

Water Quality and Seasonal Variability of the Mand River of Chhattisgarh, India, Using WQI and its Implications for Catchment Management

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Abstract:

Rivers are vital for maintaining their ecological balance, supplying water for human use and supporting the livelihoods of the people living within their watersheds. The Mand River is a tributary of the Mahanadi in central India. This study aims to evaluate the seasonal water quality of the Mand River utilizing the Water Quality Index (WQI).

The Mand River was the subject of a study employing a comprehensive approach, including field data collection, laboratory analysis, and GIS techniques. The water quality of the Mand River was evaluated using the Water Quality Index (WQI) at 11 monitoring locations throughout the monsoon, winter, and summer seasons comprising two cycles from the monsoon of 2022 to the summer of 2024. The measures of water quality include eight physico-chemical parameters. The parameters are related via Pearson correlation to identify the relationship. A comparison of water quality measures was conducted both site-wise and seasonally. The findings indicated considerable regional and temporal variability, demonstrating the impact of seasonal fluctuations and anthropogenic activities on the river's condition. Monsoon seasons consistently demonstrate the lowest water quality owing to pollutant-laden runoff. Conversely, winter seasons frequently show superior water quality owing to less runoff, lower temperatures, and higher dissolved oxygen concentrations. Summer circumstances indicate reasonable water quality at several locations, although underscore issues related to low flow and concentrated pollutants. Site-specific patterns indicated that crucial locations, such as S-9, S-10, and S-11, continuously exhibited poor water quality over all seasons and cycles, signifying ongoing pollution issues. The enhancement of sites S-5 and S-6 exhibited reasonably constant or improved trends,

indicating localized recovery. The WQI-based evaluation highlights the combined issues of seasonal fluctuations and localized contamination. While some sites show potential for recovery, persistent issues at critical locations must be addressed to ensure the long-term health and sustainability of the river.

Key Words: Water Quality Assessment, Temporal Variability, Surface Water Quality, Water Pollution

Introduction:

Rivers are essential for ecological health, providing water supplies for human use and sustaining the lives of populations within their watersheds (Madilonga et al., 2021). Globally, rivers have escalating risks from pollution, alterations in land use, and climatic variability, which can affect water quality and ecosystem health (Shil et al., 2019). The Mand River, situated in a fast-growing area, exhibits the need to study its water quality dynamics for successful watershed management.

In India, expanding agricultural, mining and industrial activity is subjecting rivers to rising anthropogenic pressures that affect water quality. The Mand River, a tributary of Mahanadi in central India, serves as a crucial freshwater supply for residential, agricultural, and industrial applications. Nonetheless, increasing land-use alterations and pollution from several sources impact water quality, which could threaten ecological integrity and human health (Bajpai et al., 2019; Khan et al., 2021).

Water quality is a measure that includes several physical, chemical, and biological attributes. These characteristics may vary considerably across geographical and temporal dimensions, affected by factors such as human activities, natural phenomena, and seasonal changes (Jonnalagadda & Mhere, 2001; Kumarasamy & Macholo, 2018; Shil et al., 2019; Lkr et al., 2020). Using a water quality index facilitates a comprehensive evaluation of water quality by consolidating several parameters into a single numeric value, which may then be utilized to determine the suitability of water for diverse applications, including irrigation, domestic consumption, and ecosystem preservation. (Jonnalagadda & Mhere, 2001; Shil et al., 2019)

The Water Quality Index (WQI) is an effective instrument for simplifying complex water quality data into a single composite score that represents overall water quality (Sutadian et al., 2015). This index facilitates water quality assessment by integrating many indicators, including pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), and nutrient levels, into a unified rating. Analyzing seasonal variations using the Water Quality Index (WQI) explains the relationship between water quality fluctuations and environmental factors, including precipitation, agricultural runoff, and wastewater discharge, which exhibit considerable differences between dry and wet seasons (Ouyang et al., 2006; Banerjee & Srivastava, 2009).

Understanding the seasonal fluctuations in the Mand River's water quality is essential for efficient watershed management. Identifying patterns and crucial periods of water quality

deterioration can guide management methods that effectively target pollution sources (Giao et al., 2021). This study aims to assess the seasonal water quality of the Mand River by calculating the Water Quality Index (WQI) at various times throughout the year. This study aims to analyze the effects of seasonal fluctuations on watershed management to promote sustainable practices that improve the health of river ecosystems and safeguard water resources for residents. The results can assist stakeholders in formulating policies and management strategies that consider both natural and anthropogenic alterations in water quality.

Material and Method:

Study Area

The Mand River is a significant tributary of the Mahanadi, located in the northern part of Chhattisgarh, India, and the catchment area contributes around 7.35% to the Mahanadi basin. It is situated between the latitudes of $21^{\circ}42'6.27''\text{N}$ and $23^{\circ}4'2.86''\text{N}$, and the longitudes of $82^{\circ}50'32.31''\text{E}$ and $83^{\circ}36'14.78''\text{E}$ (Fig. 1). The study area has an elevation ranging from 125 m to 1088 m above mean sea level. The total length of the Mand River is around 240 km, with a catchment area of 5331.44 km².

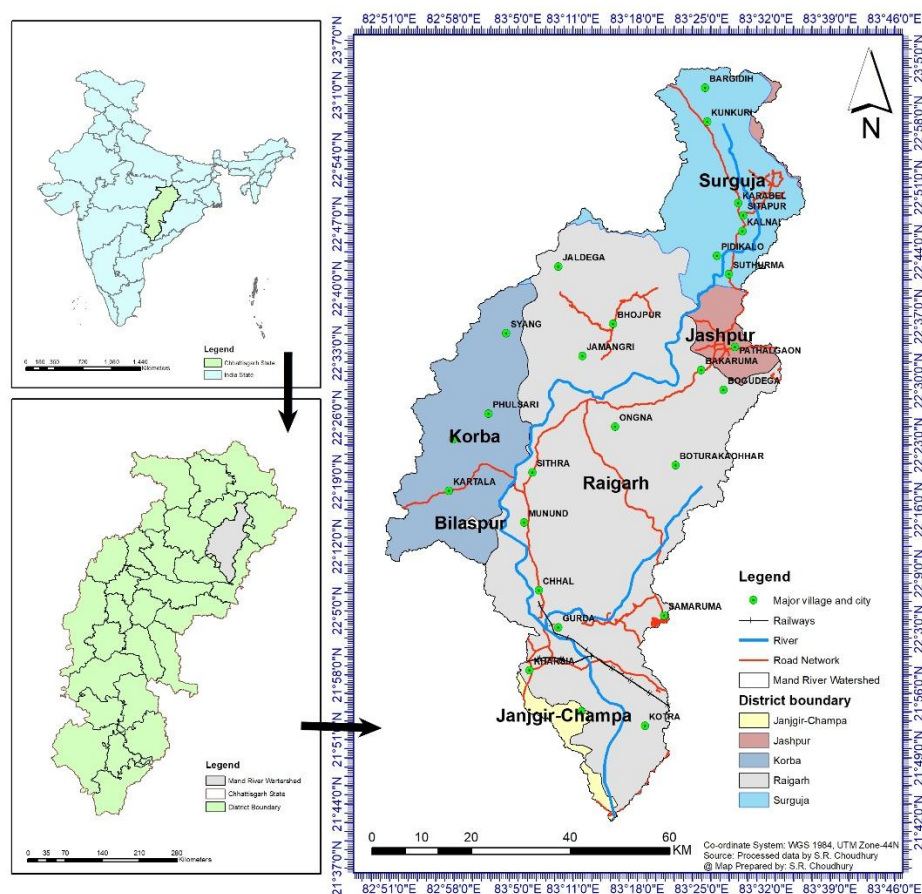


Figure.1 Map of the Mand River and its Catchment area

The Mand River originates close to Bargidih Village, located in Surguja district. The river passes through areas of five districts, namely Surguja, Jashpur, Raigarh, Korba, and Janjgir-Champa, but it is largely situated in the Raigarh district (Fig.1). It converges with the Mahanadi in the eastern region of Janjgir-Champa at Chandrapur, adjacent to the Orissa border.

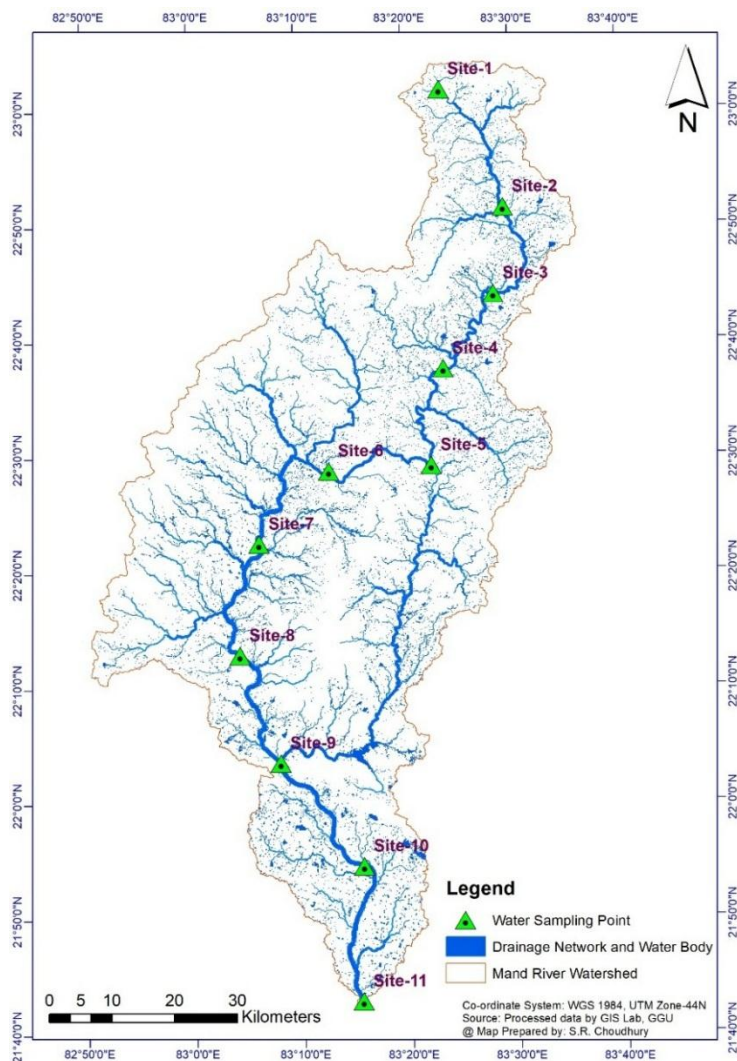


Figure.2 Drainage map of the Mand River with Water sampling Site along the Mand River

The Mand River has a subtropical monsoon climate with three distinct seasons: summer, monsoon, and winter. The southwest monsoon starts in June and continues until mid-September, whereas the winter season extends from October to February (Chandran et al., 2019). The summer season extends from March to mid-June. The research region saw an average annual precipitation of 1192.1 mm, predominantly attributed to the southwest monsoon, which serves as the primary source of groundwater recharge. The peak average temperature of 42.5 °C occurred in May, while the minimum of 8.2 °C was seen in January.

The region receives an average annual precipitation of 1,382.12 millimeters, predominantly during the southwestern monsoon season, which serves as the primary source of groundwater recharge. The Mand River area is characterized by a diverse landscape comprising dense forests, agricultural lands, and water bodies. The dominant land use and land cover in the river region consists of forest, agricultural land, and barren terrain.

Water Sampling and Analysis

The study evaluates the water quality of the Mand River watershed by field measurements, laboratory analyses, and spatial assessment techniques. A systematic approach was employed to ensure comprehensive data collection and analysis, facilitating an understanding of the river condition and the impact of land use patterns. The comprehensive methodological framework of the study includes site selection, water quality analysis, statistical evaluation, and impact assessment (Fig. 3).

Site Selection and Sampling Frequency

The Mand River has a total length of around 240 kilometers. For the physico-chemical water quality assessment, eleven sample locations were designated at regular intervals ($23 \text{ km} \pm 5 \text{ km}$) along the river (Fig. 2 & Table 1). The locations were geotagged, and seasonal water sampling was conducted over two cycles from the monsoon of 2022 to the summer of 2024. Water samples were taken thrice annually: pre-monsoon, monsoon, and post-monsoon, to document seasonal fluctuations in water quality (Table 2). The study was designed to be conducted over two years to observe long-term trends.

Table 1. Sampling site location along the Mand River watershed

Sampling Site	Nearest Locality	GPS	Cumulative Distance
Site-1	Bargidihi	23°1'40.94"N 83°23'34.12"E	0.0 km
Site-2	Vishnupur	22°51'25.69"N 83°29'23.30"E	28 km
Site-3	Radhapur	22°43'56.32"N 83°28'23.98"E	50.5 km
Site-4	Kilkila villege	22°37'29.86"N 83°23'37.36"E	73.5 km
Site-5	Near Nonaijor	22°29'7.35"N 83°22'22.67"E	97.5 km
Site-6	Dharamjaygarh bridge	22°28'43.27"N 83°12'49.51"E	120 km
Site-7	Khadgaon	22°22'28.00"N 83°6'16.03"E	145.5 km
Site-8	Barbaspur Villege	22°12'49.41"N 83° 4'20.99"E	168.5 km
Site-9	Lower to Edu Bridge	22° 3'26.59"N 83° 8'1.05"E	191 km
Site-10	Labeda Villege	21°54'26.69"N 83°15'37.10"E	214.5 km
Site-11	Chandrapur	21°42'44.52"N 83°15'25.67"E	238.5 km

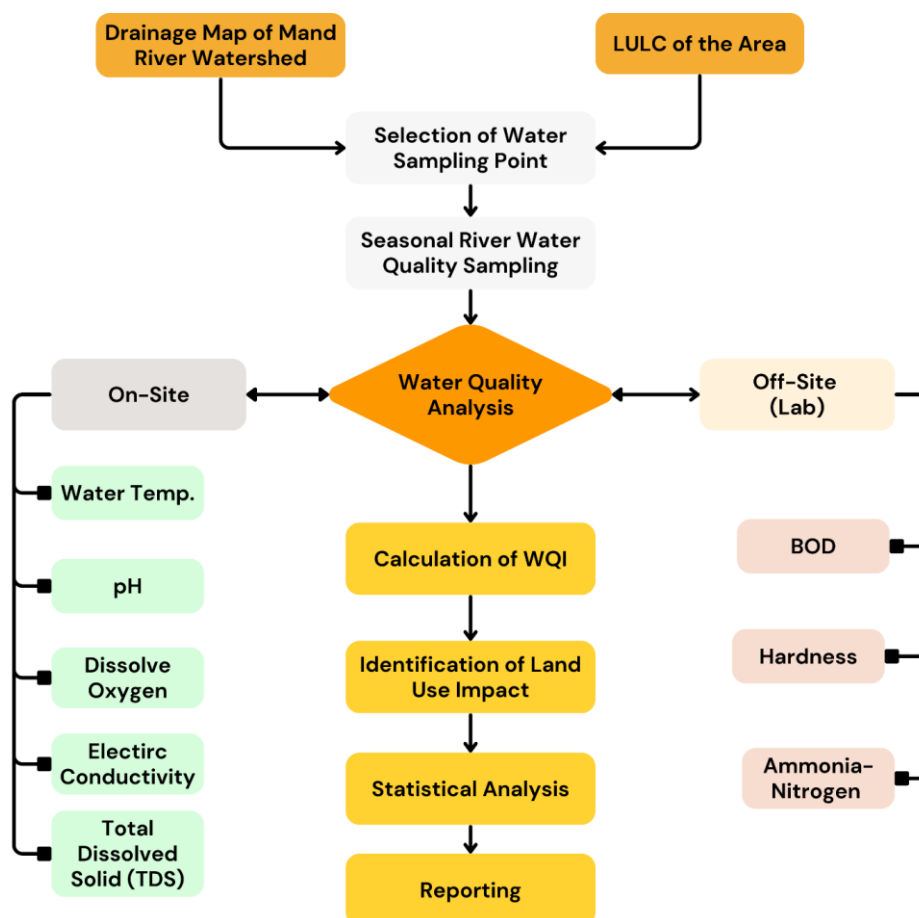


Figure.3 Detailed methodology of the study

Water Sample Collection and Analysis

Water samples were obtained at the designated sampling stations. Water collection occurs only from the flowing section of the river during all seasons, from the same site and methodology. In summer, four sampling sites, S1 to S4, having water in pit holes in the upper catchment, have not been considered for water quality assessment due to the absence of running water. Pre-cleaned plastic water bottles were utilized for the on-site assessment of water parameters. Furthermore, water samples were gathered in pre-cleaned, sterile, air-tight 1-liter plastic bottles and 300 ml borosilicate glass BOD bottles, then conveyed to the laboratory for examination.

On-site, the water quality parameters of pH, temperature, electrical conductivity, dissolved oxygen, and total dissolved solids were assessed using a portable digital Hanna HI98194 multiparameter device. Supplementary water quality measures, such as biochemical oxygen demand, hardness, and ammonia-nitrogen, were examined in the laboratory following standardized procedures.

Table 2. List of seasons in the Mand River

Season	Months	The character of River in season	Water quality is influenced by
Pre-Monsoon (Summer)	March, April, May, June	High temperatures and low water levels	evaporation and anthropogenic activities
Monsoon	July, August, September, October	increased river discharge and changes in water quality	runoff, sediment transport, and dilution of pollutants
Post-Monsoon (Winter)	November, December, January, February	Levels begin to recede, and the water becomes clearer, lower temperatures and reduced river discharge compared to the monsoon season	water quality recovery of rivers from the effects of increased flow and sedimentation. reduced flow, increased solar radiation

Water Quality Index (WQI)

The Water Quality Index (WQI) is a tool used to summarize large amounts of water quality data into a single, easily understandable score that reflects the overall water quality (Godwin & Oborakpororo, 2019; Tyagi et al., 2020). It is extensively utilized for monitoring aquatic ecosystems, evaluating environmental integrity, and conveying water quality information to the public and policymakers. This index offers a comprehensive assessment of the safety of water for drinking, swimming, or irrigation, enabling comparisons of water quality across various places throughout time (Table-3) (VishnuRadhan et al., 2015; Xie et al., 2021).

The Water Quality Index (WQI) was computed using the weighted arithmetic index approach (Brown et al., 1972). Evaluating many physicochemical characteristics like as pH, total dissolved solids, electrical conductivity, hardness, biochemical oxygen demand, and ammonia-nitrogen (Table-2).

Each measured parameter value is compared to its ideal or standard value to generate a **quality rating scale (Q_n)**. The quality rating for each parameter is calculated as follows:

$$Q_n = \left(\frac{V_0 - V_i}{V_s - V_i} \right) \times 100$$

Where:

Q_n = Quality rating of the nth parameter

V₀ = Observed value of the parameter from the sample

V_i = Ideal value (0 for all parameters except pH, where it is 7; DO, where it is 14.6)

V_s = Standard permissible value as per Bureau of Indian Standards (BIS) (2012)/WHO (2011) standard

Each parameter is assigned a **weight** based on its relative importance to overall water quality. Higher weights are assigned to more critical parameters. The unit weight (W_n) is calculated as:

$$W_n = \frac{k}{V_n}$$

Where:

W_n = Unit weight of the nth parameter

k = Constant proportionality factor

$$k = \frac{1}{\sum (1/V_s)}$$

V_n = Standard permissible value of the nth parameter

For each parameter, the sub-index (S_n) is calculated by multiplying the quality rating (Q_n) by the unit weight (W_n):

$$S_n = Q_n \times W_n$$

The overall **WQI** is the sum of all sub-indices divided by the sum of the unit weights:

$$WQI = \frac{\sum(S_n)}{\sum(W_n)}$$

Classification of WQI

After calculating the WQI, the data were compared to the quantitative category described in water quality.

Table 3. Water quality parameters and its standard for Drinking Water

S. No.	Parameter	Abbreviation	Drinking Water Standard
1	Temperature	T	40°C
2	pH	pH	6.5-8.5
3	Dissolved Oxygen	DO	>6 mg/L
4	Electrical Conductivity	EC	300 µS/cm
5	Total Dissolved Solids	TDS	500 mg/L
6	Biochemical Oxygen Demand	BOD	<3 mg/L
7	Hardness	H	200 mg/L
8	Ammonia (NH ₃ -N)	NH ₃ -N	<0.5 mg/L

Table 4. WQI standard and its portable usage of water

WQI Range	Water Quality	Description	Probable usage
0-25	Excellent	Water quality is ideal for all purposes	Drinking, irrigation, and industrial purpose
26-50	Good	Water quality is acceptable	Drinking, irrigation, and industrial purpose
51-75	Fair	Water is moderately polluted	Irrigation and industrial purpose
76-100	Poor	Water is highly polluted	For irrigation purpose
>100	Very Poor	Water is unfit for human consumption/uses	Proper treatment required for any kind of usage

The Water Quality Index (WQI) and additional water quality data were examined with Microsoft Excel to evaluate the variability and interrelationships within the research region. Seasonal water availability was also taken into account while analyzing the data. The influence of industrial, agricultural, and urban activities along the river was analyzed to assess their possible effects on water quality. The maps and some GIS analysis were done using ArcGIS 10.4 and QGIS 3.34.5

This study offers a comprehensive evaluation of the water quality dynamics in the Mand River catchment by combining diverse data sources and analytical methodologies, while also examining its connections to adjacent land use patterns. This information can enable targeted efforts to reduce water pollution and promote sustainable management of river ecosystems.

Result and Discussion:

Physicochemical water quality analysis

Water temperature is an essential physical parameter in river ecosystems, influencing aquatic life. Moreover, temperature influences dissolved oxygen (DO), the physicochemical properties of water, and the rate of biodegradation (Thomas, 2021). High solar radiation can elevate water temperature and enhance the rate of photosynthesis in aquatic environments (Bao et al., 2020; Hamid et al., 2019). The water quality at all sample locations (S1 to S11) exhibits a temperature range of 17.8 °C to 36.8 °C, consistent with the WHO recommended parameters (Table 4 & Fig. 5.A). The peak temperature occurs in the pre-monsoon period, while the minimum temperature is observed in the post-monsoon period. Krishan et al. (2022) also report the similar findings in the Gomati River in Lucknow, India. The surface water temperature typically fluctuates with variations in ambient temperature and daily solar radiation. A moving water body, such as a river, can modulate and stabilize water temperature (Das et al., 2022; Kushwaha et al., 2021). Forest cover, water depth, and riverbed are crucial factors in temperature control (Ozaki et al., 2003).

The pH of the water sample reflects its overall acidity and alkalinity. The pH level is essential for the aquatic ecosystem (Aziz et al., 2020). BSI-2012 stipulates that the permissible pH range

is 6.5 to 8.5. All sample locations (S1-S11) had pH values between 6.89 and 9.14, indicating a range from near neutral (pH=7) to mildly alkaline. The minimum pH is recorded in S-8, whereas the maximum pH of 9.14 is observed in S-10 (Table 4 & Fig. 5.B). In natural water bodies, carbonate, bicarbonate, and carbon dioxide are the governing variables of pH. The release of urban sewage, comprising soap and detergent, may be attributed to the elevated alkalinity of river water (Feng et al., 2017).

Electrical conductivity (EC) quantifies a water sample's capacity to conduct electric current, indicating the quantity of dissolved ions (McCleskey et al., 2011). This research recorded EC values at eleven sample locations (S1 to S11), with the following ranges: 104.00-275.00 $\mu\text{S/cm}$ at S1, 120.00-244.00 $\mu\text{S/cm}$ at S2, 84.00-244.00 $\mu\text{S/cm}$ at S3, 93.0-232.0 $\mu\text{S/cm}$ at S4, 94.0-312.0 $\mu\text{S/cm}$ at S5, 97.0-306.0 $\mu\text{S/cm}$ at S6, 87.0-343.2 $\mu\text{S/cm}$ at S7, 102.0-368.0 $\mu\text{S/cm}$ at S8, 93.0-523.0 $\mu\text{S/cm}$ at S9, 128.0-392.0 $\mu\text{S/cm}$ at S10, and 168.0-489.0 $\mu\text{S/cm}$ at S11 (Table-4 & Fig. 6.A). The Bureau of Indian Standards (BIS, 2012) prescribes a permissible maximum of 300 $\mu\text{S/cm}$ for electrical conductivity (EC) for drinking water. Significant seasonal electrical conductivity (EC) variation is evident seasonally and across different locations. The stations S1 to S4 demonstrated comparatively lower EC values, presumably attributable to the semi-green vegetation cover in the region, which reduces topsoil erosion. Conversely, the peak EC values were recorded in the summer at stations S8 to S11, likely attributable to sewage flows and heightened human activity along the riverbanks. A noticeable pattern was noted, with downstream stations exhibiting elevated EC values compared to upstream stations, as illustrated in Figure 5C.

Total Dissolved Solids (TDS) is quantifying dissolved particles in a water sample via direct assessment. From 2022 to 2024, TDS concentrations at the sample stations were documented as follows: 67.0-179.0 mg/L at S1, 78.0-158.0 mg/L at S2, 54.0-158.0 mg/L at S3, 60.0-150.0 mg/L at S4, 61.0-202.0 mg/L at S5, 63.0-198.0 mg/L at S6, 56.0-222.0 mg/L at S7, 66.0-239.0 mg/L at S8, 60.0-339.0 mg/L at S9, 83.0-254.0 mg/L at S10, and 109.0-317.0 mg/L at S11 (Table-4 & Fig. 6.A). The Bureau of Indian Standards (BIS, 2012) specifies that the permissible maximum for Total Dissolved Solids (TDS) is 500 mg/L for drinking water. All Stations S1 to S11 remained inside this limit. The minimum TDS values were noted at S2, whilst the maximum was documented at S9 (Table 4 & Fig. 5.A). The rising trend in TDS from S1 to S7 is attributable to elevated population density and related activities, including the discharge of solid waste, agricultural residue, wastewater, sewage, and encroachment. However, rivers are frequently exploited as disposal sites for garbage, resulting in substantial pollution and increased total dissolved solids (TDS) concentrations. This leads to unhygienic environments and heightens health hazards, particularly waterborne communicable infections.

The total hardness (TH) of river water primarily results from dissolved calcium (Ca^{++}) and magnesium (Mg^{++}) ions, as well as other divalent cations, quantified in mg/l as CaCO_3 . The ions mostly derive from the adjacent geological formations of the water bodies (Lkr et al., 2020). The maximum TH levels during the investigation were noted at station S9, at 151 mg/l, whilst the minimum values were recorded at station S5, at 31.1 mg/l (Table 4 & Fig. 6.C). All measured TH concentrations were beneath the Bureau of Indian Standards (BIS) suggested threshold of 300 mg/l (BIS, 2012). The Mand River water is classified as mild to moderately

hard based on TH levels. Typically, river water exhibits lower total hardness than groundwater.

Dissolved oxygen (DO) levels in aquatic environments indicate the overall quantity of oxygen present, affected by physical, chemical, and biological activities (Walsh, 2022). Estimating dissolved oxygen is essential for evaluating water quality, especially in pollution management (Soumaila et al., 2019). The Bureau of Indian Standards (BIS, 2012) recommends a dissolved oxygen level of 5 mg/l to sustain aquatic life. A water body is deemed contaminated when its dissolved oxygen content drops below this level.

In the study, dissolved oxygen (DO) values at sampling stations S1 to S11 varied as follows: 6.12–8.51 mg/l, 6.20–8.31 mg/l, 6.2–8.31 mg/l, 5.34–8.34 mg/l, 3.98–10.12 mg/l, 3.69–8.57 mg/l, 3.26–8.62 mg/l, 4.89–7.88 mg/l, 4.21–7.21 mg/l, 3.97–7.31 mg/l, and 3.80–8.02 mg/l, respectively (Table-4 & Fig. 5.C). Minimum dissolved oxygen levels recorded throughout summer were significantly below the recommended 5 mg/l across all locations. The four higher catchment locations are arid throughout the summer season, resulting in the absence of data during the pre-monsoon period. The reduced dissolved oxygen levels were attributed to elevated organic loads, drainage discharges, and religious activities near the riverbanks. Temperature fluctuations significantly influenced dissolved oxygen dynamics. Increased summer temperatures decreased oxygen solubility in water and affected the metabolic activity, growth, and reproduction of bacteria responsible for organic matter decomposition (Rajwa-Kuligiewicz et al., 2015; Susilowati et al., 2018).

Biochemical oxygen demand (BOD) denotes the total oxygen that aerobic bacteria necessitate to digest biodegradable organic matter in an aquatic environment (Prambudy et al., 2019). It is a metric for organic pollution, with elevated BOD levels indicating increased pollution (Bora & Goswami, 2017). BOD values beyond 5 mg/l are deemed unfavorable.

Throughout the study, BOD levels exhibited variability across sampling stations, with measurements ranging from 2.12 to 4.12 mg/l at S1, 1.48 to 3.16 mg/l at S2, 1.48 to 3.22 mg/l at S3, 2.13 to 3.81 mg/l at S4, 2.17 to 5.16 mg/l at S5, 1.83 to 5.21 mg/l at S6, 1.63 to 6.12 mg/l at S7, 4.89 to 7.88 mg/l at S8, 4.21 to 7.21 mg/l at S9, 3.97 to 7.31 mg/l at S10, and 3.80 to 8.02 mg/l at S11 (refer to Table 4 and Figure 6.B). The Bureau of Indian Standards (BIS, 2012) reported that the maximum BOD readings from S6 to S11 throughout the investigation were above permissible limits and exhibited an increasing trend from S1 to S11. Increased BOD levels at all sample sites suggest a potential for organic contamination, mostly attributed to the discharge of untreated organic waste and religious practices along the riverbanks in the lower catchment area. Factors contributing to elevated BOD encompass diminished dissolved oxygen (DO), augmented total dissolved solids (TDS), excessive waste output, and inadequate water flow.

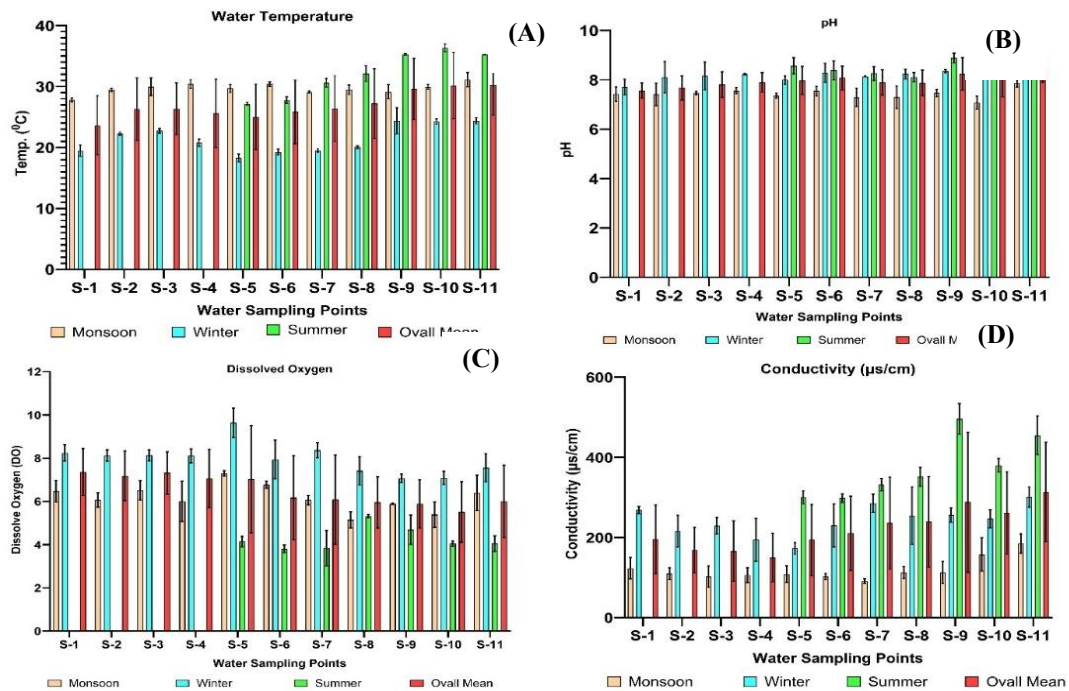


Figure.4 A, Water Temperature; B, pH; C, Dissolved Oxygen; D, Conductivity

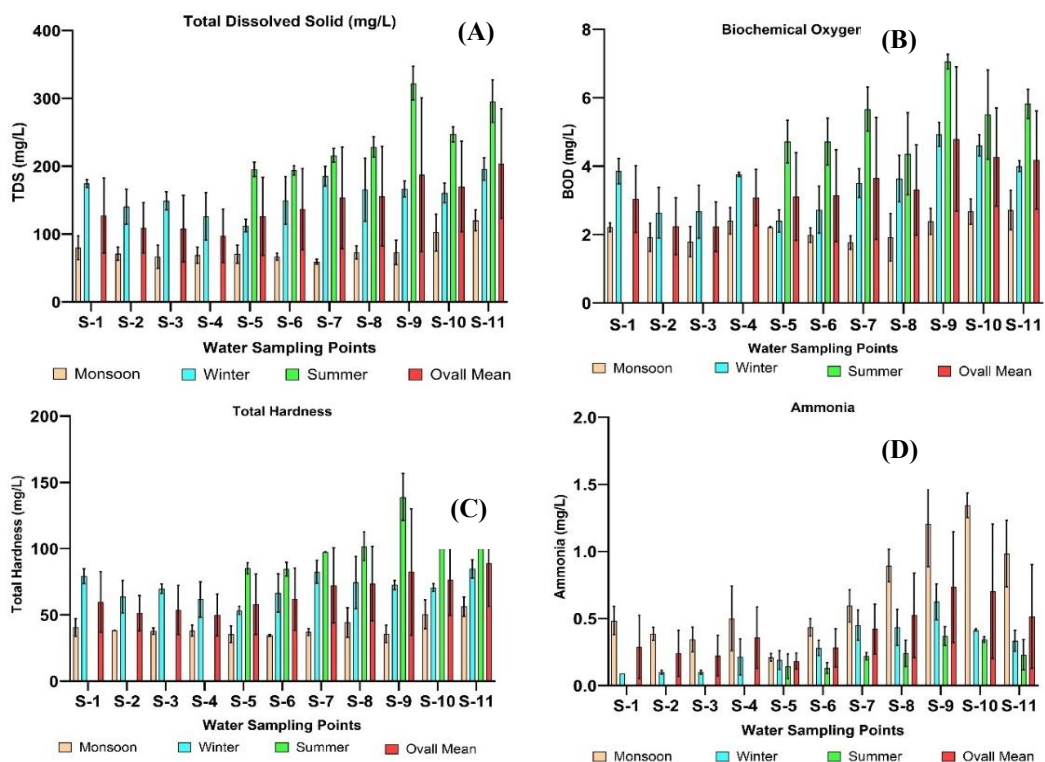


Figure.5 A, TDS; B, BOD; C, Total Hardness; D, Ammonia

The concentration of ammonia ($\text{NH}_3\text{-N}$) in water is a crucial indication of pollution, predominantly resulting from agricultural runoff, sewage, and industrial effluents. Increased ammonia concentrations can harm aquatic organisms and disturb the ecological equilibrium (Phiri et al., 2005). The Bureau of Indian Standards (BIS, 2012) stipulates a maximum allowable ammonia content of 0.5 mg/l for surface water.

In this study, ammonia concentrations at the sampling stations varied as follows: S1: 0.09–0.56 mg/l, S2: 0.09–0.41 mg/l, S3: 0.09–0.41 mg/l, S4: 0.12–0.67 mg/l, S5: 0.08–0.24 mg/l, S6: 0.10–0.48 mg/l, S7: 0.20–0.68 mg/l, S8: 0.17–0.98 mg/l, S9: 0.32–1.43 mg/l, S10: 0.33–1.41 mg/l, and S11: 0.15–1.16 mg/l (Table-4 & Fig. 6.D). The maximum ammonia content (1.41 mg/l) was documented at S10, and the minimum (0.09 mg/l) was noted at S5.

Ammonia concentrations above the acceptable threshold at many locations, notably S7 to S11, signifying significant pollution. The data indicate a gradual increase in ammonia levels from S1 to S11 during this study period. Possible sources are untreated sewage, agricultural runoff with fertilizers, and effluent discharge from adjacent communities and enterprises.

Increased ammonia levels during summer and low water flow seasons may result from less dilution capacity and heightened temperatures, which expedite the decomposition of organic waste and release ammonia into the water. The breakdown of organic waste and deceased living matter along the riverbanks certainly elevated ammonia levels.

Table 5. Detail of water quality parameters in all the sites (N=6)

	T	pH	DO	EC	TDS	BOD	H	NH₃-N
Site-1								
Min	18.82	7.21	6.12	104.00	67.60	2.12	35.80	0.09
Max	28.05	7.93	8.51	275.00	178.75	4.12	83.21	0.56
Mean	23.65	7.57	7.36	195.75	127.24	3.04	59.88	0.29
SD	4.85	0.30	1.09	85.59	55.63	0.97	22.93	0.24
Site-2								
Min	22.10	7.09	6.20	120.00	78.00	1.48	38.30	0.09
Max	30.98	8.56	8.31	244.00	158.60	3.16	72.40	0.41
Mean	26.29	7.68	7.19	168.25	109.36	2.24	51.38	0.24
SD	5.15	0.49	1.15	57.13	37.13	0.83	13.43	0.17
Site-3								
Min	22.44	7.41	6.20	84.00	54.60	1.48	36.20	0.09
Max	30.98	8.56	8.31	244.00	158.60	3.22	72.40	0.41
Mean	26.33	7.81	7.33	166.00	107.90	2.23	53.85	0.22
SD	4.27	0.52	0.98	75.79	49.27	0.72	18.59	0.15
Site-4								
Min	20.36	7.48	5.34	93.00	60.45	2.13	35.20	0.12

<i>Max</i>	30.92	8.25	8.34	232.00	150.80	3.81	71.20	0.67
<i>Mean</i>	25.60	7.90	7.06	150.00	97.50	3.09	49.98	0.36
<i>SD</i>	5.59	0.39	1.35	60.47	39.31	0.82	15.82	0.23
Site-5								
<i>Min</i>	17.81	7.29	3.98	94.00	61.10	2.17	31.10	0.08
<i>Max</i>	30.12	8.80	10.12	312.00	202.80	5.16	88.21	0.24
<i>Mean</i>	25.03	7.98	7.03	194.00	126.10	3.11	58.05	0.18
<i>SD</i>	5.37	0.57	2.49	88.40	57.46	1.29	22.77	0.06
Site-6								
<i>Min</i>	18.93	7.41	3.69	97.00	63.05	1.83	34.10	0.10
<i>Max</i>	30.68	8.66	8.57	306.00	198.90	5.21	88.20	0.48
<i>Mean</i>	25.83	8.07	6.18	210.33	136.72	3.14	61.92	0.28
<i>SD</i>	5.22	0.49	1.95	92.34	60.02	1.34	23.63	0.14
Site-7								
<i>Min</i>	19.32	7.03	3.26	87.00	56.55	1.63	35.20	0.20
<i>Max</i>	31.09	8.46	8.62	343.00	222.95	6.12	97.60	0.68
<i>Mean</i>	26.40	7.90	6.09	236.00	153.40	3.65	72.35	0.42
<i>SD</i>	5.40	0.52	2.07	114.95	74.72	1.78	28.40	0.18
Site-8								
<i>Min</i>	19.88	6.98	4.89	102.00	66.30	1.43	36.50	0.17
<i>Max</i>	33.03	8.38	7.88	368.00	239.20	5.21	109.50	0.98
<i>Mean</i>	27.22	7.88	5.96	239.50	155.68	3.31	73.58	0.52
<i>SD</i>	5.72	0.51	1.18	112.84	73.34	1.32	28.07	0.31
Site-9								
<i>Min</i>	22.89	7.36	4.21	93.00	60.45	2.12	31.20	0.32
<i>Max</i>	35.38	9.03	7.21	523.00	339.95	7.21	151.50	1.43
<i>Mean</i>	29.60	8.24	5.89	288.17	187.31	4.79	82.47	0.73
<i>SD</i>	5.00	0.65	1.11	174.78	113.60	2.11	47.57	0.41
Site-10								
<i>Min</i>	23.92	6.89	3.97	128.00	83.20	2.41	42.80	0.33
<i>Max</i>	36.81	9.14	7.31	392.00	254.80	6.43	111.70	1.41
<i>Mean</i>	30.18	8.23	5.52	261.50	169.98	4.26	76.73	0.70
<i>SD</i>	5.44	0.93	1.40	102.64	66.72	1.44	27.11	0.50
Site-11								
<i>Min</i>	24.03	7.76	3.80	168.00	109.20	2.31	51.20	0.15
<i>Max</i>	35.28	8.88	8.02	489.00	317.85	6.12	136.50	1.16
<i>Mean</i>	30.24	8.32	6.01	313.67	203.88	4.18	89.13	0.52
<i>SD</i>	4.94	0.42	1.67	124.03	80.62	1.43	32.45	0.39

Correlation analysis:

The Pearson correlation matrix illustrates the interconnections among nine essential water quality parameters: temperature (T), pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD), total hardness (TH), and ammonia nitrogen ($\text{NH}_3\text{-N}$) from 2022 to 2024 (Table 6).

Temperature demonstrated a significant negative relationship with dissolved oxygen (DO) (-0.80), suggesting that elevated water temperatures diminish oxygen solubility, a prevalent occurrence in aquatic environments (Rajesh & Rehana, 2022). It showed low to moderate positive relationships with other parameters, including BOD (0.23) and TH (0.20), indicating that elevated temperatures may affect the concentration of these pollutants. The pH exhibited a strong positive connection with EC (0.78), TDS (0.78), BOD (0.77), and TH (0.76), suggesting that elevated pH levels correlate with heightened ion concentrations and organic contamination. However, it displayed a weak negative correlation with dissolved oxygen (DO) of -0.15, indicating that minor alterations in pH do not substantially influence dissolved oxygen levels.

Dissolved oxygen (DO) exhibited a high negative correlation with temperature (-0.80) and moderate negative correlations with electrical conductivity (EC) (-0.36), total dissolved solids (TDS) (-0.36), biochemical oxygen demand (BOD) (-0.42), and total hardness (TH) (-0.38). These associations underscore dissolved oxygen loss in warmer, more contaminated, and ion-rich water. Electrical conductivity (EC) and total dissolved solids (TDS) exhibited a strong positive correlation of 0.99, confirming their close relationship as indicators of ion concentration in water. Both measurements exhibited strong positive relationships with pH (0.78), BOD (0.89), and TH (0.97 for EC and 0.98 for TDS), indicating that ionic concentration escalates with organic pollution and water hardness.

BOD exhibited a robust positive connection with EC (0.89), TDS (0.89), TH (0.88), and pH (0.77). This indicates the impact of organic contamination on water conductivity, hardness, and pH levels. It exhibited a modest negative association with DO (-0.42), aligning with the oxygen demand for organic matter breakdown.

Total Hardness (TH) exhibited a strong positive correlation with Electrical Conductivity (EC) (0.97), Total Dissolved Solids (TDS) (0.98), pH (0.76), and Biochemical Oxygen Demand (BOD) (0.88), signifying that hardness escalates with ion concentration and organic contamination. The modest negative connection with dissolved oxygen (DO) of -0.38 indicates that increased hardness marginally affects dissolved oxygen levels. Ammonia Nitrogen ($\text{NH}_3\text{-N}$) showed a moderate negative association with EC (-0.36), TDS (-0.36), TH (-0.35), and BOD (-0.29), suggesting that increased ammonia concentrations are negatively associated with ionic and organic content.

The matrix highlights substantial interdependencies across water quality metrics, with temperature and dissolved oxygen exhibiting strong inverse correlations with pollution indicators. At the same time, EC, TDS, BOD, and TH exhibit significant positive intercorrelations, indicating the impact of ions and organic matter on water quality.

Table 6. Correlation Matrix of water Quality Paramars

	T	pH	DO	EC	TDS	BOD	TH	NH3-N
T	1							
pH	-0.02	1						
DO	-0.80	-0.15	1					
EC	0.18	0.78	-0.36	1				
TDS	0.18	0.78	-0.36	0.99	1			
BOD	0.23	0.77	-0.42	0.89	0.89	1		
TH	0.20	0.76	-0.38	0.97	0.98	0.88	1	
NH3-N	0.26	-0.44	-0.15	-0.36	-0.36	-0.29	-0.35	1

Water quality assessment through WQI:

The water quality of the Mand River was evaluated at 11 monitoring stations during two cycles, encompassing the monsoon, winter, and summer seasons. The Water Quality Index (WQI) data demonstrate significant regional and temporal variability, highlighting the impact of seasonal changes and anthropogenic activities on the river's health.

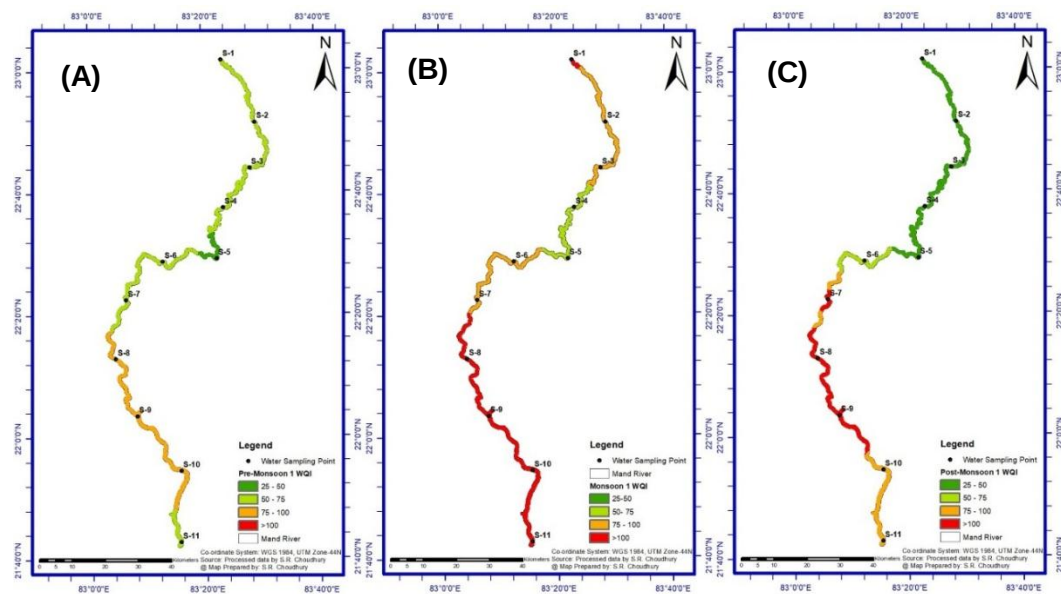


Figure.6 WQI for water Sampling cycle I: A, Pre-monsoon; B, Monsoon; C, Post-monsoon

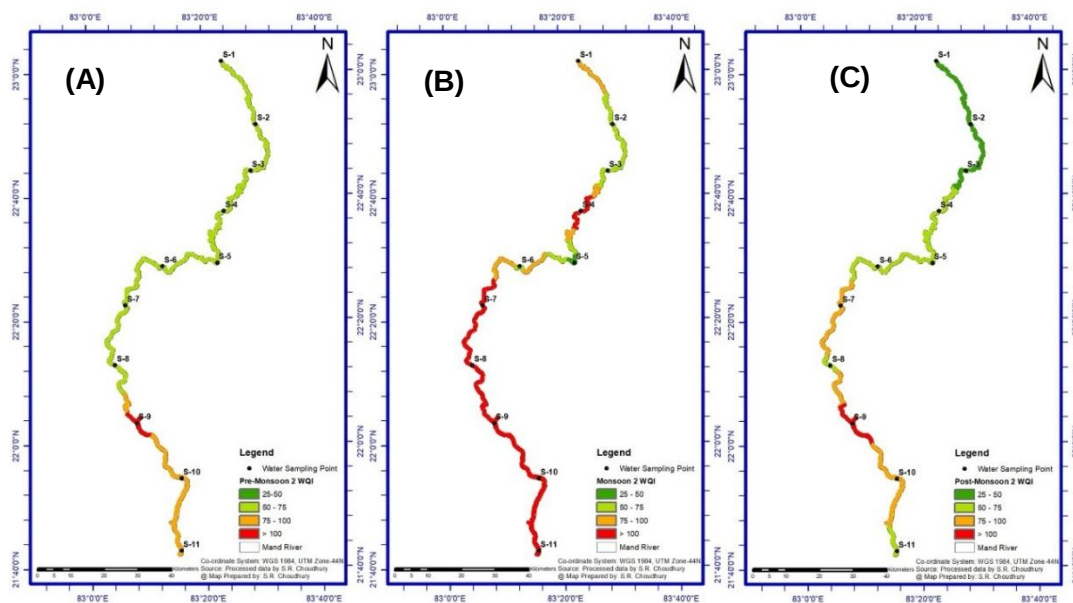


Figure.7 WQI for water Sampling cycle II: A, Pre-monsoon; B, Monsoon; C, Post-monsoon

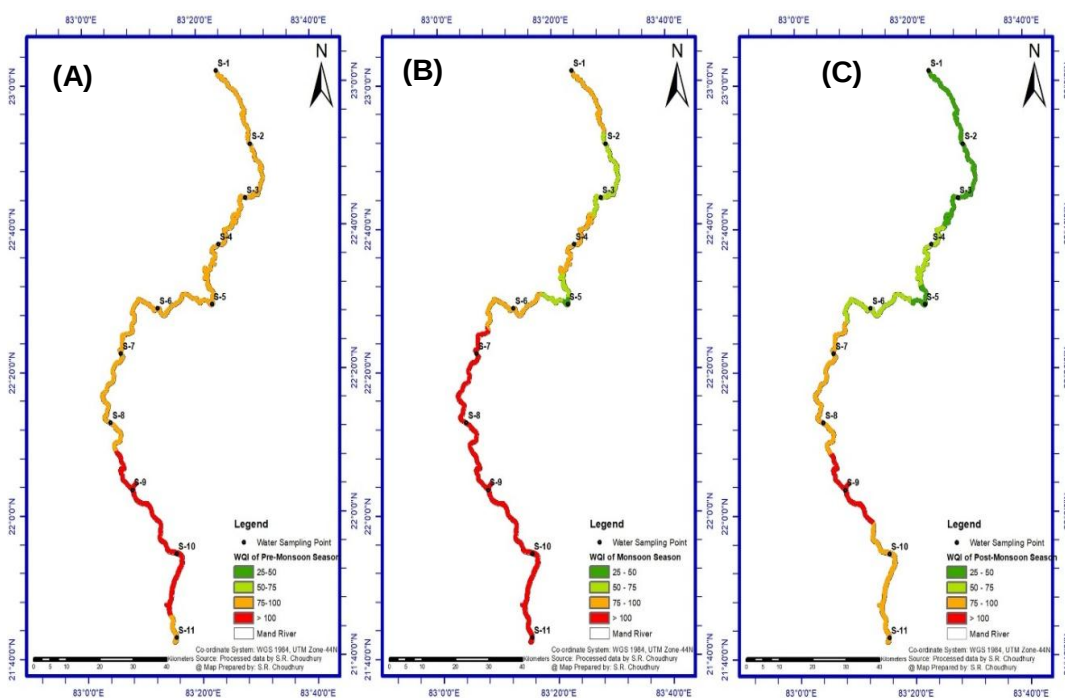


Figure.8 Overall WQI of the study area: A, Pre-monsoon; B, Monsoon; C, Post-monsoon

Seasonal Observations

- **Pre-Monsoon (Summer):** Limited data were accessible for summer; nonetheless, the observed patterns suggest moderate water quality, with several locations, including S-5, S-6, and S-7, categorized as "Fair." Seasonal low flow and heightened evaporation may have intensified pollutant concentration, resulting in a marginal decrease in the Water Quality Index (WQI) relative to winter (Fig 7A; 8A; 9A).
- **Monsoon:** Water quality was predominantly substandard throughout the monsoon season in most locations, with categories varying from "Very Poor" to "Fair." The deterioration in quality is due to heightened surface runoff, which transports contaminants like sediments, fertilizers, and organic matter into the river. Locations S-1, S-8, S-9, and S-10 were regularly categorized as "Very Poor," signifying severe pollution levels (Fig 7B; 8B; 9B).
- **Post-Monsoon (Winter):** During winter, water quality significantly improved, with many locations attaining "Good" ratings (e.g., S-1, S-2, S-3, and S-5). Reduced runoff, lower temperatures, and higher dissolved oxygen levels contributed to improved water quality during this season (Fig 7C; 8C; 9C).

Table 7. Site wise water seasonal water quality status based on the WQI

Site	Monsoon-1	Winter-1	Summer-1	Monsoon-2	Winter-2	Summer-2
S-1	Very Poor	Good	NA	Poor	Good	NA
S-2	Poor	Good	NA	Fair	Good	NA
S-3	Poor	Good	NA	Fair	Good	NA
S-4	Fair	Good	NA	Very Poor	Fair	NA
S-5	Fair	Good	Good	Good	Fair	Fair
S-6	Poor	Fair	Fair	Fair	Fair	Fair
S-7	Poor	Very Poor	Fair	Very Poor	Poor	Fair
S-8	Very Poor	Very Poor	Poor	Very Poor	Fair	Fair
S-9	Very Poor	Very Poor	Poor	Very Poor	Very Poor	Very Poor
S-10	Very Poor	Poor	Poor	Very Poor	Poor	Poor
S-11	Very Poor	Poor	Fair	Very Poor	Fair	Poor

- **Critical Sites:** Sites S-9, S-10, and S-11 consistently demonstrated subpar water quality throughout all seasons and cycles, signifying ongoing contamination issues (Table 7). These areas are probably affected by local human activities, including untreated wastewater discharge, agricultural runoff, and ceremonial practices along the riverbanks.
- **Improving Sites:** Locations such as S-5 and S-6 had generally steady or enhancing trends, attaining "Fair" or "Good" ratings throughout several seasons, indicating localized recovery or improved management methods (Table 7).
- **Temporal Trends:** Cycle 1 (2022-23) Compared to Cycle 2 (2023-24) While many sites

shown enhancements (e.g., S-2 and S-5), others, including S-4 and S-7, encountered a deterioration in quality from Cycle 1 to Cycle 2. This signifies differing levels of efficacy in pollution management and seasonal restoration initiatives (Table 7).

Overall River Health

The Mand River's water quality varies from "Very Poor" to "Good," contingent upon the location and season. Monsoon months exacerbate pollution, while winter offers partial recovery. The ongoing deterioration at essential locations underscores the necessity for immediate remedial actions, including effective waste management and treatment. Mitigation of agricultural runoff and industrial effluents. Public awareness and community engagement in river conservation.

The WQI evaluation of the Mand River highlights the combined issues of seasonal fluctuation and localized contamination. While certain sites show potential for recovery, the consistently poor quality at critical locations necessitates immediate and sustained intervention to restore the ecological balance and usability of the river.

Conclusion:

The study of the Mand River's water quality index (WQI) at 11 locations over several seasons and cycles indicates significant seasonal, geographical, and site-specific variations. In the upper catchment, S1 to S4 are dried throughout the summer, mostly because to the limited catchment areas and lack of forest cover. Moreover, the upper watershed of the region is characterized by sugarcane farming, a crop that necessitates substantial water, potentially affecting water levels during the dry season. Principal findings underscore the subsequent points:

The monsoon season consistently has the lowest water quality due to runoff transporting sediments, fertilizers, and contaminants into the river. Winter seasons often exhibit optimal water quality, due to less runoff, lower temperatures, and elevated dissolved oxygen concentrations. Summer circumstances indicate moderate water quality in several locations, although underscore the difficulties posed by low flow and concentrated pollutants.

Locations such as S-9, S-10, and S-11 have significant and ongoing water quality issues, predominantly categorized as "Very Poor." Industrial and home effluents, agricultural runoff, and various human pressures may affect these areas. Locations S-5 and S-6 exhibited relative stability or enhancement, attaining "Fair" to "Good" quality throughout several seasons. These locations possess dense forest coverage. These trends suggest localized recovery or improved pollution management initiatives. The deterioration of water quality at essential locations between the two cycles, albeit occasional seasonal improvements, highlights the necessity for ongoing monitoring and pollution mitigation strategies. The WQI evaluation underscores the necessity for focused measures to address pollution and preserve ecological balance. While some sites show potential for improvement, persistent issues at critical locations must be

addressed to ensure the river's long-term health and sustainability.

An integrated catchment management approach is essential to ensure long-term sustainability and ecological balance in the Mand River. Effective land-use planning, afforestation, and watershed conservation should be prioritized to regulate water flow and improve natural filtration processes. Buffer zones with riparian vegetation should be established to minimize pollutant runoff. Sustainable agricultural practices, such as agroforestry and reduced fertilizer application, should be promoted to mitigate nutrient loading. Additionally, rainwater harvesting and groundwater recharge initiatives could enhance water availability in the upper catchment during dry seasons.

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