1 lie in the > 2.01 CPI score category, i.e., heavily polluted which is also high among the other seasons (Table 8). The CPI results indicate that the pollution level in monsoon season is also high in temporal dynamics and also high in the lower stretch of Durgapur barrage after the Tamla Nallah confluence near the village of Mujher Mana among the other stations in all the seasons in the spatial dimension in terms of comprehensive pollution.

Spatio-temporal variations in water quality

The ANOVA results indicate that there is a significant spatial variation in water quality indices in all the seasons (pre-monsoon, monsoon, and post-monsoon). Although the bacteriological water quality indicators like TC and FC in all the seasons, and FS in monsoon and post-monsoon have no significant difference, it (FS) has significant differences in pre-monsoon season (Table 9). Further, ANOVA for temporal variation of water quality depicts that there is a significant difference in overall water quality indices (WQI and CPI), whereas there is no significant difference in ecological water quality indices (OPI and EI). Moreover, bacteriological indicators like TC and FC have significant differences, while FS has no significant differences in water quality in temporal

Table 8 Season-wise classification of water samples (percentage) in different monitoring stations based on CPI score

Seasons	CPI classification	Monitoring stations										
		1	2	3	4	5	6	7	8	9	10	11
Pre-monsoon	0.21–0.40	-	2.86	-	-	-	-	-	-	-	-	-
	0.41–1.00	71.43	85.71	85.71	85.71	91.43	82.86	85.71	94.29	94.29	31.43	77.14
	1.01–2.00	28.57	2.86	11.43	14.29	8.57	11.43	8.57	-	2.86	51.43	20.00
	> 2.01	-	8.57	2.86	-	-	5.71	5.71	5.71	2.86	17.14	2.86
Monsoon	0.21–0.40	-	-	-	2.78	-	-	-	-	-	-	-
	0.41–1.00	47.22	63.89	69.44	72.22	61.11	52.78	58.33	72.22	72.22	16.67	63.89
	1.01–2.00	36.11	25.00	19.44	19.44	27.78	33.33	30.56	19.44	19.44	69.44	30.56
	> 2.01	16.67	11.11	11.11	5.56	11.11	13.89	11.11	8.33	8.33	13.89	5.56
Post-monsoon	0.21–0.40	-	-	2.78	-	-	-	2.78	-	-	-	2.78
	0.41–1.00	80.56	91.67	86.11	77.78	83.33	77.78	88.89	86.11	91.67	30.56	91.67
	1.01–2.00	13.89	5.56	11.11	19.44	13.89	19.44	8.33	11.11	8.33	55.56	-
	> 2.01	5.56	2.78	-	2.78	2.78	2.78	-	2.78	-	13.89	5.56

Any water sample lies in the 0–0.20 CPI class category

Table 9 One-way ANOVA exhibiting the spatio-temporal variation in water quality

Indicators/ indices	Seasons	Spatial*				Temporal**			
		<i>F</i>	<i>P</i> -value	<i>F</i> -critical	Remarks	<i>F</i>	<i>P</i> -value	<i>F</i> -critical	Remarks
OPI	Pre-monsoon	7.324052	1.29E – 10	1.856045	Alternative	1.729907	0.177753	3.00339	Null
	Monsoon	1.802768	0.058429	1.855318	Null				
	Post-monsoon	5.936454	2.26E – 08	1.855318	Alternative				
EI	Pre-monsoon	5.004164	7.78E v 07	1.856045	Alternative	0.721053	0.486455	3.00339	Null
	Monsoon	5.673833	6.09E – 08	1.855318	Alternative				
	Post-monsoon	6.216809	7.86E – 09	1.855318	Alternative				
TC	Pre-monsoon	0.616517	0.799913	1.856113	Null	12.11853	6.18E – 06	3.003403	Alternative
	Monsoon	0.944453	0.492111	1.855318	Null				
	Post-monsoon	0.764638	0.663003	1.855382	Null				
FC	Pre-monsoon	1.107021	0.355525	1.856045	Null	16.50506	8.53E – 08	3.00339	Alternative
	Monsoon	1.116315	0.348389	1.855318	Null				
	Post-monsoon	1.145481	0.326891	1.855318	Null				
FS	Pre-monsoon	2.653897	0.008733	1.977476	Alternative	1.987735	0.138914	3.027669	Null
	Monsoon	1.175773	0.320146	1.956024	Null				
	Post-monsoon	1.38853	0.194878	1.917827	Null				
WQI	Pre-monsoon	3.419206	0.000266	1.856045	Alternative	28.75304	6.44E – 13	3.00339	Alternative
	Monsoon	1.905413	0.043018	1.855318	Alternative				
	Post-monsoon	2.062479	0.026552	1.855318	Alternative				
CPI	Pre-monsoon	4.855246	1.36E – 06	1.856045	Alternative	20.43489	1.89E – 09	3.00339	Alternative
	Monsoon	1.77981	0.062502	1.855318	Null				
	Post-monsoon	6.717915	1.19E – 09	1.855318	Alternative				

Degree of freedom: 10 for spatial and 2 temporal variations, significance level: 0.05; Note: * indicates the spatial variation of water quality among the different monitoring stations in a particular season; ** indicates the temporal variation of water quality from the initial years (2014) to the penultimate year (2023)

dynamics (Table 9). In general, Damodar River water quality has a significant difference in temporal variation.

Association among the water quality indicators/ indices

PCA has been performed to detect controlling and leading indices or indicators of water quality in the study area. The eigenvalue > 1 has been considered for component selection and arisen PC2 in the study. Regarding spatial component analysis, cumulative variance (PC1 and PC2) accounts for 74.49% while seasonal component analysis also portrays a varying scenario. For example, pre-monsoon, monsoon, and post-monsoon account for 78.98%, 78.08%, and 72.21% of cumulative variance. These indicate the strength of the factorial components at the spatial and temporal scales. Further, PCA factor loadings have been categorized as strong (> 0.75), moderate (0.5–0.75), and weak (0.3–0.5) (Liu et al. 2003). According to this categorical classification, TC, FC, and CPI have a strong positive loading factor for controlling the water quality in spatial dimension, while TC, FC, and CPI in pre-monsoon, TC, FC, and CPI in monsoon, and FC and CPI in post-monsoon seasons have a strong positive

loading factor for controlling the water quality in temporal variation based on PC1. However, a moderate negative loading factor was found with WQI in the spatio-temporal dimension. Moreover, based on PC2, a strong positive loading factor was found with OPI and EI in the spatial dimension; however, it was found with OPI and EI in pre-monsoon and monsoon and OPI in post-monsoon seasons (Table 10). These results indicate that TC, FC, and CPI have strong loadings while WQI has negative loadings for controlling the Damodar River water quality in the spatio-temporal dynamics.

Discussion

The present study has assessed the spatio-temporal pollution level of Damodar River water based on the ecological, bacteriological, and overall water quality using ecological pollution indices, bacteriological water quality parameters, and overall WQI and CPI. The organic pollution and eutrophication levels are high in the pre-monsoon and post-monsoon periods (dry season) indicated by the algal bloom in the Damodar River (Fig. 6f); however, low

Table 10 PCA showing leading indicators/indices of water quality

Indicators/indices	Spatial dynamics		Temporal dynamics					
			Pre-monsoon		Monsoon		Post-monsoon	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
OPI	0.030	0.833	0.360	0.813	-0.228	0.832	0.257	0.764
EI	0.194	0.796	0.297	0.829	0.013	0.870	0.550	0.656
TC	0.891	-0.180	0.893	-0.281	0.924	-0.009	0.697	-0.444
FC	0.918	-0.116	0.908	-0.243	0.943	0.043	0.804	-0.287
WQI	-0.719	0.085	-0.687	0.140	-0.728	0.026	-0.705	0.344
CPI	0.933	0.159	0.959	0.031	0.936	0.176	0.929	0.243
Total variance	3.064	1.405	3.231	1.507	3.201	1.484	2.861	1.471
Variance (%)	51.072	23.418	53.858	25.120	53.348	24.736	47.692	24.520
Cumulative variance (%)	51.072	74.491	53.858	78.978	53.348	78.084	47.692	72.212

Higher PCs indicate strong and lower PCs indicate weak loading factor for controlling the water quality

organic pollution is detected in the monsoon season due to the flushing effect. Our study finding is supported by the work of Li et al. (2014). Furthermore, Son et al. (2020) also found a high level of organic pollution and eutrophication in pre- and post-monsoon (dry seasons) seasons in the Cau River (Vietnam). Moreover, TC and FC concentrations portray that the bacteriological water quality is high in monsoon, while FS portrays it as high in pre-monsoon although it is low in the post-monsoon period. Besides, the spatio-temporal variation is also observed in bacteriological water quality based on ANOVA, and it plays a crucial role in controlling the Damodar River water in spatio-temporal dynamics as per PCA. Mezbour et al. (2018) also observed that bacteriological water quality was high in monsoon (summer) seasons in the Lake birds (ELTarf East-Algerian) water. It is also perceived that the bacteriological water quality is high near downstream of the Durgapur barrage in all the seasons. The TC and FC concentration indicates that the Damodar River water quality is unsuitable for bathing purposes in terms of bacteriological water quality as their concentration in most water samples exceeded their standard limits, while FS concentration indicates its suitability for bathing uses. A higher FC concentration bacteria may lead to a higher pathogens risk and some waterborne pathogenic diseases that can overlap with FC contamination such as typhoid fever, hepatitis A, ear infections, viral and bacterial gastroenteritis, and dysentery (Geldreich 1996; An et al. 2020). The major source of higher TC and FC concentrations in Damodar River water is the discharge of domestic waste with animal manure (Fig. 6a) and they directly contaminate water (Mezbour et al. 2018). Discharging untreated organic matter containing FC into the river can be harmful to the environment reducing the oxygen level due to aerobic decomposition. This may lead to decreased river water oxygen levels to kill fish and other river life

(Dufatanye et al. 2022). Hence, decreasing the FC concentration in wastewater could be prioritized all over the year as 91.69%, 96.97%, and 93.18% of water samples in the pre-monsoon, monsoon, and post-monsoon seasons, respectively, exceeded its environmental standard (1000 MPN/100 ml).

WQI and CPI reveal the overall Damodar River water quality is suitable for irrigation and equivalent purposes in all seasons as per the categorical classification of overall water quality (Table 6). However, the reach downstream of the Durgapur barrage contains heavily polluted water which is unsuitable for irrigation, especially during monsoon season. Son et al. (2020) also found the Cau River (in Vietnam) water is suitable for irrigation supply. However, several studies (e.g., Sarkar et al. 2022) exhibited the most unacceptable water quality of the river in pre-monsoon seasons due to the impact of the agri-industrial effluent. They found that the monsoonal water quality is good compared to the other seasons due to the dilution of pollution with pollutants as the impact of monsoonal regimes. However, our study depicted the most unacceptable monsoon water quality due to the washout of numerous pollutants from the basin areas and the discharging of multiple intoxicant pollutants through the various Nallah discharging higher concentrations of $\text{NH}_3\text{-N}$, TC, PO_4^{3-} , TSS, and turbidity-inducing higher pollution level in monsoon.

Moreover, the study found an escalated level of water pollution in the lower stretch of the river. However, some studies (e.g., Sarkar et al. 2021b) demonstrated that the upper stretch of the River was more polluted than the lower one due to the industrial effluents' impact in the upper stretch, while tidally influenced lower stretches exhibited lower pollution due to precipitation of pollutants. In the previous discussion, the main cause of higher pollution near downstream of the Durgapur barrage, after the Tamla Nallah confluence in Damodar River water (i.e., station 10) in all the seasons, is due to the



Fig. 6 Sources of Damodar River pollution and environmental impacts: **a** agricultural practice and cattle farm on the mid-channel bar of Damodar near upstream of Durgapur barrage; **b**, **c** Singaran Nallah running through Durgapur Steel Plant dumping site and discharging industrial effluents into the Damodar, near upstream of Durgapur barrage, Waria, West Bardhaman; **d** discharging urban-industrial effluents into the river through Tamla Nallah, near downstream of Durgapur barrage, **e** on-bed agricultural practice near upstream of Damodar road bridge, near Jamalpur, Purba Bardhaman; **f** eco-

logical impact of pollution due to algal bloom in the river water, near Jamalpur, Purba Bardhaman which is located further downstream (30 km) from the monitoring in station 11; however, we have included this place to indicate the effect of eutrophication on downstream waterbody. (Note: field photographs collected from February, 2021, to February, 2022, demonstrate the role of typical land use in riverine pollution. The spatial association between the photographed locations and stretches of water pollution is also clearly observed in Figs. 2, 3, 4, and 5)

discharge of Asansol-Durgapur urban-industrial effluents through Singaran and Tamla *Nallahs* (Fig. 6c and d). On the contrary, it is found that station 11 has lower pollution effects due to its distant (63 km downstream) location from the point source pollution of Tamla *Nallah* which causes distance decay effects in the pollution level (Sarkar et al. 2021b).

In brief, the anthropogenic interventions on the Damodar River systems through dams, barrages, and weirs control the river water and create a stagnant situation, especially during pre- and post-monsoon seasons. Furthermore, urban-industrial and agricultural effluents with numerous intoxicants are directly mixed with the Damodar River and water quality depletes to a great extent (Fig. 6 a–f) (Hoque et al. 2022a).

Thus, the study findings can inform the stakeholders of the Damodar River basin, for example, the monsoon water of the Damodar River should be avoided for domestic use, especially for drinking use. Furthermore, the lower Damodar River water below the Durgapur barrage after the Tamla *Nallah* confluence should strictly be avoided for irrigation, domestic, drinking use, and bathing purposes, especially in monsoon. Urgent treatment is needed before the use of Damodar River water for this stretch of the river especially in monsoon. The treatment is also required for the use of monsoon Damodar river water especially for domestic water supply or drinking use. The present study has analyzed the spatial and temporal change of the Damodar River River water quality in terms of three seasons—pre-monsoon, monsoon, and post-monsoon. However, temporal changes (year-wise or decadal) could be another dimension of future work. Moreover, future attempts are welcome in the field of heavy metal pollution, and environmental flow assessment at a spatially continuum reaches over a longer period integrating regional planners, agri-engineers, and ecological river engineering for sustainable river basin management.

Conclusions

The present investigation has examined large water samples of Damodar River spreading over pre-monsoon, monsoon, and post-monsoon seasons for ecological, bacteriological, and overall water quality standards. The ecological water quality of Damodar River is most unacceptable in the pre-monsoon season, while the overall water quality of the river is most unacceptable in the monsoon season. Moreover, higher EI scores of all the stations are recorded especially during the pre- and post-monsoon periods (dry season), indicating severe eutrophication due to the standstillness of the water. However, bacteriological water quality is most unacceptable in monsoon in terms of the TC and FC concentration, while it is most unacceptable in pre-monsoon in terms of the FS concentration. The CBWQI exhibits the overall unsuitability of the Damodar River for bathing purposes.

Regarding spatial dynamics, heavy water pollution, as per the WQI classification, is found for stretches of the Damodar River downstream of the Durgapur barrage. According to the CPI classification of water, 80.52%, 59.09%, and 80.56% of water samples in pre-monsoon, monsoon, and post-monsoon seasons, respectively, have slight comprehensive pollution. Besides, ANOVA depicts that Damodar River water quality has a significant difference in spatio-temporal dimensions. The PCA portrays that the bacteriological indicators such as TC and FC and overall water quality indices such as WQI and CPI play a vital role in controlling the Damodar River water quality in the spatio-temporal dynamics. The major reason behind the most unacceptable monsoonal water quality is the higher concentration of physio-chemical and biological parameters like BOD, DO, FC, COD, and F⁻ and the escalated concentration of TSS, and turbidity due to the discharge of Asansol-Durgapur urban-industrial effluents through Tamla *Nallah*. The study findings may be useful for planners and different stakeholders for risk assessment, and target water treatment priorities that are necessary for water resource management and river restoration.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11356-024-32185-5>.

Acknowledgements We would acknowledge the data support provided by the West Bengal Pollution Control Board, Kolkata, India.

Author contribution Md. Mofizul Hoque: conceptualization, data curation, formal analysis, investigation, methodology, software, and writing—original draft; Aznarul Islam: formal analysis, investigation, methodology, writing—original draft, and supervision.

Funding This study was funded by the University Grants Commission (UGC) Junior Research Fellowship (JRF), Govt. of India vide letter number 3286/(OBC)(NET-JAN 2017) dated September 1, 2017, to carry out the Ph.D. work of the first author (Md. Mofizul Hoque) of this paper.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

- Aboyeji OO (2013) Freshwater pollution in some Nigerian local communities, causes, consequences and probable solutions. *Acad J Interdiscip Stud* 2(13):111. <https://doi.org/10.5901/ajis.2013.v2n13p111>

- Al-Hadithi M, Hasan K, Algburi A, Al-Paruany K (2019) Groundwater quality assessment using irrigation water quality index and GIS in Baghdad, Iraq. *J Earth Environ Sci* 10(1):15–20
- An XL, Wang JY, Pu Q, Li H, Pan T, Li HQ, ... Su JQ (2020) High-throughput diagnosis of human pathogens and fecal contamination in marine recreational water. *Environ Res* 190:109982. <https://doi.org/10.1016/j.envres.2020.109982>
- Banerjee US, Gupta S (2010) Seasonal assessment of irrigation water suitability of river Damodar in West Bengal, India. *J Crop Weed* 6(1):6–12
- Banerjee K, Banerjee R, Sen A, Mukhopadhyay S, Sen ACH, Singh D, Mandal B (2003) Damodar river pollution and health hazards. *J Indian Med Assoc* 101(2):104–106
- Baron JS, Poff NL, Angermeier PL, Dahm CN, Gleick PH, Jr Hairston NG, ... Steinman AD (2002) Meeting ecological and societal needs for freshwater. *Ecol Appl* 12(5):1247–1260. <https://doi.org/10.1890/1051-0761>
- Bhateria R, Jain D (2016) Water quality assessment of lake water: a review. *Sustain Water Resour Manag* 2:161–173. <https://doi.org/10.1007/s40899-015-0014-7>
- Chen CW, Ju YR, Chen CF, Dong CD (2016) Evaluation of organic pollution and eutrophication status of Kaohsiung Harbor, Taiwan. *Int Biodeterior Biodegrad* 113:318–324. <https://doi.org/10.1016/j.ibiod.2016.03.024>
- Chen Y (2021) Analysis on the evolution trend of seawater quality and eutrophication in Tianjin Hangu agricultural and fishery area from 2010 to 2019. In: *E3S Web of Conferences*, Vol. 245. EDP Sciences, p 02024. <https://doi.org/10.1051/e3sconf/202124502024>
- Das CR, Das S (2023) Assessment of surface water quality for drinking by combining three water quality indices with their usefulness: case of Damodar River in India. *Water Air Soil Pollut* 234(5):1–20. <https://doi.org/10.1007/s11270-023-06342-4>
- Dkhar EN, Dkhar PS, Anal JMH (2014) Trace elements analysis in drinking water of Meghalaya by using graphite furnace-atomic absorption spectroscopy and in relation to environmental and health issues. *J Chem* 2014. <https://doi.org/10.1155/2014/975810>
- Dufatanye I, Lee Y, Kim H, Lee S (2022) Industrial wastewater discharge and compliance investigation for environmentally resilient Rwanda. *Water* 14(19):3100. <https://doi.org/10.3390/w14193100>
- Dutta T, Chaudhuri H, Maji C (2021) Water pollution in Damodar River Basin—a statistical analysis. In *Advances in Water Resources Management for Sustainable Use*. Springer, Singapore, pp 187–215. https://doi.org/10.1007/978-981-33-6412-7_15
- El Baba M, Kayastha P, Huysmans M, De Smedt F (2020) Evaluation of the groundwater quality using the water quality index and geo-statistical analysis in the Dier al-Balah Governorate, Gaza Strip, Palestine. *Water* 12(1):262. <https://doi.org/10.3390/w12010262>
- Falowo OO, Akindureni Y, Ojo O (2017) Irrigation and drinking water quality index determination for groundwater quality evaluation in Akoko Northwest and Northeast areas of Ondo State, Southwestern Nigeria. *Am J Water Sci Eng* 3(5):50–60. <https://doi.org/10.11648/j.ajwse.20170305.11>
- Geldreich EE (1996) Pathogenic agents in freshwater resources. *Hydrol Process* 10(2):315–333. [https://doi.org/10.1002/\(SICI\)1099-1085\(199602\)10:2<315::AID-HYP361%3e3.0.CO;2-H](https://doi.org/10.1002/(SICI)1099-1085(199602)10:2<315::AID-HYP361%3e3.0.CO;2-H)
- George J, Thakur SK, Tripathi RC, Ram LC, Gupta A, Prasad S (2010) Impact of coal industries on the quality of Damodar river water. *Toxicol Environ Chem* 92(9):1649–1664. <https://doi.org/10.1080/02772241003783737>
- Ghosh AR, Banerjee R (2012) Qualitative evaluation of the Damodar River water flowing over the coal mines and industrial area. *Int J Sci Res Publ* 2(10):1–6
- Ghosh S, Sarkar B, Islam A, Shit PK, Quesada-Román A, Gazi HAR (2022a) Surface water and groundwater suitability for irrigation based on hydrochemical analysis in the Lower Mayurakshi River Basin, India. *Geosciences* 12(11):415. <https://doi.org/10.3390/geosciences12110415>
- Ghosh S, Hoque MM, Saha UD, Islam A (2022b) Assessment of dam-induced changes in ecogeomorphological behaviour and fluvial functionality in the Damodar River, West Bengal, India. *AQUA Water Infrastruct Ecosyst Soc* 71(6):722–750. <https://doi.org/10.2166/aqua.2022.003>
- Ha NN, Huong TTT, Van TT (2021) Surface water pollution risk from Vietnam water quality index (VN-WQI) in the Ca Mau City, Mekong Delta. *Nat Environ Pollut Technol* 20(4). <https://doi.org/10.46488/NEPT.2021.v20i04.007>
- Hoque MM, Islam A, Ghosh S (2022a) Environmental flow in the context of dams and development with special reference to the Damodar Valley Project, India: a review. *Sustain Water Resour Manag* 8(3):62. <https://doi.org/10.1007/s40899-022-00646-9>
- Hoque MM, Islam A, Mahammad S (2022b) Assessing the surface and bottom river water quality for drinking purpose and human health risk analysis: a study of Damodar River, India. *Arab J Geosci* 15(23):1734. <https://doi.org/10.1007/s12517-022-10987-6>
- Hoque MM, Islam A, Islam ARMT, Pal SC, Mahammad S, Alam E (2023) Assessment of soil heavy metal pollution and associated ecological risk of agriculture dominated mid-channel bars in a subtropical river basin. *Sci Rep* 13(1):11104. <https://doi.org/10.1038/s41598-023-38058-0>
- Hoque MM, Islam A, Sarkar B, Saha UD (2022c) Assessing the surface and bottom river water quality for irrigation: a study of Damodar River, India. *Int J Energy Water Resour* 1–18. <https://doi.org/10.1007/s42108-022-00206-z>
- Inyinbor Adejumoke A, Adebesein Babatunde O, Oluyori Abimbola P, Adelani Akande Tabitha A, Dada Adewumi O, Oreofe Toyin A (2018) Water pollution: effects, prevention, and climatic impact. *Water Challenges Urban World* 33:33–47. <https://doi.org/10.5772/intechopen.72018>
- Islam A, Sardar N, Mohinuddin S, Hoque MM, Sengupta S, Das BC, ... Sengupta B (2023) Quasi-equilibrium channel metamorphosis in planform of a subtropical river in India in post-dam period. *CATENA* 221:106793. <https://doi.org/10.1016/j.catena.2022.106793>
- Jayaswal K, Sahu V, Gurjar BR (2018) Water pollution, human health and remediation. *Water Remediat* 11–27. https://doi.org/10.1007/978-981-10-7551-3_2
- Karataş A, Karataş E (2016) Environmental education as a solution tool for the prevention of water pollution. *J Surv Fish Sci* 61–70. <https://doi.org/10.17762/sfs.v3i1.100>
- Leal MF, de Simone LRL, Lacerda ACF, da Silva EL, Pinheiro TG (2021) Current distribution of the invasive mollusk *Corbicula fluminea* (OF Müller, 1774) (Bivalvia, Cyrenidae) in Brazil, including a new record from the state of Piauí. *Check List* 17(1):151–157. <https://doi.org/10.15560/17.1.151>
- Li HM, Tang HJ, Shi XY, Zhang CS, Wang XL (2014) Increased nutrient loads from the Changjiang (Yangtze) River have led to increased harmful algal blooms. *Harmful Algae* 39:92–101. <https://doi.org/10.1016/j.hal.2014.07.002>
- Liu CW, Lin KH, Kuo YM (2003) Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. *Sci Total Environ* 313(1–3):77–89. [https://doi.org/10.1016/S0048-9697\(02\)00683-6](https://doi.org/10.1016/S0048-9697(02)00683-6)
- Liu S, Lou S, Kuang C, Huang W, Chen W, Zhang J, Zhong G (2011) Water quality assessment by pollution-index method in the coastal waters of Hebei Province in western Bohai Sea, China. *Mar Pollut Bull* 62(10):2220–2229. <https://doi.org/10.1016/j.marpolbul.2011.06.021>
- Mahammad S, Islam A, Shit PK (2022) Geospatial assessment of groundwater quality using entropy-based irrigation water quality index and heavy metal pollution indices. *Environ Sci Pollut Res* 1–24. <https://doi.org/10.1007/s11356-022-20665-5>

- Mezbour R, Reggam A, Maazi MC, Houhamdi M (2018) Evaluation of organic pollution index and the bacteriological quality of the water of the Lake of birds (ELTarf East-Algerian). *J Mater Environ Sci* 9(3):971–979. <https://doi.org/10.26872/jmes.2018.9.3.108>
- Mouhoumed EI, Abdillahi MMA, Elmi YM, Doubad CO, Dirieh EAN (2020) Classification of various bottled mineral waters marketed in Djibouti. *World J Eng Technol* 8(4):720–738. <https://doi.org/10.4236/wjet.2020.84052>
- Ochir A, Davaa G (2011) Application of index analysis to evaluate the water quality of the Tuul River in Mongolia. *J Water Resour Prot* 2011. <https://doi.org/10.4236/jwarp.2011.36050>
- Perret SR (2002) Water policies and smallholding irrigation schemes in South Africa: a history and new institutional challenges. *Water Policy* 4(3):283–300. [https://doi.org/10.1016/S1366-7017\(02\)00031-4](https://doi.org/10.1016/S1366-7017(02)00031-4)
- Rainwaterharvesting (2022) Pollution of River Damodar. Accessed on 2 March 2022. <http://www.rainwaterharvesting.org/Crisis/Damodar.htm>
- Sarkar B, Islam A (2019) Assessing the suitability of water for irrigation using major physical parameters and ion chemistry: a study of the Churni River, India. *Arab J Geosci* 12:1–16. <https://doi.org/10.1007/s12517-019-4827-9>
- Sarkar B, Islam A, Majumder A (2021a) Seawater intrusion into groundwater and its impact on irrigation and agriculture: evidence from the coastal region of West Bengal, India. *Reg Stud Mar Sci* 44:101751. <https://doi.org/10.1016/j.rsma.2021.101751>
- Sarkar B, Islam A, Das BC (2021b) Role of declining discharge and water pollution on habitat suitability of fish community in the Mathabhanga-Churni River, India. *J Clean Prod* 326:129426. <https://doi.org/10.1016/j.jclepro.2021.129426>
- Sarkar B, Islam A, Shit PK, Ghosh S (2022) Assessment of water pollution and aquatic toxicity of the Churni River, India. *River Health Ecol South Asia: Pollution, Restoration, and Conservation* 303–327. https://doi.org/10.1007/978-3-030-83553-8_13
- Singh AK, Mondal GC, Kumar S, Singh TB, Tewary BK, Sinha A (2008) Major ion chemistry, weathering processes and water quality assessment in upper catchment of Damodar River basin, India. *Environ Geol* 54(4):745–758. <https://doi.org/10.1007/s00254-007-0860-1>
- Singh A, Deo B, Singh SP (2014) Risk analysis on the use of Damodar river water for drinking purposes. *Inte J Curr Eng ogy* 4(1):560
- Singh RK, Chaturvedi A, Kumari K (2019) Water-quality assessment of Damodar River and its tributaries and subtributaries in Dhanbad Coal mining areas of India based on WQI. *Sustain Water Resour* 5:381–386. <https://doi.org/10.1007/s40899-017-0159-7>
- Some S, Mondal R, Mitra D, Jain D, Verma D, Das S (2021) Microbial pollution of water with special reference to coliform bacteria and their nexus with environment. *Energy Nexus* 1:100008. <https://doi.org/10.1016/j.nexus.2021.100008>
- Son CT, Giang NTH, Thao TP, Nui NH, Lam NT, Cong VH (2020) Assessment of Cau River water quality assessment using a combination of water quality and pollution indices. *J Water Supply Res Technol AQUA* 69(2):160–172. <https://doi.org/10.2166/aqua.2020.122>
- Sulthonuddin I, Hartono DM, Said CAA, Utomo SW (2019) River water pollution indication in the Cimanuk river downstream, Indramayu District. In: IOP Conference Series: Earth and Environmental Science, 239(1):012010, IOP Publishing. <https://doi.org/10.1088/1755-1315/239/1/012010>
- Sunitha V, Reddy YS, Suvarna B, Reddy BM (2021) Human health risk assessment (HHRA) of fluoride and nitrate using pollution index of groundwater (PIG) in and around hard rock terrain of Cuddapah, AP South India. *Environ Chem Ecotoxicol* 4:113–123. <https://doi.org/10.1016/j.enceco.2021.12.002>
- Thi Minh Hanh P, Sthiannopkao S, The Ba D, Kim KW (2011) Development of water quality indexes to identify pollutants in Vietnam's surface water. *J Environ Eng* 137(4):273–283. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0000314](https://doi.org/10.1061/(ASCE)EE.1943-7870.0000314)
- WBPCB (2022) Water Quality: West Bengal Pollution Control Board Water Quality Information System. Accessed 2 June 2022. <https://www.wbpcb.gov.in/>
- WBPCB (2023) Surface Water Quality Criteria: West Bengal Pollution Control Board Water Quality Information System. Accessed 15 December 2023. <https://www.wbpcb.gov.in/>

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

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.