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Spatio-temporal assessment of water quality in the Indrayani River, Western Ghats: Application of Weighted Arithmetic Water Quality Index (WAWQI)

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ABSTRACT

Rapid urbanization and industrial expansion in monsoon-dominated basins are intensifying pressures on secondary river systems in India. This study presents a three-year (2022–2024) multi-season assessment of the Indrayani River, a Western Ghats tributary of the Bhima basin, to evaluate spatial and temporal trends in water quality using physicochemical analyses and the Weighted Arithmetic Water Quality Index (WAWQI). Surface-water samples were collected from 22 stations representing upstream, midstream, and downstream segments during pre-monsoon, monsoon, and post-monsoon seasons. Key parameters, including pH, EC, TDS, DO, BOD_5, COD, nitrate, and chloride, were analyzed in accordance with APHA protocols and compared with BIS, WHO, and CPCB standards. Results revealed a consistent longitudinal deterioration in water quality. Upstream reaches maintained "Good" status (WQI < 50), while downstream segments exhibited "Very Poor/Unsafe" conditions (WQI > 250–300). Elevated BOD_5 (up to 28 mg L^{-1}), COD (up to 54 mg L^{-1}), and nitrate (up to 47 mg L^{-1}), coupled with DO levels below 4 mg L^{-1}, indicate a eutrophic-to-hypereutrophic transformation in the lower reaches. Degradation is structurally driven by untreated municipal sewage, industrial effluents, agricultural runoff, pilgrimage-related inputs, and reduced pre-monsoon dilution. Correlation analysis identified strong coupling among ionic enrichment indicators (EC–TDS–chloride) and organic load parameters (BOD_5–COD), with inverse relationships to DO. The study highlights the urgency of sub-basin-scale management, expanding wastewater infrastructure, nutrient interception strategies, and WQI-based monitoring, all aligned with SDG-6 and integrated river basin management frameworks.

Keywords: *Eutrophication, Indrayani River, Seasonal Variation, Urban River Pollution, Water Quality Index, Western Ghats.*

Highlights

- Three-year spatio-temporal assessment at 22 river stations.
- WQI increased from <50 upstream to >300 downstream.
- BOD_5 reached 28 mg L^{-1}, exceeding CPCB limits.
- Nitrate enrichment intensified in urban–industrial reaches.
- WQI supports sub-basin river management planning

1. Introduction

Freshwater ecosystems are among the most vulnerable environmental systems globally and are increasingly subjected to multifaceted anthropogenic pressures. Accelerated urban expansion, industrial intensification, agricultural intensification, and climate variability collectively contribute to progressive degradation of riverine environments [1]. Contemporary global assessments indicate that a substantial fraction of municipal and industrial wastewater continues to be discharged into rivers and streams without adequate treatment, particularly within rapidly developing regions. Such discharges contribute to nutrient enrichment, organic pollution, salinization, and ecosystem impairment [2,3,4]. The most recent global update on wastewater treatment progress further highlights persistent infrastructure deficits and unequal treatment coverage across low- and middle-income countries [5]. Consequently, river systems worldwide are experiencing declining dissolved oxygen concentrations, elevated biochemical oxygen demand (BOD), enhanced eutrophication, and biodiversity loss, with direct implications for ecosystem services and public health [6,7,8,9].

Climate-driven hydrological variability further exacerbates these pressures. Intensified precipitation events enhance contaminant mobilisation, sediment transport, and non-point source runoff, whereas prolonged dry periods concentrate pollutants and intensify oxygen stress [10,11]. In tropical and monsoon-dominated basins, this seasonal contrast is particularly pronounced, producing complex spatio-temporal gradients in water quality that challenge conventional monitoring frameworks [12,13]. Such variability necessitates multi-season, multi-year diagnostic approaches that can distinguish dilution effects from concentration-driven degradation.

India exemplifies the convergence of rapid demographic expansion, urban growth, and limited wastewater infrastructure capacity. National river monitoring programmes have repeatedly identified stretches of rivers characterised by elevated BOD, nutrient enrichment, and organic contamination [14,15]. Large-scale governmental initiatives, including the Namami Gange Programme, reflect institutional commitment to river restoration through basin-scale management strategies [16,17]. However, recent assessments of polluted river stretches underscore that smaller tributaries and peri-urban rivers require systematic stretch-wise monitoring and targeted interventions [18,19]. While flagship basins have received substantial attention, secondary rivers of hydrological, ecological, and cultural importance often lack comprehensive longitudinal and seasonal diagnostics.

Rivers originating in the Western Ghats, recognised globally as a biodiversity hotspot, are ecologically sensitive systems increasingly subjected to anthropogenic stress. Tributaries within the Bhima River basin, particularly those traversing Maharashtra's industrial and agricultural corridors, have exhibited progressive deterioration in water quality due to municipal sewage discharge, industrial effluents, and agrochemical runoff [10,20,21,22]. Seasonal hydrology further modulates these contamination patterns. Monsoon-driven runoff introduces pulses of suspended solids and nutrients, whereas dry-season flow reductions diminish dilution capacity and intensify pollutant concentrations [13,20]. Such hydrologically mediated variability necessitates integrative analytical frameworks that synthesize multiple physicochemical parameters into policy-relevant indicators.

The Water Quality Index (WQI) has emerged as a widely applied tool for condensing complex water chemistry datasets into a single numerical descriptor that facilitates spatial and temporal comparison [23,24]. By integrating parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nutrient concentrations, WQI provides a comprehensive assessment of river health and suitability for designated uses [25]. Recent investigations in tropical river systems demonstrate that WQI effectively captures anthropogenic stress gradients and seasonal variability associated with land-use transformation [10,26].

The Indrayani River originates in the Sahyadri ranges near Lonavala and flows eastward to join the Bhima River. Along its 108 km course, the river traverses forested headwaters, agricultural landscapes, rapidly expanding peri-urban settlements, and major industrial hubs including Talegaon, Chakan, and Pimpri-Chinchwad. In addition to continuous municipal and industrial discharges, episodic stress arises from large-scale pilgrimage gatherings, which can temporarily elevate organic and nutrient loading. Despite its ecological, hydrological, and religious significance, comprehensive multi-year and multi-season assessments incorporating high-resolution longitudinal gradients remain limited.

A critical research gap, therefore, persists. Although regional studies have documented seasonal water chemistry trends within Maharashtra's river systems [20,21], comparatively few investigations provide: (i) high-resolution longitudinal assessment spanning headwater to downstream urban stretches; (ii) multi-season, multi-year evaluation capable of distinguishing hydrological dilution from concentration-driven stress; and (iii) index-based diagnostics explicitly aligned with policy monitoring frameworks and SDG-6 performance indicators [27,28].

National monitoring networks identify polluted river stretches; however, systematic integration of correlation structure, trophic interpretation, and WQI-based prioritisation for peri-urban Western Ghats tributaries remains underdeveloped [15,18]. Addressing this gap is essential for generating transferable, performance-trackable evidence to inform restoration planning in rapidly urbanising, monsoon-dominated basins. Accordingly, the present study aims to: (i) evaluate spatial and seasonal variations in physicochemical parameters along the Indrayani River continuum; (ii) compute the Weighted Arithmetic Water Quality Index (WAWQI) to quantify longitudinal and temporal water quality trends; and (iii) identify dominant pollution drivers through correlation analysis and trophic-state interpretation.

By integrating multi-season monitoring with WAWQI diagnostics, this investigation establishes a robust evidence-based baseline for sustainable watershed management within the rapidly urbanizing Pune region and contributes to broader river-basin governance frameworks aligned with SDG-6 and integrated water resource management objectives.

2. Materials and Methods

2.1 Study area

The Indrayani River originates near Kurvande village (Station 1: 18°43′35.78″ N, 73°22′40.34″ E) in the Sahyadri ranges of the Western Ghats, approximately 60 km northwest of Pune city (Figure 1). The river flows eastward for approximately 108 km before joining the Bhima River at Tulapur village (Station 21: 18°40′16.10″ N, 73°59′46.54″ E). Along its course, the river traverses distinct ecological and land-use gradients, including forested headwaters, agricultural landscapes, peri-urban settlements, and major urban-industrial clusters such as Talegaon, Chakan, and Pimpri-Chinchwad. The elevation within the basin ranges from approximately 500 m to 1090 m above sea level. Annual rainfall varies strongly across the basin, ranging from about 700 mm in rain-shadow regions to nearly 2300 mm along the windward slopes of the Western Ghats [29,30]. Two reservoirs, including the Valvan Dam near Lonavala, regulate discharge patterns and influence seasonal hydrological dynamics. These physiographic and hydrological attributes create distinct upstream–downstream gradients in dilution capacity, residence time, and pollutant transport.

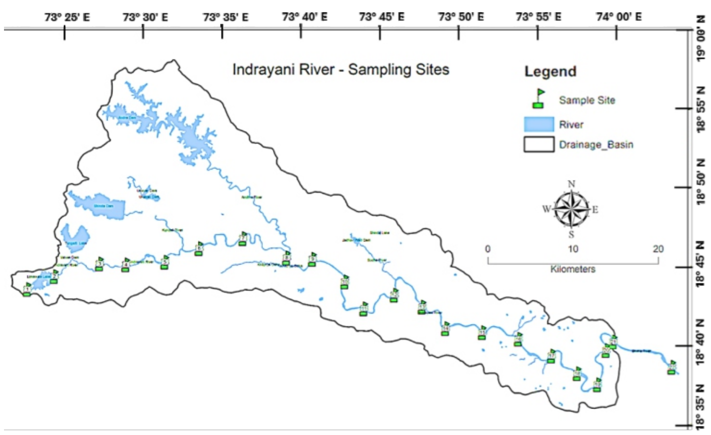

Figure 1. Study area location (Indrayani River) with sampling sites.

2.2 Land use and Land cover

The Indrayani catchment has undergone substantial land-use transformation over the past two decades. Remote-sensing analyses indicate that the built-up area expanded from approximately 79 km^2 to 105 km^2 between 2000 and 2020, largely replacing agricultural lands, which declined from approximately 286 km^2 to 257 km^2 during the same period [31,32]. Vegetative cover increased moderately (223 km^2 to 280 km^2), attributable to plantation and reforestation initiatives, while barren land areas decreased.

Rapid urbanisation in the Pimpri-Chinchwad and Talegaon regions, coupled with inadequate sewage infrastructure, has resulted in the routine discharge of untreated domestic and industrial effluents into the river system. Additional anthropogenic pressures include brick kiln extraction, sand mining, channel modification, and inadequate regulatory enforcement. Religious activities, particularly mass-bathing events at Dehu and Alandi, contribute episodic nutrient and organic loading. These land-use transitions and anthropogenic inputs collectively influence water chemistry and longitudinal water-quality gradients.

2.3 Sampling strategy

To comprehensively capture the longitudinal gradient from headwaters to confluence, 22 sampling stations were established along the river continuum (Figure 1; Table 1). Stations were categorised into upstream (Stations 1–3), midstream (Stations 4–9), and downstream (Stations 10–22) segments based on physiographic and land-use characteristics. Sampling was conducted triannually during the pre-monsoon (summer), monsoon, and post-monsoon (winter) seasons over three years (2022–2024), thereby representing hydrological extremes and transitional phases. This multi-season, multi-year design enabled assessment of both seasonal variability and interannual consistency.

At each station and season, we collected surface-water samples in pre-cleaned 1-L polyethene bottles following standard protocols described in APHA [33]. We used separate 300 mL BOD bottles for DO and BOD_5 analysis. We performed in situ measurements of pH, temperature, EC, and TDS using calibrated portable multi-parameter instruments. Dissolved oxygen samples were fixed immediately in the field using Winkler reagents to prevent atmospheric exchange. All collected samples were preserved in insulated containers at ≤ 4 °C and transported to the laboratory within 24 hours for subsequent analysis.

Table 1: Sampling sites with coordinates

Station No.	Station Name	Latitude	Longitude
St1	Kurvande Village	18°43' 35.78" N	73°22' 40.34" E
St2	Lonavala Lake	18°44' 25.32" N	73°24' 22.91" E
St3	Waksai	18°45' 12.82" N	73°27' 15.13" E
St4	Karla Malawali Bridge	18°45' 09.14" N	73°28' 55.14" E
St5	Pathargaon Bridge	18°45' 19.48" N	73°31' 23.38" E
St6	Kamshet -Nane Bridge	18°46' 11.48" N	73°33' 34.01" E
St7	Kanhe Bridge	18°46' 49.54" N	73°36' 20.12" E
St8	Sangavi- Jambhul Ghat	18°45' 35.50" N	73°39' 05.79" E
St9	Ambi Ghat	18°45' 30.57" N	73°40' 44.48" E
St10	Induri Ghat	18°44' 04.53" N	73°42' 47.58" E
St11	Kanhewadi Ghat	18°42' 22.13" N	73°43' 59.71" E
St12	Dehu Ghat	18°43' 14.27" N	73°45' 55.23" E
St13	Talawade-Chakan Bridge	18°42' 28.56" N	73°47' 41.30" E
St14	Chikhli-Moi Bridge	18°41' 07.02" N	73°49' 09.92" E
St15	Moshi-Chimbli Bridge	18°40' 51.30" N	73°51' 29.71" E
St16	Alandi Ghat	18°40' 26.41" N	73°53' 46.85" E
St17	Dhanori Bund	18°39' 22.66" N	73°55' 52.79" E
St18	Wadgaon Shinde Bund	18°38' 15.18" N	73°57' 30.17" E
St19	Bhawadi	18°37' 33.42" N	73°58' 47.24" E
St20	Markal Bund	18°39' 43.53" N	73°59' 19.79" E
St21	Tulapur Triveni Confluence	18°40' 16.10" N	73°59' 46.54" E
St22	Bhima-Koregaon	18°38' 39.61" N	74° 03' 29.56" E

2.4 Analytical methods

Ten key physicochemical parameters were analysed using standardised procedures outlined in APHA [33], as summarised in Table 2. Physical parameters, including temperature, pH, EC, TDS, and transparency, were measured using calibrated digital instruments. Dissolved oxygen was determined using the Winkler azide titration method. Biochemical oxygen demand (BOD_5) was quantified following five-day incubation at 20 °C. Chemical oxygen demand (COD) was measured using the dichromate reflux method.

Nitrate (NO_3^-) concentration was determined spectrophotometrically at 220 nm with correction at 275 nm using a UV–VIS spectrophotometer. Chloride (Cl^-) was quantified using argentometric titration. Instrument specifications, limits of detection (LOD), and limits of quantification (LOQ) are detailed in Table 2. All measured values were evaluated against standards prescribed by the Bureau of Indian Standards [35] and World Health Organization guidelines [33], as summarised in Table 3.

Instrument calibration was performed daily using certified reference standards. Analytical precision was ensured through procedural blanks, duplicate samples, and standard reference solutions. LOD and LOQ were calculated as three and ten times the standard deviation of replicate blanks, respectively. These quality assurance procedures ensured analytical accuracy, reproducibility, and transparency.

Table 2: Physicochemical parameters analyzed and analytical methods used for Indrayani River water samples

Parameter	Method [34]	Instrument / Model	LOD	LOQ
Temperature	2550 B	Digital thermometer (Hanna HI 93510)	0.1 °C	0.3 °C
pH	4500-H^+ B	Portable pH meter (Eutech pH 700)	0.01	0.03
EC	2510 B	Conductivity meter (Hanna HI 8733)	1 µS/cm	3 µS/cm
TDS	2540 C	TDS meter (Hanna HI 99300)	2 mg/L	6 mg/L
Transparency	2130 B	Nephelometer (Hach 2100N)	0.02 NTU	0.05 NTU
DO	5210 B	Winkler iodometric titration	0.1 mg/L	0.3 mg/L
BOD5	5210 B	5-day incubation at 20°C + titration	0.5 mg/L	1.5 mg/L
COD	5220 B	COD digester (HACH DRB 200)	2 mg/L	6 mg/L
Nitrate (NO_3^-)	4500-NO_3^- B	UV–VIS spectrophotometer (Shimadzu UV-1800)	0.02 mg/L	0.06 mg/L
Chloride (Cl^-)	4500-Cl^- B	Argentometric titration	1 mg/L	3 mg/L

2.5 Water Quality Index (WQI) computation

The Weighted Arithmetic Water Quality Index (WAWQI) method [23,34] was employed to integrate the influence of individual parameters into a composite index.

For each parameter n, the quality rating (Q_n) was calculated as:

$$Q_n = \frac{(V_n - V_i)}{(S_n - V_i)} \times 100$$

where:

V_n = observed value of parameter *n*, V_i = ideal value (0 for most parameters; 7 for pH; 14.6 mg L^{-1} for DO), S_n = standard permissible limit (Table 3)

Each parameter was assigned a weight (W_n) proportional to its relative importance to aquatic life and public health, and weights were normalized such that $\Sigma W_n = 1$. The final WAWQI was calculated as:

$$WQI = \sum(Q_n \times W_n)$$

Measured parameter values were compared against Bureau of Indian Standards [35] and WHO [36] standards (**Table 3**). Table 4 presents the classification scheme used for interpretation**,** ranging from "Excellent" (WQI ≤ 25) to "Very Poor/Unsafe" (WQI > 100). Values exceeding 300–400 indicate that the water is unsuitable for any direct use without advanced treatment. We evaluated seasonal and spatial WQI trends using descriptive statistics and graphical visualisation in Microsoft Excel and MATLAB.

Table 3: Water quality parameters as per BIS [35] and WHO [36] standards for drinking water

Sr. No.	Parameter	Ideal Value (Vi)	Permissible Limit (Sn)	Unit	Remark
1	Temperature	25	35	^{0}C	CPCB guideline for aquatic life [37]
2	pH (Potenz of Hydrogen)	7.0	6.5- 8.5	-	Beyond the range – No relaxation. Acceptable range for drinking water [35,36]
3	Turbidity	0	1.0	NTU	Desirable limit: up to 5 NTU permissible in the absence of an alternative source [35,36]
4	Total Dissolved Solids (TDS)	0	500	mg/L	Acceptable limit: up to 2000 mg/L [35,36]
5	Dissolved Oxygen (DO)	14.6	≥6.0	mg/L	Drinking water source without conventional treatment, CPCB Class A [37]
6	Biochemical Oxygen Demand (BOD)	0	≤ 2.0	mg/L	Pristine water quality criterion CPCB Class A [37]
7	Phosphate	0	5*	mg/L	*No BIS/WHO guideline; value adopted for eutrophication control [37,38]
8	Electric Conductivity	0	300-1500	µS/cm	Typical drinking water range (300–1500 µS/cm) [36]
9	Nitrate (NO_3^-)	0	45	mg/L	Limit to prevent methemoglobinemia [35,36]
10	Chloride (Cl^-)	0	250	mg/L	Taste threshold: up to 1000 mg/L [35,36]

Table 4: This study used the WQI classification scheme [23,34] to describe water quality status and suitability for use

WQI Range [14,50]	Water Quality Category	Description of Water Quality	Likely Suitability of Water
0 – 25	Excellent	Pristine quality; no pollution	Suitable for all uses (drinking, irrigation, industrial) without treatment
26 – 50	Good	Minor contamination; acceptable	Safe for primary uses (drinking, etc.) with minimal or no treatment
51 – 75	Fair (Moderate)	Moderately polluted	Suitable for irrigation and industrial use; treatment required for drinking
76 – 100	Poor	Heavily polluted	Useful only for irrigation/industrial use after extensive treatment
> 100	Very Poor (Unsafe)	Very heavily polluted; "unfit."	Unsuitable for drinking; requires advanced treatment even for other uses

2.6 Trophic status classification

Trophic status was interpreted using multi-year average WAWQI values in conjunction with nutrient–oxygen indicators, including DO, BOD_5, nitrate concentration (NO_3^-), and transparency. Although WAWQI does not directly compute trophic state, elevated index values reflect increasing nutrient enrichment and organic loading—primary drivers of eutrophication. Trophic categories were assigned based on established ecological descriptors that link nutrient availability and oxygen dynamics to productivity levels [39,40,41]. Operational thresholds were defined as follows:

a. Oligotrophic: WQI < 50; DO > 6 mg L^{-1}; low BOD_5 and nitrate; high transparency

b. Mesotrophic: WQI 50–75; moderate nutrient enrichment; occasional DO reduction

c. Eutrophic: WQI 75–150; elevated BOD/COD and nitrate; frequent DO depression (<5 mg L^{-1})

d. Hypereutrophic: WQI > 150; persistently high organic load; recurrent hypoxic conditions (<3–4 mg L^{-1})

These criteria were applied consistently across stations, using multi-year seasonal averages, to ensure a robust longitudinal trophic classification.

2.7 Statistical analysis

Descriptive statistical analysis quantified spatial and interannual variability in physicochemical parameters. For each year (2022, 2023, and 2024), observations from all 22 stations across three seasons were pooled, yielding 66 observations per parameter per year. For each parameter, the minimum, maximum, mean, and standard deviation (SD) were computed to assess central tendency and dispersion (Table 5). These descriptive metrics facilitated comparison across years and assessment of compliance with WHO, BIS, and CPCB regulatory benchmarks. All statistical computations were performed using Microsoft Excel 2021. Descriptive statistics were integrated with graphical outputs (Figures 2–4) to examine spatial gradients, seasonal variation, and interannual consistency.

3. Results

3.1 Physicochemical characteristics

Year-wise descriptive statistics (Table 5) and detailed station-wise seasonal data (Supplementary Tables S1–S3) reveal pronounced longitudinal enrichment and seasonally modulated variability in the Indrayani River during 2022–2024. While annual mean values remained broadly consistent, the wide ranges and high standard deviations reflect spatially structured anthropogenic influence, particularly in downstream segments. Water temperature ranged from 16.5 °C to 29.9 °C. Although no strict BIS drinking-water limit exists for temperature, CPCB guidelines for aquatic life [37] recommend temperatures that do not significantly alter ambient ecological conditions. The elevated mean observed in 2024 (24.08 ± 4.59 °C) indicates intensified pre-monsoon thermal loading.

Downstream warming is attributable to reduced riparian canopy cover, shallow channel morphology, urban heat transfer, and reduced flow velocity. Elevated temperature accelerates microbial metabolism, increases oxygen demand, and reduces DO solubility, thereby predisposing impacted reaches to hypoxia.

Table 5: Descriptive statistics of physicochemical parameters of Indrayani River (pooled 2022–2024)

Parameter	2022				2023				2024			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Temperature (°C)	16.80	29.60	22.86	3.85	16.80	29.90	22.89	3.80	16.50	29.60	24.08	4.59
EC (µS/cm)	155.00	555.00	298.67	108.83	155.00	550.00	310.38	108.70	120.00	555.00	302.73	113.25
Turbidity (NTU)	2.03	4.00	2.81	0.59	2.00	4.29	2.99	0.63	2.03	4.29	2.97	0.53
TDS (mg/L)	160.00	550.00	268.60	109.56	160.00	444.00	234.38	81.80	165.00	465.00	241.17	86.75
pH	6.55	8.15	7.46	0.38	6.55	8.34	7.60	0.44	6.75	7.98	7.44	0.37
Chloride (mg/L)	5.00	78.00	21.14	16.49	6.00	59.00	20.02	13.58	6.00	69.00	20.59	15.30
Nitrate (mg/L)	1.25	47.00	10.80	12.70	1.25	47.00	10.80	12.70	1.25	46.00	10.77	12.77
BOD_5 (mg/L)	2.00	28.00	10.24	7.79	1.20	26.50	9.67	7.53	2.00	28.00	10.24	7.79
COD (mg/L)	2.00	49.00	18.88	13.62	2.70	49.00	18.62	13.18	1.50	54.00	18.87	14.48
DO (mg/L)	3.20	8.40	5.40	1.45	3.20	8.90	5.61	1.66	3.49	8.90	5.73	1.50

Electrical conductivity (EC) exhibited mean annual values between 298.67 and 310.38 µS cm^{-1}, with maxima reaching 555 µS cm^{-1} (Table 5). These values fall within the WHO typical drinking-water range (300–1500 µS cm^{-1}; Table 3), yet the progressive downstream increase indicates anthropogenic ionic enrichment. Elevated EC reflects dissolved salts from sewage discharge, industrial effluents, fertiliser runoff, and urban stormwater inflow. The strong correlation between EC and TDS, as well as chloride (Table 8), confirms shared sources related to wastewater intrusion and catchment-scale land-use intensification.

Total dissolved solids (TDS) ranged from 160 to 550 mg L^{-1}. Although most observations remained within the BIS desirable limit of 500 mg L^{-1} (Table 3), peak downstream values approached or exceeded this threshold, particularly during low-flow pre-monsoon conditions. Such concentration-driven exceedances reflect reduced dilution capacity combined with cumulative pollutant loading. Persistent TDS enrichment downstream indicates chronic rather than episodic contamination.

Turbidity values (2.00–4.29 NTU) remained below the WHO/BIS permissible limit of 5 NTU (Table 3). However, systematic downstream elevation, particularly during the monsoon, indicates enhanced sediment mobilization and particulate transport. Monsoon runoff likely entrains suspended solids from exposed soils, construction sites, sand mining zones, and eroding riverbanks. While turbidity alone did not exceed potable thresholds, its coupling with organic and nutrient enrichment suggests the co-transport of pollutants adsorbed onto suspended particulates.

Collectively, the physicochemical dataset demonstrates a structurally consistent downstream increase in ionic load, suspended solids, and thermal stress, consistent with progressive anthropogenic disturbance.

3.2 Chemical characteristics

Chemical parameters provide more direct evidence of water quality impairment relative to global and national regulatory standards (Table 3). The pH values (mean 7.44–7.60) remained within WHO and BIS permissible limits (6.5–8.5). The slightly alkaline tendency observed downstream likely reflects enhanced biological productivity and bicarbonate buffering associated with sewage inputs. Although pH remained within compliance limits, its stability suggests that degradation is driven primarily by organic and nutrient loading rather than by acidification.

Chloride concentrations ranged from 5 to 78 mg L^{-1}, remaining below the BIS limit of 250 mg L^{-1}. However, elevated maxima in downstream segments reflect anthropogenic contributions from domestic sewage and industrial discharge. Chloride serves as a conservative tracer of wastewater contamination, and its downstream enrichment confirms the influence of municipal inflow, particularly in peri-urban stretches.

Nitrate concentrations (1.25–47 mg L^{-1}) showed pronounced variability. Although annual means (~10.8 mg L^{-1}) remained below the BIS drinking-water limit of 45 mg L^{-1}, peak downstream concentrations approached this regulatory threshold. Such levels are environmentally significant even when compliant with drinking-water standards, as nitrate concentrations exceeding 10 mg L^{-1} often contribute to eutrophication in lotic systems. Elevated nitrate in downstream reaches reflects agricultural runoff, livestock activity, septic leakage, and untreated domestic wastewater. The high standard deviation (~12.7 mg L^{-1}) indicates localized nutrient hotspots consistent with land-use intensification.

Biochemical oxygen demand (BOD_5) represents a critical indicator of organic pollution. Mean annual values (9.67–10.24 mg L^{-1}) substantially exceed CPCB Class B (<3 mg L^{-1}) and Class C (<6 mg L^{-1}) criteria [37]. Downstream maxima up to 28 mg L^{-1} confirm heavy organic loading. Such elevated BOD_5 indicates substantial input of biodegradable organic matter from untreated municipal sewage, industrial effluents, and pilgrimage-related waste discharge.

Similarly, COD values (mean ~18.6–18.9 mg L^{-1}; maxima up to 54 mg L^{-1}) confirm significant oxidizable organic and inorganic contamination. The strong BOD_5–COD correlation ($r \approx 0.94$; Table 8) indicates that organic pollution is a dominant degradation pathway.

Dissolved oxygen (DO) exhibited mean values between 5.40 and 5.73 mg L^{-1}, marginally meeting CPCB minimum criteria (≥5 mg L^{-1}). However, minima as low as 3.2–3.5 mg L^{-1} were recorded in downstream segments, falling below ecological safety thresholds. DO depletion directly reflects elevated BOD_5, nutrient enrichment, and increased microbial respiration. The strong negative correlation between DO and BOD_5/COD (Table 8) confirms oxygen depletion driven by organic and nutrient loading.

Mechanistically, water quality degradation in the Indrayani River is driven by: (i) untreated municipal sewage discharge from expanding peri-urban settlements, (ii) industrial effluent inflow from Talegaon–Chakan–Pimpri-Chinchwad industrial clusters, (iii) agricultural runoff introducing nitrate and dissolved salts, (iv) pilgrimage-related organic waste input at Dehu and Alandi, (v) reduced dilution during pre-monsoon low-flow periods, intensifying pollutant concentration, and (vi) channel morphology and reduced gradient downstream, prolonging residence time and enhancing oxygen depletion.

Thus, although several parameters remain within drinking-water limits, ecological thresholds for river health are consistently exceeded in downstream reaches. The convergence of organic loading, nutrient enrichment, and reduced oxygen availability confirms progressive transition from mesotrophic to eutrophic–hypereutrophic conditions.

3.3 Spatio-temporal variability based on average WQI

The spatial distribution of average WQI values (Figure 2a–c) integrates cumulative physicochemical effects and clearly illustrates longitudinal and interannual variability. Across all three years, upstream segments consistently remained within the "Good" category, reflecting low nutrient and organic loading. In contrast, midstream segments exhibited moderate to poor conditions, while downstream stretches were classified as very poor to unsuitable. The WQI maps demonstrate: (i) a persistent downstream degradation gradient; (ii) expansion of poor-quality zones in lower reaches; (iii) interannual stability in upstream reference conditions; and (iv) intensification of impairment near peri-urban and industrial clusters.

These spatial patterns correspond directly to descriptive statistics (Table 5) and station-wise values (Supplementary Tables S1–S3), in which elevated nitrate, BOD_5, and COD, and reduced DO were concentrated downstream. Although mean annual parameter values remained relatively stable, the spatial extent of degraded zones increased slightly in 2023–2024, indicating gradual downstream expansion of impaired stretches.

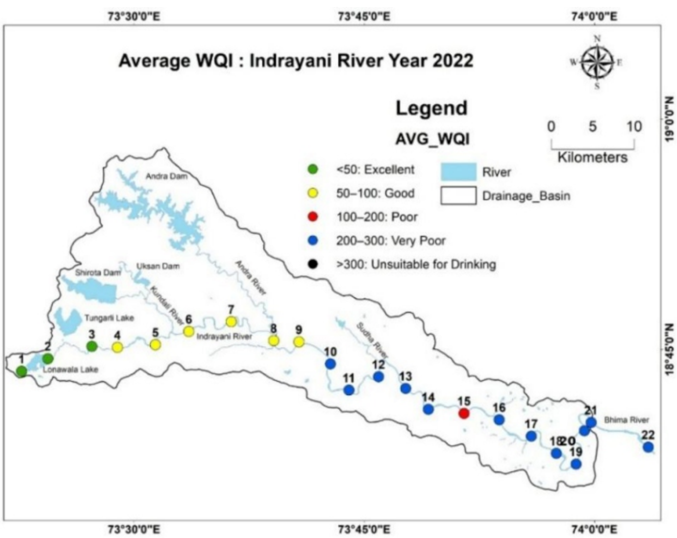

Figure 2a. Spatial distribution of average WAWQI along the Indrayani River in 2022

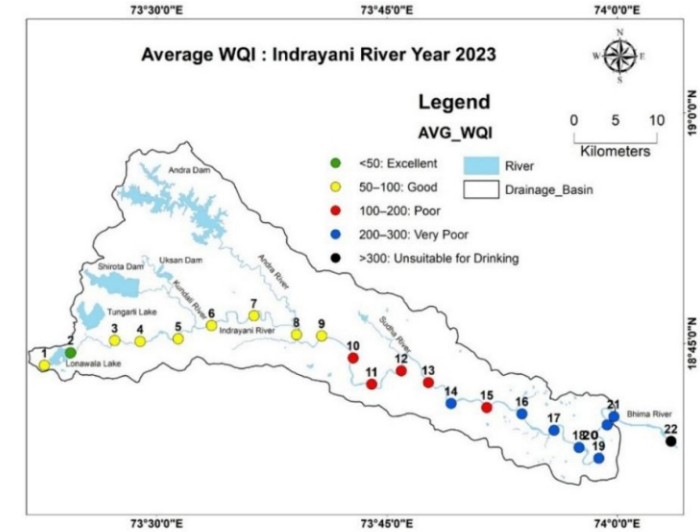

Figure 2b. Spatial distribution of average WAWQI along the Indrayani River in 2023

Collectively, the evidence confirms that degradation in the Indrayani River is structurally driven rather than episodic. Persistent nutrient enrichment, organic loading, and oxygen depletion in downstream segments are attributable to untreated municipal sewage, industrial discharges from the Talegaon–Chakan–Pimpri-Chinchwad corridor, agricultural runoff, and reduced dilution during pre-monsoon low-flow conditions.

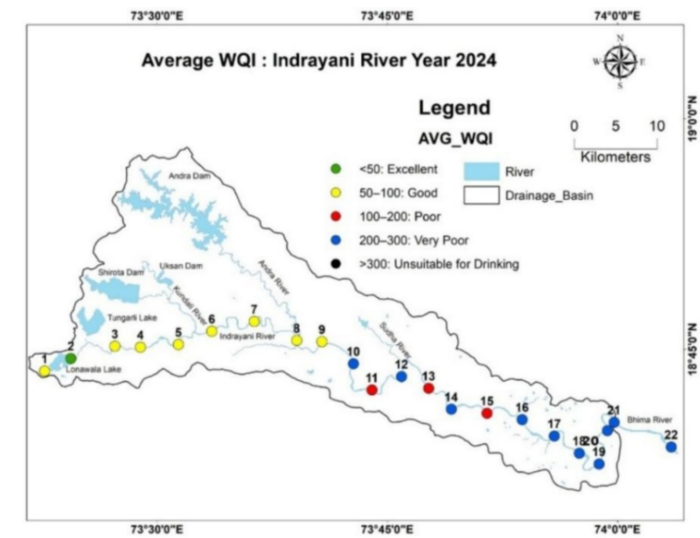

Figure 2c. Spatial distribution of average WAWQI along the Indrayani River in 2024

3.4 Water Quality Index (WQI)

The calculated WQI values (Table 6) integrate the effects of individual parameters to represent the composite water quality status of the Indrayani River. Upstream stations (1–3: Kurvande, Lonavala, and Waksai) recorded mean WQI values between 46 and 55, corresponding to "Good" water quality suitable for most domestic uses following minimal treatment.

High DO and low BOD_5 levels indicate limited anthropogenic disturbance in these headwater reaches.
Midstream stations (4–9) showed a marked decline in quality, with WQI values ranging from approximately 55 to 100. Agricultural runoff, highway emissions, and localized effluent discharge collectively increased turbidity and organic load. Kamshet (St-6) and Kanhe Bridge (St-7) frequently entered the "Very Poor" category, while Ambi Ghat (St-9) occasionally exceeded 100, denoting water unsuitable for domestic consumption.

Table 6: Year-wise and seasonal variation in the Water Quality Index (WQI) along the Indrayani River (2022–2024)

Sampling station		Average year-wise WQI			Season-wise mean		
No.	Name	2022	2023	2024	Summer	Monsoon	Winter
1	Kurvande Village	48.59	50.08	51.38	50.32	50.90	48.84
2	Lonavala lake	49.30	48.60	51.02	53.24	46.09	49.59
3	Waksai	49.11	53.18	52.08	54.12	50.84	49.39
4	Karla Malawali bridge	54.21	56.43	56.09	55.02	59.19	52.51
5	Pathargaon bridge	65.69	66.29	67.79	74.28	61.14	64.36
6	Kamshet-Nane bridge	66.95	67.55	84.68	73.84	65.12	65.99
7	Kanhe bridge	78.54	77.20	78.08	77.34	75.90	80.58
8	Sangavi Jambhul Ghat	83.09	82.19	83.52	80.61	80.38	87.80
9	Ambi Ghat	97.26	94.73	95.35	88.31	97.16	101.87
10	Induri Ghat	207.15	147.85	200.90	90.92	191.82	273.16
11	Kanhewadi Ghat	201.05	186.56	199.91	100.45	219.48	267.59
12	Dehu Ghat	205.29	189.93	200.62	104.70	255.03	236.11
13	Talwade-Chakan bridge	200.81	190.80	191.81	110.64	257.62	215.17
14	Chikhli-Moi bridge	206.07	200.71	204.48	160.21	290.34	160.71
15	Moshi-Chimbli bridge	195.41	191.90	197.99	170.36	287.38	127.56
16	Alandi Ghat	217.74	211.68	220.20	226.14	292.22	131.26
17	Dhanori bund	285.93	274.72	287.12	304.84	394.58	148.35
18	Wadgaon Shinde bund	285.67	279.67	293.44	310.61	388.40	159.77
19	Bhawadi	281.03	288.92	287.60	316.61	362.43	178.50
20	Markal bund	295.91	290.31	299.29	305.01	383.92	196.59
21	Tulapur Triveni Sangam	294.56	290.32	307.02	304.60	363.52	223.77
22	Bhima-Koregaon	292.84	307.00	293.93	287.36	347.13	259.28

Downstream stations (10–22) exhibited severe degradation. Induri Ghat (St-10) recorded WQI values between 147 and 273, while Alandi Ghat (St-16) averaged approximately 220. Dhanori Bund (St-17) reached a maximum of approximately 395. Tulapur (St-21) and Bhima-Koregaon (St-22) consistently exceeded 300, indicating the water was unfit even for irrigation. These results delineate a clear longitudinal transition from "Good" upstream conditions to "Very Poor/Unsafe" downstream status (Table 6; Figure 3).

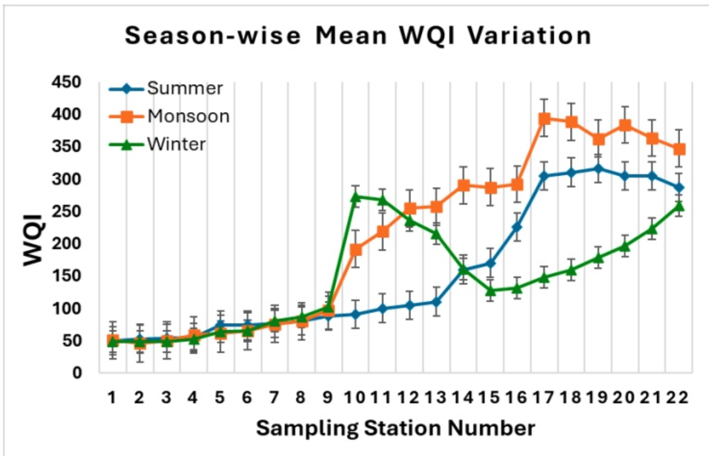

Figure 3: Season-wise mean WQI variation in the Indrayani River

3.5 Spatial and seasonal variations

Seasonal WQI analysis (Figure 3) revealed consistent patterns across all three years. Pre-monsoon (summer) conditions produced the highest WQI values due to reduced dilution, elevated temperatures, and elevated pollutant concentrations. In 2024, summer WQI ranged from 48 (Lonavala) to 319 (Markal). Monsoon conditions exhibited mixed responses. Upstream improvements were observed due to dilution, whereas downstream deterioration occurred due to surface runoff and sewer overflows. The highest recorded WQI (407) occurred during monsoon 2024 at Bhima-Koregaon. Post-monsoon (winter) conditions showed partial recovery, with upstream WQI values remaining low (~51) while downstream segments continued to exhibit elevated values (up to 263).
Interannual variation (Figure 4) was minimal, with consistent spatial hierarchy across 2022–2024. Stations 1–3 remained within the "Excellent–Good" range (WQI < 75), Stations 4–9 within the "Moderate–Poor" range (75–100), and Stations 10–22 consistently within the "Very Poor" range (>100).

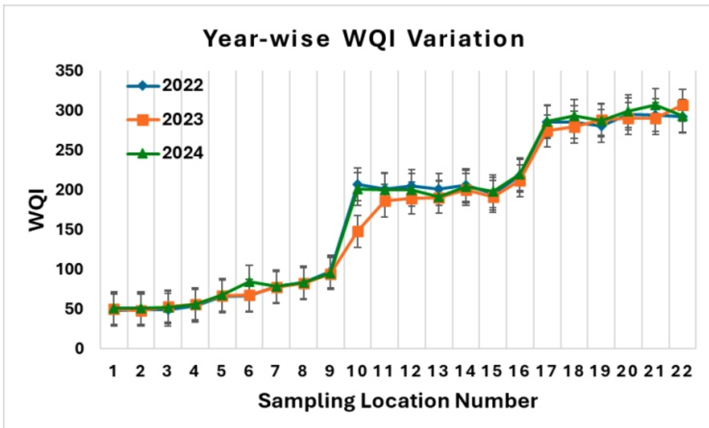

Figure 4: Year-wise WQI variation for 2022, 2023, and 2024 in the Indrayani River

3.6 Trophic status

Trophic classification derived from WQI ranges (Table 7) and nutrient–oxygen indicators reveal a clear longitudinal transition. Upstream stations (1–3) exhibited oligotrophic to mesotrophic conditions, characterized by high transparency, elevated DO, and low BOD_5 and Nutrient levels. These conditions are maintained via riparian protection, land-use controls, and erosion prevention. Midstream stations (4–9) transitioned to mesotrophic–eutrophic states, reflecting moderate nutrient enrichment and intermittent DO reductions. Downstream stations (10–22) were predominantly eutrophic to hypereutrophic. These segments exhibited elevated BOD_5/COD, high nitrate concentrations, and recurrent DO minima approaching hypoxic thresholds. Hypereutrophic conditions were particularly evident at Stations 17–22 and consistent across seasons. These classifications align with observed ecological indicators, including algal proliferation, odour generation, and reduced aquatic biodiversity in downstream reaches, consistent with established eutrophication models [39,42,43].

Table 7: Trophic status of Indrayani River segments based on observed WQI ranges at each station (multi-year average)

Station No.	Station Name	WQI Range (Avg.)	Water Quality Status	Trophic Category
1	Kurvande Village	48–51	Good – Poor	Oligotrophic → Mesotrophic
2	Lonavala Lake	46–53	Good – Poor	Oligotrophic → Mesotrophic
3	Waksai	49–54	Good – Poor	Oligotrophic → Mesotrophic
4	Karla Malawali Bridge	54–59	Poor	Mesotrophic
5	Pathargaon Bridge	61–74	Poor	Mesotrophic
6	Kamshet–Nane Bridge	65–88	Poor – Very Poor	Mesotrophic → Eutrophic
7	Kahne Bridge	75–80	Very Poor	Eutrophic (incipient)
8	Sangavi Jambhul Ghat	80–88	Very Poor	Eutrophic
9	Ambi Ghat	88–101	Very Poor – Unsuitable	Eutrophic
10	Induri Ghat	147–273	Unsuitable	Eutrophic
11	Kanhewadi Ghat	186–267	Unsuitable	Eutrophic
12	Dehu Ghat	189–236	Unsuitable	Eutrophic
13	Talwade–Chakan Bridge	190–215	Unsuitable	Eutrophic
14	Chikhli–Moi Bridge	160–290	Unsuitable	Eutrophic
15	Moshi–Chimbli Bridge	170–287	Unsuitable	Eutrophic
16	Alandi Ghat	211–292	Unsuitable	Eutrophic
17	Dhanori Bund	274–395	Unsuitable	Hypereutrophic
18	Wadgaon Shinde Bund	280–388	Unsuitable	Hypereutrophic
19	Bhawadi	281–362	Unsuitable	Hypereutrophic
20	Markal Bund	290–384	Unsuitable	Hypereutrophic
21	Tulapur (Triveni Confluence)	290–364	Unsuitable	Hypereutrophic
22	Bhima-Koregaon	287–347	Unsuitable	Hypereutrophic

3.7 Pearson correlation analysis of water quality parameters

Pearson's product–moment correlation analysis (**Table 8**) was conducted on the complete dataset (all stations, all seasons, 2022–2024), yielding 137 pairwise correlation coefficients among 17 physicochemical variables. Of these, 54 correlations were strong ($r > 0.70$), 15 were moderate (0.50–0.70), 31 were weak (< 0.50), and 37 were negative. Strong positive correlations were observed among salinity indicators: EC showed high correlations with TDS, chloride, and sulphate (e.g., EC–TDS: $r \approx 0.89$). Total hardness strongly correlated with magnesium and alkalinity, reflecting co-variation in dissolved ion concentrations derived from wastewater inputs and geochemical background.

Organic load indicators exhibited pronounced coupling. BOD_5 and COD showed a very strong positive correlation ($r \approx 0.94$). Dissolved oxygen displayed strong negative correlations with BOD_5, COD, and nitrite, confirming oxygen depletion under elevated organic and nutrient loads. pH demonstrated weak correlations ($r < 0.30$) with most variables, suggesting effective buffering capacity and limited short-term responsiveness to pollutant fluctuations.

Two principal clusters emerged: (i) EC–TDS–major ions representing ionic enrichment processes; and (ii) BOD_5–COD–nutrients inversely associated with DO, representing organic pollution and eutrophication dynamics. These correlation patterns confirm shared pollution sources, primarily sewage and industrial effluents, and support the use of representative proxies (e.g., EC for ionic load; BOD_5/COD for organic load) in streamlined monitoring frameworks.

Table 8: The correlation matrix of water quality parameters 2022-23-24

Parameters	Temp	Turbidity	EC	TDS	pH	Alk.	TH	Mg	Cl	S	P	NO_3	NO_2	Amm. Nitrate	BOD_5	COD	DO
Temperature	1.00	0.24	0.26	0.14	-0.03	0.29	0.36	0.36	0.22	0.21	0.23	0.25	0.30	-0.15	0.31	0.29	-0.20
Turbidity		1.00	-0.63	-0.72	0.17	-0.64	-0.58	-0.74	-0.56	-0.62	-0.58	-0.66	-0.70	-0.44	0.89	0.63	0.05
EC			1.00	0.89	0.13	0.13	0.89	0.82	0.85	0.85	0.86	0.89	0.89	0.16	0.89	0.80	-0.89
TDS				1.00	0.24	0.86	0.74	0.69	0.94	0.96	0.71	0.97	0.79	0.00	0.81	0.63	-0.71
pH					1.00	0.24	-0.18	-0.23	0.32	0.24	0.08	0.16	-0.05	-0.44	-0.12	-0.33	0.05
Alkalinity						1.00	0.85	0.82	0.82	0.80	0.87	0.85	0.93	0.19	0.88	0.78	-0.88
Total Hardness							1.00	0.90	0.71	0.71	0.82	0.79	0.90	0.24	0.94	0.91	-0.89
Mg								1.00	0.55	0.57	0.75	0.68	0.91	0.52	0.89	0.93	-0.95
Cl									1.00	0.96	0.70	0.94	0.71	-0.20	0.75	0.52	-0.61
Sulphate										1.00	0.66	0.98	0.69	-0.17	0.77	0.56	-0.62
Phosphate											1.00	0.67	0.82	0.33	0.76	0.69	-0.81
NO_3												1.00	0.78	-0.07	0.85	0.68	-0.70
NO_2													1.00	0.40	0.90	0.88	-0.91
Amm. Nitrate														1.00	0.15	0.36	-0.43
BOD_5															1.00	0.94	-0.87
COD																1.00	-0.89
DO																	1.00

4. Discussion

4.1 Spatial and temporal water quality trends

The longitudinal decline in water quality along the Indrayani River (Tables 5–6; Figures 3–4) reflects a systematic transition from relatively undisturbed headwaters to severely impaired downstream reaches. The upstream segments near Kurvande, Lonavala, and Waksai maintain comparatively high dissolved oxygen levels and low BOD_5/COD concentrations, consistent with limited anthropogenic interference and effective natural self-purification. These headwater reaches function as ecological reference zones. In contrast, downstream segments exhibit progressive enrichment of dissolved ions, nutrients, and organic matter, accompanied by recurrent DO depression. The persistence of this pattern across three consecutive years confirms that degradation is structural rather than episodic.

Seasonal variability further modulates this gradient. Pre-monsoon low-flow conditions intensify pollutant concentration, elevate temperature, and reduce dilution capacity, resulting in the highest WQI values. Monsoon periods introduce hydrological dilution upstream but simultaneously transport sediments, nutrients, and untreated runoff into downstream stretches. Post-monsoon recovery remains partial and spatially uneven. Similar seasonal oscillations have been documented in the Ganga [44] and Godavari [45], indicating that flow regime and anthropogenic inputs jointly regulate the water quality of tropical rivers.

4.2 Regional importance of the Indrayani River and emerging threats

The Indrayani River is hydrologically, ecologically, culturally, and economically significant within the Bhima sub-basin. Originating in the Western Ghats biodiversity hotspot, it supports riparian ecosystems, irrigated agriculture, peri-urban water demand, and downstream communities before merging with the Bhima River. Additionally, pilgrimage centres such as Dehu and Alandi impart substantial socio-religious importance, drawing large seasonal gatherings.

However, the river is increasingly subjected to multiple converging threats:

a. Rapid urban expansion: The Pimpri–Chinchwad and Talegaon–Chakan industrial corridor has expanded substantially over the past two decades [31,32]. Wastewater infrastructure has not expanded in proportion, resulting in the discharge of untreated or partially treated sewage.

4.3.3 Hydrological controls

Flow regime significantly modulates pollution intensity. During pre-monsoon low-flow periods, dilution capacity declines, increasing pollutant concentration. Conversely, monsoon events enhance downstream runoff-driven loading. Reduced gradient and channel modification in lower reaches prolong water residence time, limit hyporheic exchange, and intensify oxygen depletion [49,52]. Thus, degradation arises from the interaction between pollutant input and altered hydro-morphology.

4.4 Comparative regional and global context

The degradation trajectory of the Indrayani River parallels patterns observed in other rapidly urbanising tropical basins. Within western India, the Bhima River exhibits poor to very poor WQI in urban stretches [11,46], while the Mula–Mutha system includes Priority-I stretches due to $BOD_5 > 30$ mg L^{-1} [14].

Indrayani's distinct feature, however, is its dual stress: religious tourism and industrialisation, which produce spatially heterogeneous spikes in organic and nutrient pollution [14,54]. Globally, comparable WQI gradients have been documented in the Mekong Delta [12,55,56], Saigon River [57] and the Chao Phraya Basin [58], where mixed land-use pressures drive spatially heterogeneous yet persistent declines in water quality. These parallels position the Indrayani River within a broader class of urbanising monsoon-fed rivers undergoing progressive eutrophication under combined industrial, agricultural, and urban stress.

4.5 Broader implications for water resource management and policy

The findings of this study have direct implications for regional water governance and policy frameworks. First, the clear upstream–downstream gradient underscores the need for sub-basin-scale management rather than uniform basin-wide strategies. Prioritise protection of oligotrophic headwaters through land-use regulation and riparian restoration.

Second, the persistent exceedance of CPCB ecological thresholds downstream indicates inadequate wastewater treatment capacity. Expansion of decentralised sewage treatment plants (STPs) with nutrient removal in peri-urban clusters is essential. Third, agricultural policy should integrate nutrient interception through vegetative buffer strips, constructed wetlands, and precision fertilizer application. Fourth, pilgrimage-related management requires event-based sanitation planning, temporary waste infrastructure, and intensified seasonal monitoring.

From a governance perspective, WQI-based monitoring provides a transparent decision-support tool that aligns with SDG-6 reporting frameworks [27,28]. Integrating WQI diagnostics with trophic classification provides a policy-relevant metric for tracking restoration progress.

The study also highlights the importance of Integrated River Basin Management (IRBM) approaches [59], which address hydrological, ecological, and socio-cultural dimensions simultaneously. Without coordinated intervention, the downstream hypereutrophic segments risk crossing ecological tipping points characterised by chronic hypoxia, biodiversity collapse, and impaired ecosystem services.

4.6 Ecological consequences

The trophic gradient identified in Table 7 corresponds to biological transitions commonly associated with eutrophication. Oligotrophic headwaters likely support diverse benthic macroinvertebrates and fish species, whereas eutrophic downstream reaches are expected to favour pollution-tolerant taxa (e.g., Chironomidae, Oligochaeta). DO minima below 4 mg L^{-1} threaten sensitive aquatic organisms and disrupt metabolic balance.

In hypereutrophic sections (Stations 17–22), sustained oxygen depletion may promote anaerobic conditions, internal nutrient recycling, and excessive macrophyte proliferation. Such feedback mechanisms accelerate ecological degradation, as described in global eutrophication frameworks [43,60].

5. Conclusion:

This three-year, multi-season assessment of the Indrayani River reveals consistent, progressive deterioration in water quality along its longitudinal gradient.

The WAWQI demonstrated stable upstream–downstream differentiation from 2022 to 2024, with headwater stations (1–3) maintaining “Good” conditions (WQI < 50), while downstream reaches (10–22) persistently fell within “Very Poor/Unsafe” categories (WQI > 250–300). This pattern confirms structural degradation rather than episodic contamination.

Elevated BOD_5 and COD concentrations, recurrent nitrate enrichment, and dissolved-oxygen minima below ecological thresholds collectively indicate advanced eutrophic-to-hypereutrophic conditions in the lower segments. Although several parameters remained within BIS and WHO drinking-water limits, ecological benchmarks for river health were consistently exceeded downstream. The principal drivers of impairment include untreated municipal sewage discharge, industrial effluents from the Talegaon–Chakan–Pimpri-Chinchwad corridor, agricultural runoff, pilgrimage-related organic inputs, and hydrological concentration during pre-monsoon low-flow conditions.

The findings underscore the ecological significance of protecting upstream oligotrophic reaches as reference zones while prioritising downstream restoration. Sub-basin-scale management interventions are urgently required, including expanding decentralized sewage treatment infrastructure with nutrient removal, strictly monitoring industrial compliance, implementing agricultural buffers, and structuring the management of pilgrimage-associated waste.

The WQI framework applied here provides a transparent, policy-relevant diagnostic tool aligned with SDG-6 monitoring and the principles of Integrated River Basin Management (IRBM).

Future research should integrate biological indicators, quantify sediment-associated nutrient fluxes, conduct source-apportionment analyses, and model climate-driven hydrological variability to assess long-term resilience. Without coordinated watershed-level action, downstream reaches risk ecological tipping points. However, the persistence of relatively healthy headwaters demonstrates that recovery remains feasible through timely, evidence-based intervention.

Use of AI Statement:

During manuscript preparation, the authors used AI solely to assist with sentence-level editing and grammar refinement. All text was subsequently reviewed and revised by the authors, who accept full responsibility for the content of the published article.

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