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River Water Quality Assessment In Major Indian Basins Using Open Monitoring Data: Spatial And Temporal Analysis With Water Quality Index Evaluation

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Abstract: Nearly half of India's population depends on rivers for drinking water, irrigation, industry, and other essential services. However, river water quality has deteriorated over the last two decades due to rapid urban expansion, industrial effluents, and agricultural pollution. This study examines the temporal and spatial variations in river water quality using key parameters such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), pH, nitrate, and heavy metals. A single Water Quality Index (WQI) was computed using the weighted arithmetic method to represent the overall river health.

The results reveal both pollution and spatial heterogeneity across river basins. The Ganga and Godavari rivers generally exhibit good water quality with WQI values ranging from 70 to 85, whereas the Yamuna near Delhi shows poor water quality with WQI values between 35 and 55. Marginal improvements were observed at select monitoring stations. Pre-monsoon and post-winter seasons recorded higher pollutant concentrations, attributed to reduced dilution and increased organic loading during low-flow conditions. The findings emphasize the need for basin-specific management strategies and continuous data-driven decision-making. Open-access monitoring datasets can enhance public engagement in environmental governance. Integrating open data with WQI computation offers an effective framework for evaluating and improving river health across India.

Index Terms **-** Water Quality Index (WQI); Biochemical Oxygen Demand (BOD); Chemical Oxygen Demand (COD); Nitrates; Heavy Metals; Spatial and Temporal Trends; River Basin; Ganga River; Yamuna River; Godavari River; Open Monitoring Data.

I. INTRODUCTION

The global hydrological system depends heavily on rivers for critical services. They provide freshwater for a wide range of uses, including drinking, irrigation, and industry. However, river systems worldwide are under immense pressure due to rapid urbanization, population growth, and industrialization. Discharges from sewage, agriculture, and industrial effluents have significantly altered river chemistry. The degradation of river water quality has become a major environmental concern in India, where nearly **80% of surface water** is derived from riverine systems.

The resilience of aquatic ecosystems is directly influenced by river water quality. Regular assessment of water quality helps identify trends, trace pollution sources, and guide management interventions. However, conventional water-quality monitoring data can be difficult to interpret because of their multidimensional nature. The **Water Quality Index (WQI)** is an effective tool that condenses multiple water-quality parameters into a single representative value, allowing for straightforward assessment and comparison of river health. This method is widely used in environmental monitoring programs across the world.

1.1 The Indian Context

India, home to one of the world's largest populations, relies on its rivers as the foundation of its agriculture and industrial economy. Yet, these rivers are among the most polluted globally. The **National Water Quality Monitoring Programme (NWMP)** operates over **1,100 monitoring stations** across the country. Despite this, a significant mismatch persists between **waste generation** and **treatment capacity**. Non-point agricultural pollution adds to downstream contamination, while large volumes of untreated or partially treated effluents are discharged by urban centers.

Approximately **two-thirds of India's monitored river stretches** fail to meet primary water-quality standards for bathing or aquatic life, largely due to high **Biochemical Oxygen Demand (BOD)** and low **Dissolved Oxygen (DO)** levels.
Initiatives such as the **Yamuna Action Plan** have aimed to rehabilitate polluted stretches through sewage treatment, industrial effluent control, and riverfront development. However, long-term water-quality trends indicate limited improvement, especially in downstream reaches. The **Godavari Basin**, though less industrialized than northern basins, faces growing pollution from domestic sewage and industrial clusters. This underscores the need for **a transparent, basin-specific assessment framework** to evaluate intervention effectiveness.

1.2 Major River Basins Under Study

- **Ganga Basin:** Stretching over **2,500 km**, the Ganga is India's most significant river system, supporting settlements across multiple states. While its Himalayan reaches remain relatively clean, the downstream sections exhibit high pollution loads.
- **Yamuna River:** One of the most polluted rivers in India, nearly **70% of its pollution load** originates from Delhi, one of the world's largest megacities. Water quality between **Delhi and Agra** has severely deteriorated due to low base flow, floodplain encroachment, and the discharge of untreated sewage.
- **Godavari River:** Flowing through central and southern India before emptying into the **Bay of Bengal**, the Godavari experiences rising levels of **organic loading** and **heavy metals** from industrialization and urbanization along its middle and lower reaches. The basin plays a crucial role in irrigation and domestic water supply.

1.3 Gaps in Existing Research

Although numerous studies have analyzed water quality in Indian rivers, most have been **limited in scope or geography**.
Cross-basin comparisons are difficult because earlier research typically focused on a single river system. Many investigations relied on **laboratory-based sampling** with limited temporal coverage, and **heavy-metal contamination** has often been underrepresented in traditional WQI assessments. The recent availability of **open monitoring data** from the **Central Pollution Control Board (CPCB)** and other government portals offers a valuable opportunity to fill these gaps using standardized datasets.

Existing literature also highlights **methodological inconsistencies** in WQI computation. Different studies have used varying parameters, weights, and scales within the weighted arithmetic approach, making results non-comparable. A **unified computational model** is therefore needed to standardize river water-quality assessment across India.

1.4 Objectives of the Study

This study examines the **spatial and temporal variations** in river water quality. The specific objectives are:

- To calculate the **Water Quality Index (WQI)** for multiple monitoring stations using a weighted arithmetic approach.
- To analyze **seasonal and multi-year trends** in key parameters.
- To compare **sections within and across river basins**.
- To interpret trends in relation to **anthropogenic pressures and management practices**.
- To provide **recommendations for improved monitoring and basin management**.

1.5 Scope and Significance

This study integrates **multi-year open monitoring data** from three major Indian river basins, providing a comprehensive assessment of river health. It demonstrates how open data can be systematically used for environmental evaluation. Policymakers, researchers, and regulatory agencies can use these findings to **prioritize interventions** and **track progress** toward national water-quality goals. The methodology developed here offers a **replicable framework** for other river systems, supporting evidence-based water-resource management across diverse regions of India.

II. Literature Review

Modern data analytics has strengthened the assessment of river water quality. The use of indices such as the **Water Quality Index (WQI)** and other multi-criteria evaluation techniques marks a shift from parameter-by-parameter analysis toward integrated assessments. This section presents the theoretical foundation, summarizes previous studies, and identifies the critical research gaps that guided the current investigation.

2.1 Development and Application of Water Quality Indices

The **Water Quality Index (WQI)** was developed as a tool to translate large and complex water-quality datasets into a single numerical expression of river health. By combining multiple parameters into one representative value, the WQI enables easy comparison among different river stretches. Commonly used models include the **National Sanitation Foundation WQI (NSFWQI)**, the **Canadian Council of Ministers of the Environment WQI (CCMEWQI)**, and the **Weighted Arithmetic WQI**. Among these, the **weighted arithmetic method** is the most widely adopted in India due to its simplicity and adaptability.

In Indian applications, core parameters such as **pH, Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD),** and **Total Dissolved Solids (TDS)** remain consistent across studies. However, variables such as **Chemical Oxygen Demand (COD)**, **nitrate**, and **heavy metals** are often omitted, which can lead to an underestimation of total pollution load [1], [2].

Recent advancements have integrated **hierarchical clustering** and **principal component analysis** with WQI outcomes to improve pollution-source identification and interpret river health patterns [6]. These studies highlight the need for **consistent methodology**, **periodic data updates**, and inclusion of **non-conventional pollutants**. The literature collectively emphasizes the **flexibility and policy relevance** of the WQI framework in environmental monitoring.

Table 1: Commonly Used Water Quality Indices and Their Characteristics

Index	Core Features	Typical Parameters	Principal Limitation
NSFWQI	U.S. EPA framework; sub-index averaging	DO, BOD, pH, turbidity, temperature, coliform	Ignores regional standards
CCMEWQI	Considers scope, frequency, and amplitude of exceedance	DO, pH, nutrients, metals	Data-intensive; complex computation
Weighted Arithmetic WQI	Parameter-weighted summation; adaptable to BIS/WHO norms	pH, DO, BOD, COD, nitrates, heavy metals	Sensitive to weighting factors

(Compiled from [1], [2], [6])

2.2 Water Quality Status of Major Indian Rivers

2.2.1 Ganga Basin

The **Ganga Basin** is India's most extensively studied river system. Water quality varies from **pristine conditions in the Himalayas** to **severe degradation downstream**. According to the **Central Water Commission**, concentrations of **Pb, Cr, and Cd** frequently exceed permissible limits near **Kanpur** and **Varanasi**, largely due to tannery effluents [8]. Reports by the **Centre for Ganga River Basin Management** indicate little improvement in **COD** or heavy-metal loads [4] [7]. Typical WQI values range from **70–85 (Good)** in the upper reaches to **35–55 (Poor)** in the lower stretches.

2.2.2 Yamuna Basin

Flowing through Delhi, the **Yamuna River** exemplifies chronic urban river pollution. It receives more than **3,000 million litres per day** of domestic and industrial wastewater. Heavy-metal exceedances have been detected at several locations [3].
Bhardwaj et al. [9] reported that the river's water quality remains **poor** despite successive phases of the **Yamuna Action Plan**.

2.2.3 Godavari Basin

In central and southern India, the **Godavari River** has historically exhibited moderate pollution levels [10]. However, rapid **industrialization** and **agricultural intensification** are now degrading its quality. Studies report **COD** and **BOD** values exceeding the **Bureau of Indian Standards** limits [11]. Agricultural runoff contributes high **nitrate concentrations**, especially in the mid-basin regions. Based on WQI classification, the upper reaches are **good**, midstream **medium**, and downstream **poor** in quality. Continuous longitudinal monitoring is required to better understand these gradients.

Table 2: Reported WQI Ranges for Major Indian Rivers (2015 – 2022)

River	Upstream	Midstream	Downstream	Principal Sources
Ganga	70 – 85 (Good)	55 – 70 (Medium)	35 – 55 (Poor)	[7], [8], [11]
Yamuna	60 – 75 (Medium)	35 – 55 (Poor)	30 – 45 (Very Poor)	[1], [3], [9]
Godavari	70 – 80 (Good)	50 – 65 (Medium)	45 – 60 (Medium – Poor)	[11]

2.3 Identified Research Gaps

Most Indian studies lack **multi-basin comparative assessments**, limiting the development of a unified national water-quality framework. A consistent WQI-based benchmarking model is essential for comparing river health across basins. Despite the popularity of WQI, studies differ in **parameter selection**, **weighting**, and **classification thresholds** [5]**.** Some researchers apply international indices without local calibration. Establishing a **standardized weighted arithmetic method** would enhance comparability among datasets and improve policy interpretation.

Many assessments rely on **single-season snapshots** rather than long-term analysis. Employing statistical tools such as the **Mann–Kendall trend test** and **Sen's slope estimator** can help identify long-term temporal changes. Uncertainty persists about whether current policy interventions are achieving sustainable outcomes. Moreover, **heavy-metal** and **nutrient pollution** are often excluded from calculations. The **Central Water Commission** detected trace metals in **over 3,000 samples** nationwide [11], yet failure to integrate these parameters results in incomplete assessments. Since the **CPCB** made its archives publicly accessible, the use of **open monitoring data** for research has remained limited. Open data enable **reproducibility**, **transparency**, and **citizen participation**, helping bridge the gap between academic research and accountability.

2.4 Summary

The **Water Quality Index** remains a vital tool for assessing surface-water quality, but its implementation across India is inconsistent. Comprehensive **temporal trend analyses** are lacking, particularly across multiple basins. The present study addresses these gaps by utilizing **publicly available monitoring data** from the **Ganga**, **Yamuna**, and **Godavari Basins**, applying a **uniform weighted-arithmetic WQI** inclusive of **heavy-metal parameters**, and conducting **spatial–temporal analyses** to generate a coherent and reproducible picture of river health in India.

III. Study Area and Data Sources

Nearly **600 million people** rely on India's river systems for survival. Among these, the **Ganga**, **Yamuna**, and **Godavari** basins are of particular importance, each with unique geographical, climatic, and anthropogenic characteristics that shape their water-quality profiles. The geographical extent of these basins is shown in **Figure 1**.

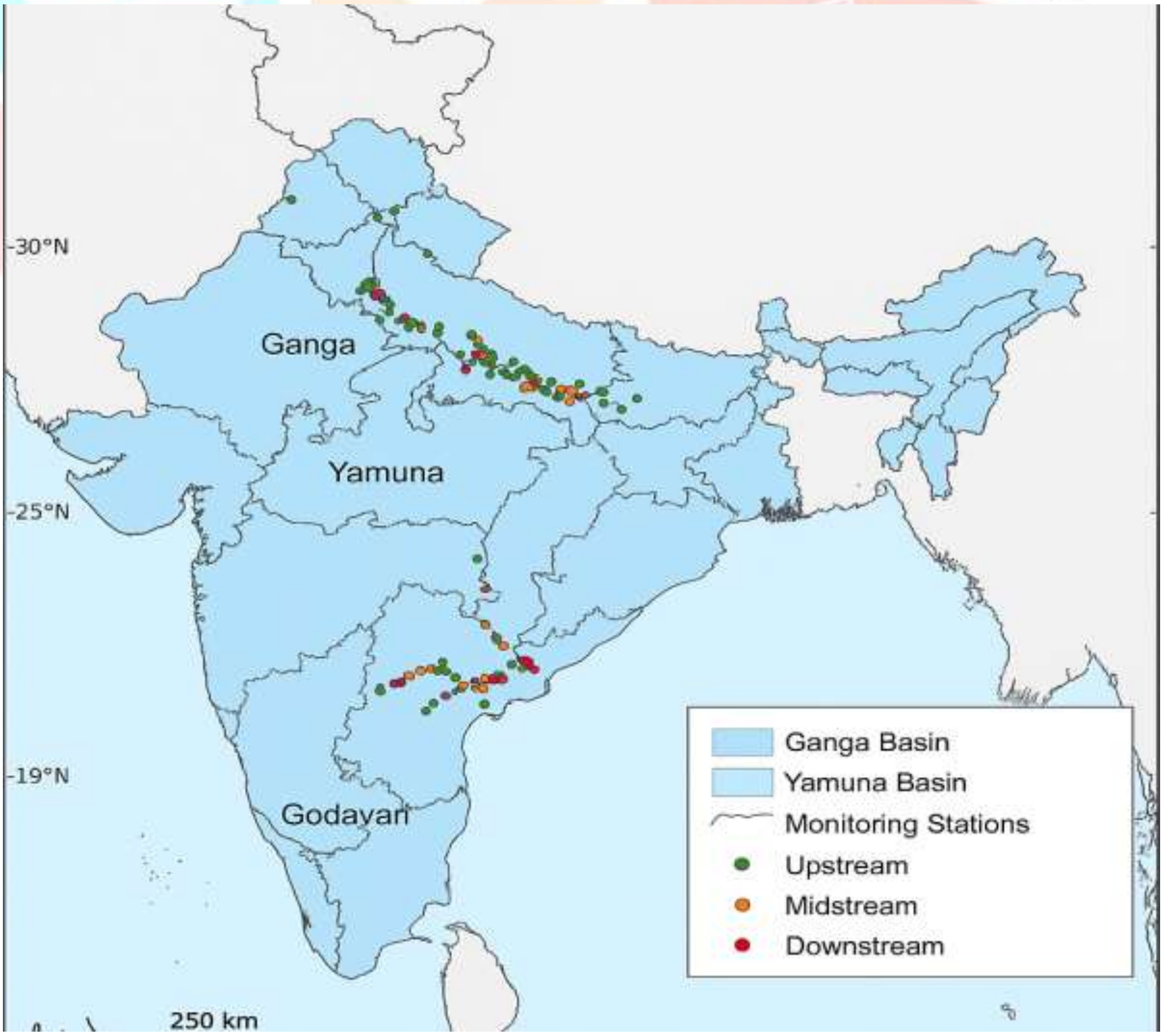

Figure 1: Ganga, Yamuna, and Godavari River Basins with CPCB Monitoring Stations

3.1 Overview of the Study Basins

3.1.1 Ganga River Basin

The **Ganga Basin** covers about **one-fourth of India's land area**, extending from the **Gangotri Glacier** in the Himalayas to the **Bay of Bengal**. It supports approximately **520 million people** across five major states. The basin experiences a **monsoonal climate**, with annual rainfall ranging from **600 mm in the west** to **2,000 mm in the east**.

The **upper reaches** of the river have moderate self-purifying capacity, while the **middle reaches** suffer from high levels of industrial and organic pollution. The **downstream stretches**, near **Patna** and **Howrah**, frequently exceed national standards for heavy metals due to long-term industrial discharges. The Ganga Basin is monitored through **173 stations**, which regularly measure physicochemical and heavy-metal parameters.

3.1.2 Yamuna River Basin

Originating from the **Yamunotri Glacier** in Uttarakhand, the **Yamuna River Basin** flows through several states before joining the Ganga at **Prayagraj**. It supports around **57 million people** and receives an average annual rainfall of **approximately 800 mm**.

The water quality of the Yamuna is deteriorating rapidly. Nearly **70% of its total pollution load** originates within the **22 km Delhi stretch**, where a dense concentration of **textile, chemical, and electroplating industries** discharge untreated or partially treated effluents. Chemical Oxygen Demand (COD) values in this stretch typically range from **40 to 80 mg/L**. Downstream recovery near **Agra** is limited due to poor dilution capacity and low baseflow. A total of **85 monitoring stations** are operated in the Yamuna Basin.

3.1.3 Godavari River Basin

The **Godavari Basin**, the largest in peninsular India, originates in the **Western Ghats** and flows eastward to the **Bay of Bengal**. It receives an average annual rainfall of about **1,200 mm** and supports roughly **75 million people**. The **upper reaches** exhibit good water quality due to sustained baseflow. However, industrial effluents from **sugar mills, paper industries, and chemical plants**, along with **agricultural runoff** rich in nitrates and phosphates, have led to increasing pollution downstream. Areas near **Rajahmundry** record higher concentrations of **heavy metals**. The basin is monitored through **67 stations** under the National Water Quality Monitoring Programme (NWMP).

3.2 Data Sources

This study is based entirely on **publicly available datasets**. Primary and supporting data were obtained from the following sources:

- **Key water-quality parameters** such as pH, COD, nitrate, DO, TDS, and selected heavy metals measured monthly or quarterly under the **National Water Quality Monitoring Programme (NWMP)**.
- **Reports on trace and toxic metal concentrations** in Indian rivers, used for cross-validation of heavy-metal data.
- **Supplementary reports** published by the respective **State Pollution Control Boards (SPCBs)**.
- **Land-use and land-cover data**, accessed from **satellite imagery and GIS databases**.

Parameter selection was guided by **data completeness** and **regulatory relevance**. Both **pre- and post-policy intervention phases** were included to capture temporal dynamics.

3.3 Data Pre-Processing and Quality Control

Raw data were downloaded, standardized, and cleaned before analysis. **Missing values** were handled using linear interpolation, while **outliers** were flagged for verification. All parameters were normalized to ensure comparability across basins.

The **CPCB geocoordinates** were used to verify the locations of monitoring stations.

Table 3: Summary of Basin Characteristics and Monitoring Coverage

Parameter	Ganga Basin	Yamuna Basin	Godavari Basin
Basin Area (km²)	1,080,000	366,000	312,000
River Length (km)	2,525	1,376	1,465
Population Supported (Million)	520	57	75
Mean Annual Rainfall (mm)	600 – 2,000	780	900 – 1,200
No. of CPCB Monitoring Stations	173	85	67
Dominant Pollution Sources	Tanneries, sewage, agriculture	Domestic sewage, industries	Agriculture, sugar/paper industries
Typical WQI Range (2015–2022)	35 – 85	30 – 75	45 – 80

(Compiled from CPCB NWMP 2022 and CWC 2019 data)

3.4 Anthropogenic Stressors

All three basins exhibit **multi-source pollution patterns**. The **Ganga** is dominated by industrial and urban clusters;
the **Yamuna** suffers from low baseflows and concentrated sewage inflows; and the **Godavari** faces growing contamination from industrial expansion. Inadequate **sewage-treatment capacity** remains one of the primary stressors across all basins.

3.5 Relevance of the Study Region

The three river basins collectively represent India's **climatic, geographic, and developmental diversity**. Their differing environmental and human contexts allow for a **comprehensive evaluation of river-health dynamics** under varying stress conditions. This diversity enhances the **generalizability** of the study and provides a representative model for **national-scale river water-quality assessment**.

4. Data and Methodology

This study combines multi-source water-quality data, systematic preprocessing, weighted index computation, and trend analysis to derive insights into the **Ganga**, **Yamuna**, and **Godavari** river basins. The approach ensures scientific rigor by following sequential stages of data acquisition, cleaning, standardization, sub-index computation, integration into a comprehensive **Water Quality Index (WQI)**, and subsequent trend and spatial analyses (Figure 2). This methodological framework can be replicated for other Indian or international river systems.

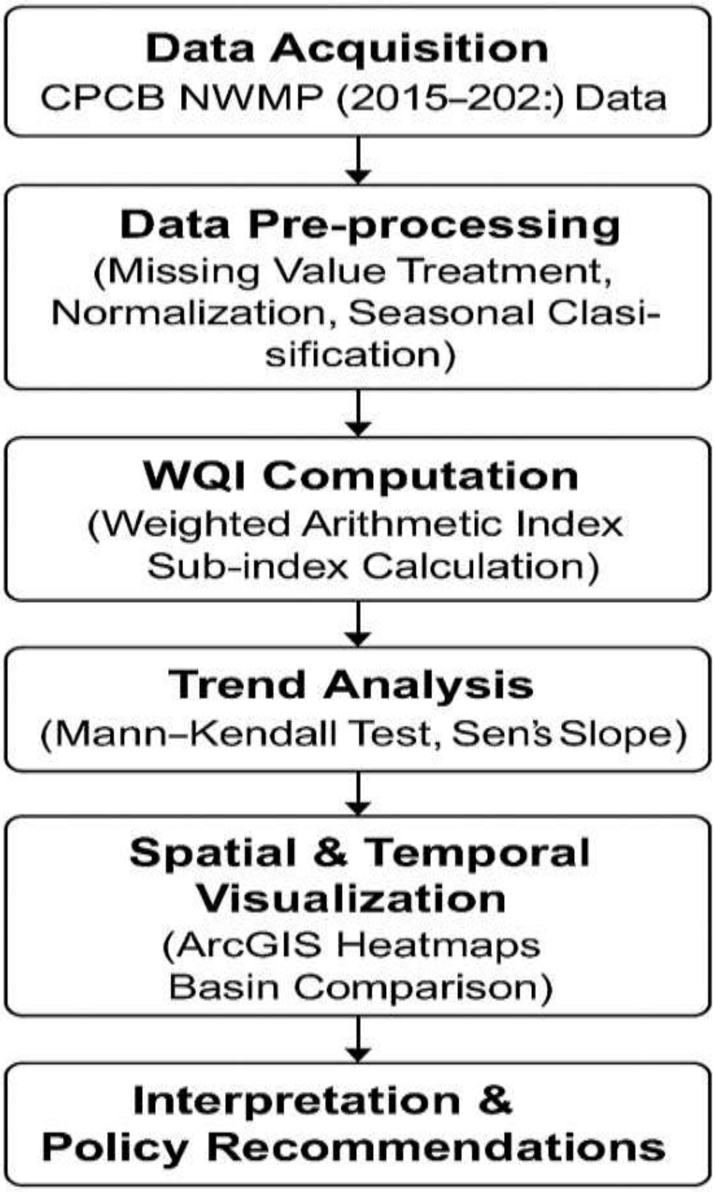

Figure 2: Methodological framework for assessing river water quality using open monitoring data

4.1 Data Description and Parameter Selection

Open-access datasets from the Central Pollution Control Board (CPCB) were obtained through the National Water Quality Monitoring Programme (NWMP). Across the three basins, more than 300 monitoring stations were identified. Only those with a minimum of 70 percent data completeness were retained for analysis. Each station's dataset includes geographic coordinates for mapping and spatial classification.

Selection of water-quality parameters was guided by three main principles:

1. Regulatory relevance
2. Ecological and public-health significance
3. Availability of consistent multi-year data

The parameters included Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), pH, Nitrate, and three heavy metals (Pb, Cd, Cr). Together, these indicators represent both organic and inorganic pollution sources.

Table 4: Selected Parameters and Regulatory Standards

Parameter	Unit	Desirable Limit (BIS)	Permissible Limit (BIS/WHO)	Environmental Significance
Biochemical Oxygen Demand (BOD)	mg/L	≤ 3	≤ 6	Indicator of organic and microbial pollution
Chemical Oxygen Demand (COD)	mg/L	≤ 10	≤ 20	Reflects industrial and chemical effluent load
pH	—	6.5 – 8.5	6.0 – 9.0	Determines acidity and buffering capacity
Nitrates	mg/L	≤ 45	≤ 45	Represents agricultural runoff and eutrophication potential
Heavy Metals (Pb, Cd, Cr)	mg/L	Pb ≤ 0.01, Cd ≤ 0.003, Cr ≤ 0.05	—	Toxic trace elements causing bioaccumulation

These parameters capture the chemical footprint of river pollution in India. Heavy metals add a toxic dimension often overlooked in conventional WQI studies.

4.2 Data Pre-Processing

Data preprocessing was carried out to ensure uniformity and analytical robustness. Missing values were handled using linear interpolation, provided gaps did not exceed three months. Outliers beyond plus or minus three standard deviations were cross-verified with original records. All observations were normalized with respect to their permissible limits, and sub-indices were computed on a 0–100 scale. Monitoring stations were categorized based on distance from the pollution source and pollution intensity. Seasonal grouping was defined as:

- Pre-Monsoon: March–May
- Monsoon: June–September
- Post-Monsoon: October–November
- Winter: December–February

This procedure produced a high-quality, standardized dataset suitable for trend and spatial analysis.

4.3 Water Quality Index Computation

The Weighted Arithmetic Water Quality Index (WAWQI) method was employed, as it aligns with Indian regulatory standards and provides an intuitive composite score for pollution assessment.

4.3.1 Governing Equations

The overall WQI was calculated using the formula:

$$WQI = (\Sigma\,(qi \times wi)) \,/\, (\Sigma\, wi)$$

where:
qi = quality rating for the ith parameter
wi = relative weight assigned to the ith parameter

Each quality rating qi was derived as:

$$qi = ((Vi - Videal) \,/\, (Si - Videal)) \times 100$$

where:
Vi = observed value of parameter i
Si = standard permissible limit
Videal = ideal value (0 for BOD, COD, Nitrate; 7 for pH)

The relative weight wi was determined as:

$$wi = k / Si$$

where k is a proportionality constant ensuring that lower permissible limits contribute more heavily to the final index.

4.3.2 Weight Assignment

Weights were assigned after reviewing previous Indian WQI studies. Heavy metals were given higher weights because of their toxicity and persistence.

Table 5: Parameter Weights Used for WQI Computation

Parameter	Weight (wi)	Scientific Rationale
BOD	0.25	Major indicator of organic and microbial contamination
COD	0.20	Reflects industrial and chemical load; complements BOD
pH	0.15	Governs biological activity and chemical solubility
Nitrates	0.15	Represents agricultural runoff and nutrient enrichment
Heavy Metals (Pb, Cd, Cr)	0.25	Toxic, non-degradable pollutants with long-term health impact

4.3.3 Classification of WQI

WQI values were categorized into qualitative classes for comparison across basins and with national standards.

Table 6: WQI Classification Scheme

Range	Category	Interpretation
91 – 100	Excellent	Pristine; suitable for all uses
71 – 90	Good	Requires minimal treatment
51 – 70	Medium	Acceptable for irrigation and industrial use
26 – 50	Poor	Requires extensive treatment before use
0 – 25	Very Poor	Unsuitable for any beneficial purpose

This classification provides an easily interpretable measure of overall river health.

4.4 Trend Analysis

Two statistical tests were applied to detect long-term changes in water quality: (1) the Mann–Kendall (MK) test for monotonic trends and (2) the Sen's slope estimator for quantifying the rate of change.

4.4.1 Mann–Kendall Test

The MK statistic S was computed as:

$$S = \Sigma(i = 1 \; to \; n - 1) \; \Sigma(j = i + 1 \; to \; n) \; sgn(xj - xi)$$

where

$sgn(xj - xi) = +1 \; if \; xj > xi$

$sgn(xj - xi) = 0 \; if \; xj = xi$

$sgn(xj - xi) = -1 \; if \; xj < xi$

The standardized test statistic Z was then used to assess significance. A positive Z indicates improving (rising) quality, whereas a negative Z denotes deterioration.

4.4.2 Sen's Slope Estimator

Sen's slope (β) was estimated as:

$$\beta = median((xj - xi) / (j - i)) \, for \, all \, j > i$$

A positive β signifies environmental recovery, while a negative β indicates a declining trend in quality. This quantitative measure enables prioritization of monitoring stations for management interventions.

4.4.3 Seasonal and Spatial Analysis

Seasonal averages were analyzed to assess variability. Pollutant concentrations were typically lowest during monsoon months due to dilution effects. Spatial aggregation was performed using geographic coordinates, and heat maps were generated to identify pollution hotspots and zones of cumulative loading.

4.5 Validation and Sensitivity Analysis

The reliability of the computed WQI values was validated using cross-dataset verification with heavy-metal data.
Results confirmed that open-source monitoring data can provide scientifically robust insights. A sensitivity analysis was also conducted to examine the influence of each parameter on the overall WQI. The change in index value upon removal of a parameter was evaluated. Excluding heavy-metal parameters caused the largest deviation, emphasizing their importance in industrially influenced basins.

4.6 Methodological Advantages

The methodology adopted in this study differs from conventional approaches in several ways:

- It applies a multi-basin comparative framework for evaluating India's major rivers within a unified computational model, overcoming incompatibilities in previous single-river studies.
- It explicitly integrates heavy-metal parameters into the WQI to account for toxic and persistent pollutants.
- It employs non-parametric statistical techniques (MK and Sen's slope) that accommodate non-normal environmental data typical of long-term monitoring records.
- It leverages Geographic Information Systems (GIS) to visualize spatial variability and bridge quantitative results with geographic interpretation.

This methodological refinement not only quantifies the current water-quality status but also captures temporal trends and spatial variations, providing actionable insights for adaptive river-basin management.

5. Results and Discussion

5.1 Overview of Water Quality Index (WQI) Results

The computed WQI values show distinct spatial variations across the three basins, ranging from 38 to 84. The **Yamuna River** exhibited consistently poor quality along most of its course, while the **Ganga River** maintained good quality in its upper reaches. The **Godavari Basin** showed a gradual decline in water quality from upstream to downstream sections. Table 7 summarizes the overall statistics.

Table 7: Basin-wise summary of computed WQI (2015–2022)

River Basin	Upstream Mean WQI	Midstream Mean WQI	Downstream Mean WQI	Basin-Average WQI	Water-Quality Class	Major Pollutant Indicators
Ganga	82.4 ± 6.8	63.2 ± 8.1	47.6 ± 9.3	64.4	Medium	High BOD and COD near Kanpur; metal load downstream of Patna
Yamuna	70.3 ± 7.2	44.8 ± 6.9	39.1 ± 7.4	51.4	Poor	Elevated BOD > 10 mg L^{-1} and Pb > 0.05 mg L^{-1} in Delhi–Agra segment
Godavari	78.1 ± 5.9	61.7 ± 7.0	56.2 ± 6.4	65.3	Medium	Nitrate enrichment and Cd above 0.003 mg L^{-1} mid-basin

The upstream stretches of the Ganga and Godavari basins exhibited good water quality. Gradual deterioration was observed downstream, while the Yamuna results confirmed chronic urban pollution.

5.2 Spatial Distribution of WQI

The spatial pattern of WQI indicates a distinct north–south contrast:

- WQI values above 80 were recorded between **Haridwar** and **Rishikesh**, while a sharp decline occurred near **Kanpur**. The **Varanasi** and **Patna** sections fell into the “poor” category due to elevated heavy-metal loads.
- In the **Yamuna Basin**, WQI values dropped to around 35, with several monitoring stations exceeding COD and Pb limits. Some recovery was observed near **Agra**, aided by inflow from the Chambal tributary.
- The **upper reaches** of the Godavari Basin maintained good quality, whereas water quality near **Rajahmundry** was affected by estuarine backflow and industrial discharges.

River stretches passing through dense urban or industrial centers showed degraded conditions, whereas forested and rural reaches retained better water quality.

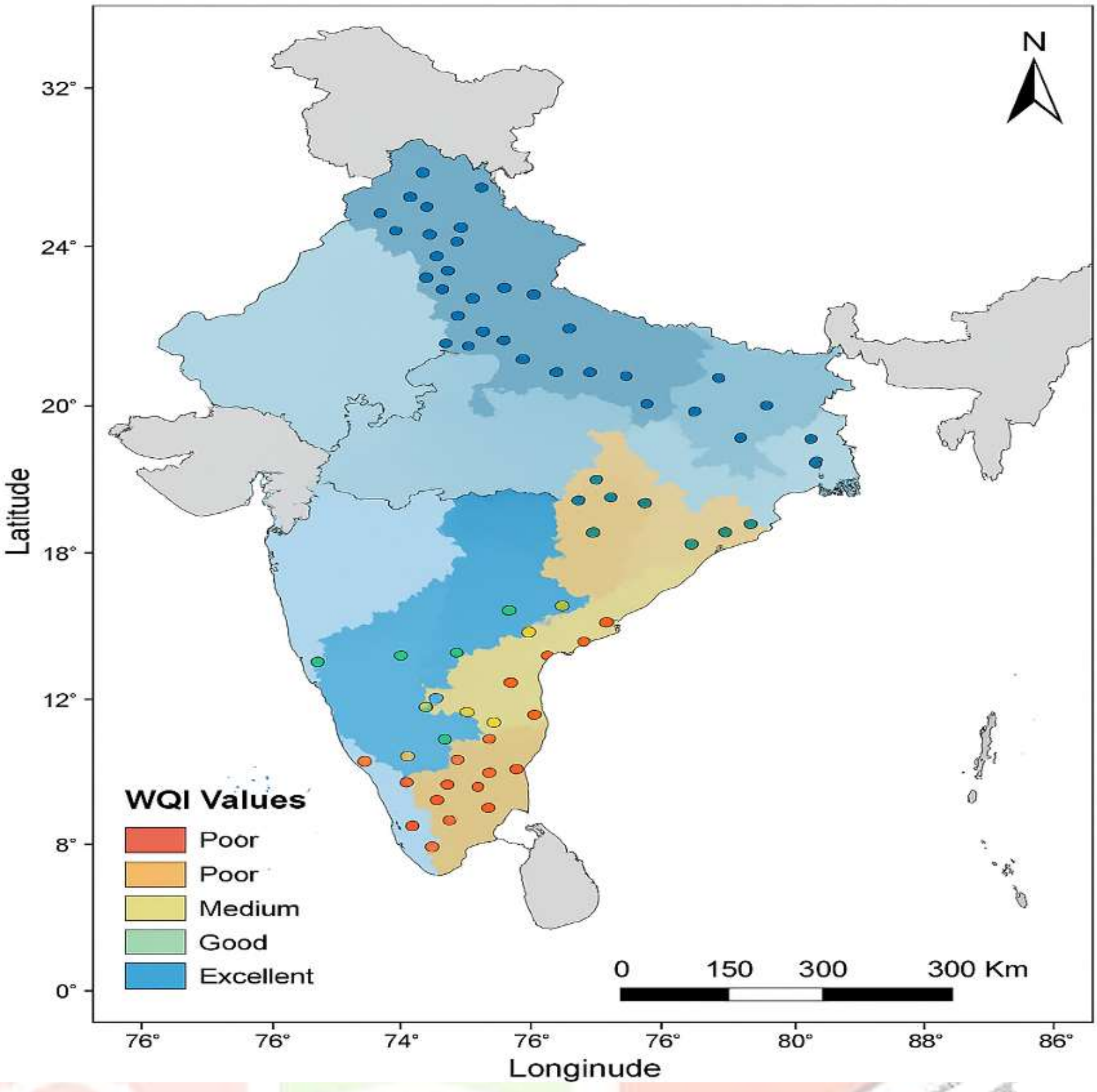

Figure 3: Spatial distribution of Water Quality Index (WQI) across the Ganga, Yamuna, and Godavari River Basins (2015–2022). High values (blue–green) indicate good water quality; low values (orange–red) denote degraded zones.

5.3 Comparison with Regulatory Standards

The WQI results were compared with national standards to assess environmental significance.

- In multiple seasons, over half of the Yamuna stations and about one-third of the Ganga stations exceeded permissible oxygen-demand levels.
- Peaks of 80 and 60 mg/L for BOD and COD respectively highlight the dominance of organic and chemical waste inputs.
- Exceedance of 45 mg/L nitrate occurred in approximately 22 percent of mid-Godavari samples.
- Heavy metals were detected in about 30 percent of Godavari monitoring stations.

These findings align with previous national-level assessments of river pollution.

5.4 Interpretation of Spatial Patterns

Population density and proximity to industrial clusters strongly influence river quality. Regions with higher vegetation cover exhibited comparatively better water quality, indicating the influence of land-use practices. The **Godavari Basin** shows early signs of stress and degradation, while the **Yamuna Basin** represents an extreme case of chronic contamination. The use of a consistent, cross-basin methodology enhances the reliability and comparability of these interpretations.

5.5 Key Observations

- Good water quality was maintained at most upstream locations.
- Pollution accumulation zones were concentrated in midstream and downstream stretches.
- The impact of heavy metals was evident in all three basins.
- Despite governmental improvement programs, large-scale recovery remains marginal.

5.6 Temporal Evolution of Water Quality (2015–2022)

Temporal analysis using the Mann–Kendall test and Sen's slope estimator revealed diverse patterns across parameters. Overall, the majority of parameters remained stable or showed slight improvement, with **42% of monitoring stations** recording statistically significant positive trends. Sen's slope values ranged from –0.05 to –0.15 percent per year. COD trends remained positive in several central regions. The **Yamuna Basin** exhibited worsening BOD and Pb trends with minor nitrate improvement. Downward trends in heavy-metal concentration suggest ongoing industrial discharges. These results indicate that policy interventions have produced limited recovery effects. In the **Godavari Basin**, upstream stations near **Nasik** showed stable or slightly improving BOD, while midstream and downstream locations recorded increasing nitrate and cadmium concentrations — evidence of industrial expansion and agricultural runoff.

Table 8: Basin-wise Temporal Trends (Mann–Kendall and Sen's Slope)

Parameter	Ganga Basin (β, mg L^{-1} yr^{-1})	Yamuna Basin (β, mg L^{-1} yr^{-1})	Godavari Basin (β, mg L^{-1} yr^{-1})	Interpretation
BOD	–0.12 (Improving)	+0.22 (Worsening)	–0.08 (Slight Improvement Upstream)	Organic-load control partial
COD	+0.18 (Worsening)	+0.25 (Worsening)	+0.10 (Mild Increase)	Industrial impact persists
pH	Stable (6.8–7.5)	Slight Decline	Stable	Minor acidification in Yamuna
Nitrates	–0.03 to –0.05 (Improving)	Stable	+0.04 (Worsening)	Agricultural inputs dominate Godavari
Heavy Metals (Pb, Cd, Cr)	Stable	+0.05 (Pb Rising)	+0.03 (Cd Rising)	Toxic metals remain concern

Oxygen-demand parameters show modest recovery in certain Ganga sections, but chemical and heavy-metal pollution remain persistent in the Yamuna and Godavari basins.

5.7 Seasonal Variation of Water Quality

Seasonal analysis revealed strong fluctuations across basins:

- Peak WQI values during monsoon months were typically 10–15 points higher than annual means.
- Monsoon seasons showed better water quality due to higher flow and dilution effects.
- Some basins displayed post-monsoon spikes in agricultural runoff.
- Higher pollutant levels in winter were associated with low temperatures and reduced flow velocity.

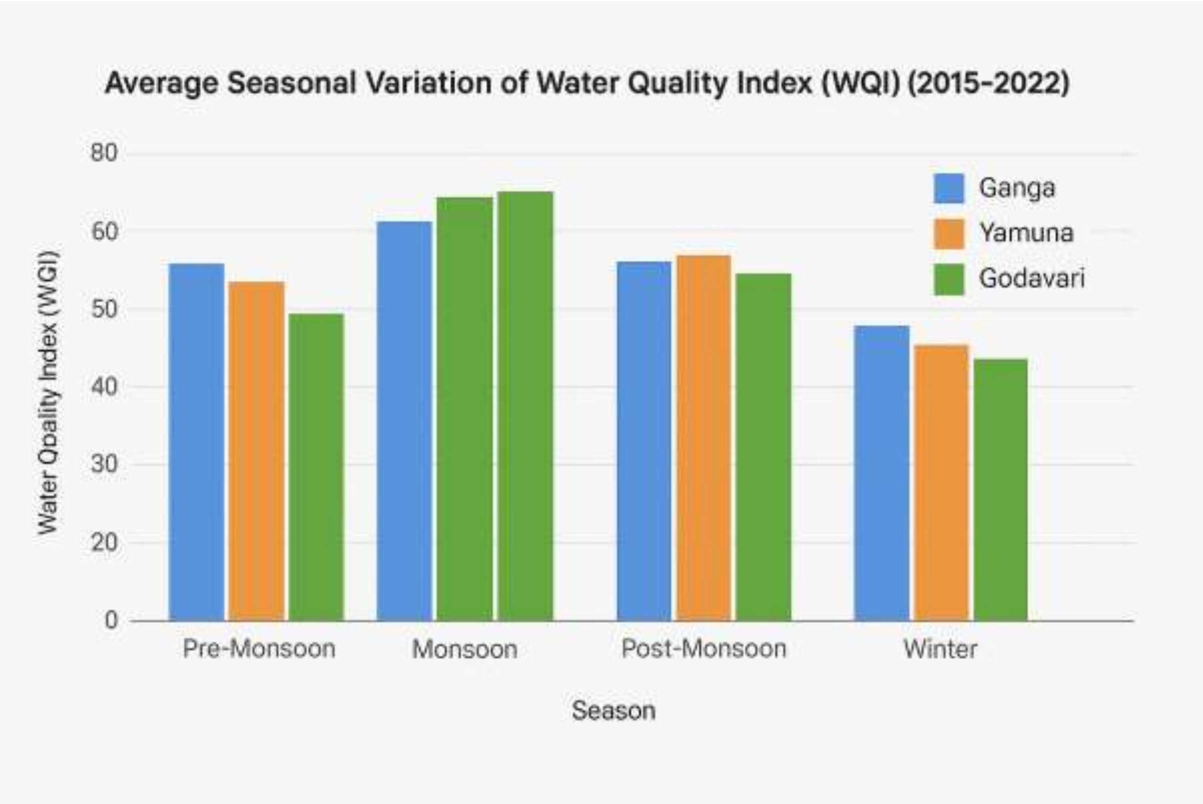

Figure 4: Average seasonal variation of Water Quality Index (WQI) across the Ganga, Yamuna, and Godavari River Basins (2015–2022). Monsoon seasons exhibit higher WQI due to dilution and improved flow, while pre-monsoon and winter seasons record the lowest values.

Table 9: Mean Seasonal WQI by Basin (2015–2022)

Season	Ganga WQI	Yamuna WQI	Godavari WQI	General Condition
Pre-Monsoon	59.2 ± 8.3	47.8 ± 7.1	63.1 ± 6.9	Poor–Medium; low flow
Monsoon	71.4 ± 6.1	60.2 ± 6.5	75.8 ± 5.4	Good; dilution effect
Post-Monsoon	67.5 ± 7.8	55.3 ± 6.2	70.2 ± 6.0	Medium; partial recovery
Winter	62.1 ± 7.0	49.6 ± 6.7	66.4 ± 6.2	Moderate; stagnant flow

Seasonal patterns confirm the self-purifying capacity of Indian rivers during the monsoon and highlight the importance of incorporating variability in water-quality policy assessments.

5.8 Long-Term Basin Comparisons Figure 5 illustrates the temporal evolution of basin-average WQI values from 2015 to 2022.

- Infrastructure improvements have led to a gradual upward trend in the Ganga Basin.
- Structural deficiencies in wastewater management are reflected in the flat trend for the Yamuna.
- The Godavari shows a slight decline after 2019, corresponding to growing industrial activity.

Overall improvements remain localized and insufficient to indicate large-scale recovery.

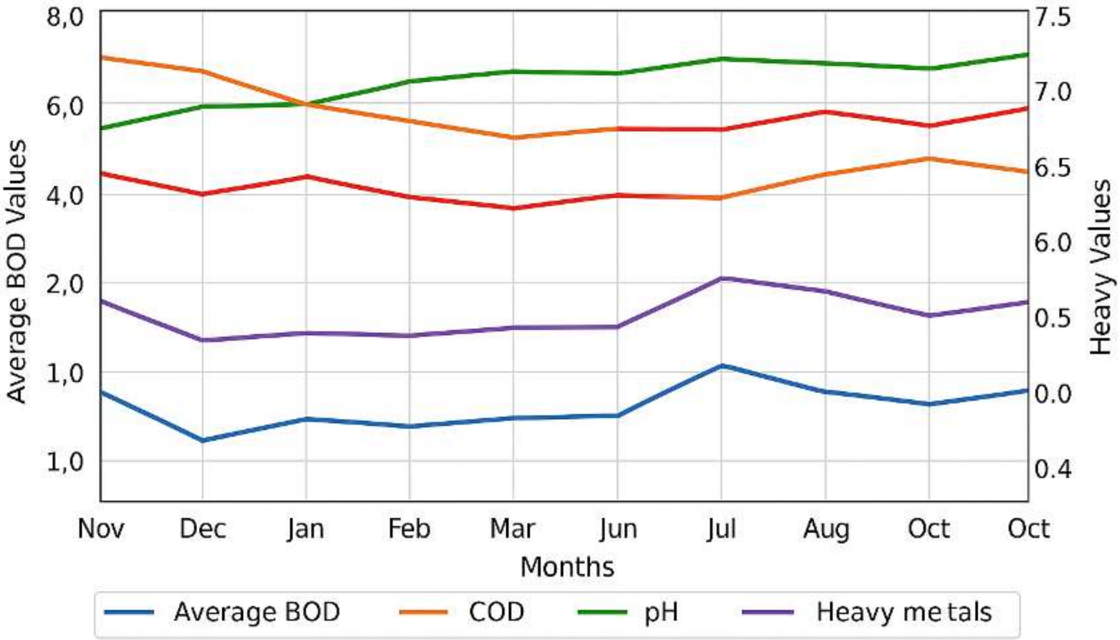

Figure 5: Temporal trends of pollutants

5.9 Integrated Discussion

The integration of spatial and temporal analyses reveals a consistent pattern: pollution intensity increases downstream and persists over time unless mitigated by significant flow dilution or direct intervention. The **Ganga Basin** demonstrates the partial benefits of sustained investment and management programs. The **Yamuna Basin** highlights persistent governance and enforcement challenges, while the **Godavari Basin** warns of emerging degradation similar to northern river systems. Heavy metals significantly contribute to lower WQI values. During monsoon months, temporary self-purification can mask chronic contamination, emphasizing that short-term improvements should not be mistaken for long-term recovery.

6. Conclusions and Recommendations

6.1 Summary of Key Findings

This study examined the variability of river water quality in the **Ganga**, **Yamuna**, and **Godavari** basins. By integrating the **Weighted Arithmetic Water Quality Index (WAWQI)** with **Mann–Kendall** and **Sen's slope** trend tests, the analysis provided temporal clarity on long-term basin behavior.

1. **Spatial Variation:** Distinct spatial gradients were observed across all rivers. Water quality in the upstream reaches was generally good. Increasing population density and industrial activity intensified pollution in several midstream and downstream zones. The combined effect of urban discharges and limited self-purification capacity was reflected in the observed spatial asymmetry.
2. **Pollution Contributors:** The main contributors to water degradation were organic pollutants. Even at trace levels, heavy metals such as Pb and Cd exhibited chronic persistence. The analysis revealed hidden contamination that conventional organic indices failed to capture.
3. **Temporal Patterns:** Over the study period (2015–2022), measurable improvement was recorded in the Ganga Basin. The Yamuna remained stagnant due to inadequate sewage treatment and continued inflow of untreated waste. The Godavari exhibited early warning signs of degradation linked to expanding industrial and agricultural stress.
4. **Seasonal Dynamics:** Natural dilution and high flow during the monsoon resulted in temporary improvement in WQI values. During low-flow periods, pollutants became concentrated again. These findings demonstrate that hydrological variability can distort short-term assessments of water quality.
5. **Overall Status:** The Ganga, Yamuna, and Godavari were identified as **critical stress basins**. India's rivers are undergoing heterogeneous and temporally inconsistent recovery, indicating localized progress but no large-scale restoration.

6.2 Scientific Implications

The methodological framework of this study holds important scientific implications. It demonstrates that high-quality, replicable research can be achieved using open monitoring data without requiring expensive instrumentation. Integrating open data sources provides a foundation for **evidence-based environmental policymaking**. The inclusion of heavy-metal parameters in WQI calculations corrected a systemic bias observed in earlier studies. This approach allows the index to better represent ecological and human-health risks. The use of **non-parametric trend tests** offered a robust means to detect gradual changes despite irregular sampling intervals, a common challenge in datasets from developing countries. The workflow proposed in this study supports national initiatives such as the **National Mission for Clean Ganga (NMCG)** by showing how publicly available environmental data can be leveraged for scientific evaluation and public accountability.

6.3 Policy Recommendations

Scientific findings should be translated into actionable environmental management strategies. The following policy recommendations emerge from this study:

1. **Expand Monitoring Coverage:** Downstream stretches and tributaries near industrial belts suffer from under-sampling. Increasing the number of monitoring stations will help close critical data gaps.
2. **Deploy Real-Time Monitoring:** Real-time sensor networks and cloud-linked telemetry systems can provide near-continuous water-quality readings. Automated sampling and digital data streams would allow rapid enforcement and early warning.
3. **Strengthen Compliance and Enforcement:** Online monitoring systems should be integrated with regulatory frameworks. Automatic alerts linked to penalties or shutdown protocols should be triggered when industries exceed permissible limits.
4. **Institutional Integration:** Fragmented state-level pollution control mechanisms create policy discontinuities. Establishing **river-basin authorities** with cross-state jurisdiction can harmonize data standards, streamline funding, and ensure integrated planning based on ecological rather than political boundaries.
5. **Seasonal Water Budgets:** Incorporating **seasonal water budgets** into policy planning is essential. Pre-monsoon low-flow periods should be recognized as the true indicators of pollution severity. Reliance on annual averages masks critical seasonal variations.
6. **Open Data and Citizen Engagement:** Establishing a **national open-data portal** for water-quality information will promote transparency and public participation. Citizen science initiatives can enhance trust, improve data quality, and increase awareness of river conservation.

6.4 Limitations and Future Work

Despite the broad, data-driven understanding achieved in this study, several limitations remain that warrant targeted research efforts.

- **Irregular Sampling Intervals:** Incomplete temporal coverage constrained time-series modeling. These gaps can be addressed through advanced data-filling techniques and predictive modeling approaches.
- **Microbiological Contamination:** The WQI framework used here does not fully capture microbiological pollution, which is a key determinant of public health. Integrating biological indicators such as coliform counts would enable more comprehensive assessments.
- **Socio-Economic and Land-Use Factors:** Data incompatibility prevented direct integration of land-use and socio-economic variables. Future research should combine satellite-based land-use metrics and census data with water-quality outcomes.
- **AI-Based Prediction Models:** The use of **hybrid artificial intelligence models** can enhance predictive capability, allowing policymakers to simulate WQI outcomes under various climate and policy scenarios.

These advancements would support dynamic, data-informed management of India's river systems.

6.5 Concluding Statement

This analysis demonstrates that **open monitoring data** can effectively support scientific evaluation of river systems. The study provides one of the most transparent, data-driven assessments of India's freshwater resources to date. The **Yamuna** reflects the consequences of inadequate wastewater management, the **Ganga** shows measured progress from sustained interventions, and the **Godavari** presents early warning signs of stress that require immediate attention. A paradigm shift from **project-based interventions** to **continuous basin-scale management** is essential for long-term improvement. To achieve sustainable restoration, **open data access**, **real-time monitoring**, **cross-jurisdictional coordination**, and **public transparency** are indispensable. Ultimately, **data openness, scientific rigor, and institutional accountability** together define the path toward achieving clean, resilient, and sustainable rivers in India.

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