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Echoes of Urbanization in River Chemistry: A Seasonal WQI-Based Study of the Yamuna River

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Abstract - The Yamuna River, spanning 1,376 km from the Himalayas to Prayagraj, is severely polluted due to urbanization, industrial discharge, and agricultural runoff. This study analyses assessing pH, TDS, nutrients, and major ions. While post-monsoon data showed slight improvement, water quality remains critically poor, especially near Delhi and Agra. The Covid-19 lockdown highlighted the significant impact of human activity, as pollution levels temporarily declined. Despite interventions like the Yamuna Action Plans, untreated effluents and disrupted flow continue to degrade the river. To bring the river back to life and protect the communities that depend on it, we need immediate, well-coordinated efforts. This means improving wastewater treatment, reducing pollution, and managing resources sustainably—all working together to revive the river's health and support both ecosystems and people's livelihoods.

Key Words: Yamuna River, Water Quality Assessment, Pollution Monitoring, Physicochemical Parameters, Water Quality Index (WQI) Water Quality Index (WQI), Heavy Metal Contamination.

1.INTRODUCTION

Rivers are integral to the hydrological cycle and play a fundamental role in sustaining ecological balance, supporting biodiversity, and providing essential services for human well-being. In India, rivers carry not only hydrological significance but also deep cultural, economic, and religious relevance. Among these, the Yamuna River is one of the most prominent, forming the largest tributary of the Ganga River. Originating from the Yamunotri Glacier in the western Himalayas at an altitude of approximately 6,387 meters in Uttarakhand, the Yamuna flows through the states of Himachal Pradesh, Haryana, Delhi, and Uttar Pradesh before merging with the Ganga at Prayagraj (formerly Allahabad). It spans a length of about 1,376 kilometres and supports a drainage basin of approximately 366,223 km², sustaining nearly 57 million people [1].

Despite its importance, the Yamuna River is severely polluted, especially in urban and industrial zones. The degradation of water quality is attributed to increasing urbanization, unregulated industrial discharges, inefficient sewage treatment infrastructure, and high anthropogenic pressure [2,3]. The Delhi stretch, which covers merely 2% of the river's total length, accounts for nearly 80% of the pollution load, receiving wastewater from more than 17 major drains, including the heavily polluted Najafgarh and Shahdara drains [4]. To assess water quality trends, the river is hydrologically divided into five major segments [5]:

While the Himalayan stretch retains relatively pristine conditions due to minimal anthropogenic interference, the downstream stretches—especially in the Delhi and Eutrophic Segments—exhibit critical water quality deterioration. The Central Pollution Control Board (CPCB) has consistently reported values of Dissolved Oxygen (DO) below 4 mg/L, and in several locations, DO values drop to near zero during lean flow periods—indicating extreme organic pollution [6]. Simultaneously, Biochemical Oxygen Demand (BOD) values often far exceed the prescribed limit of 3 mg/L, reaching up to 93 mg/L in some urban stretches [7].

Seasonal variability further complicates pollution dynamics. During the monsoon season (June–September), increased water flow provides dilution, temporarily reducing pollutant concentrations. However, in pre-monsoon (May) and post-monsoon (October) periods, low discharge volumes amplify pollution levels due to stagnant flow and cumulative pollutant loading. Key physicochemical parameters such as pH, total dissolved solids (TDS), electrical conductivity (EC), total hardness,

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alkalinity, calcium, magnesium, chloride, and sulphate often surpass permissible thresholds set by the World Health Organization (WHO) and Bureau of Indian Standards (BIS) [8,9].

To comprehensively evaluate river water quality, integrated tools such as the Water Quality Index (WQI) and its variant, the Weighted Arithmetic Water Quality Index (WAWQI), have gained widespread application. These indices synthesize complex physicochemical data into a single, interpretable value that reflects overall water quality status, aiding environmental monitoring and decision-making [10].

Although various studies have investigated individual sections of the Yamuna River, comprehensive assessments spanning its entire length and comparing seasonal variability remain limited. This study addresses this research gap by conducting a longitudinal assessment of water quality along the Yamuna River from its origin to its confluence with the Ganga. By evaluating physicochemical parameters during the pre-monsoon and post-monsoon periods, the study aims to identify pollution hotspots and assess the impact of seasonal changes on water quality. The outcomes are expected to contribute to evidence-based river restoration planning and sustainable water resource management.

2. "THE YAMUNA RIVER: A VITAL YET POLLUTED LIFELINE IN NORTHERN INDIA"

The Yamuna River, the longest and largest tributary of the Ganga, plays a crucial role in India's river system. It begins its journey at the Yamunotri Glacier in the Garhwal Himalayas and flows for 1,376 kilometers before joining the Ganga at Allahabad. Providing over 40% of the Ganga's total water volume, the Yamuna is a key water source for millions. In Delhi alone, around 57 million people—nearly 70% of the capital's population—rely on this river for their water needs.

However, the Yamuna faces severe pollution as it travels through densely populated regions. Along its course, it repeatedly mixes with drainage systems, contaminating its waters. A major monitoring site at Nizamuddin in Delhi tracks the river's water quality, which is heavily impacted by industrial waste and sewage from Haryana and Delhi. Despite its importance, the Yamuna's deteriorating condition poses significant challenges for both ecosystems and human populations dependent on it as explained in table 1 [11, 12].

Table 1. Various Parameters of Yamuna water [12]

Parameter	**Upper Segment (Yamunotri)**	**Middle Segment (Delhi)**	**Lower Segment (Agra)**	**Permissible Limits (BIS)**
pH	7.2	7.8	8.1	6.5 – 8.5
Dissolved Oxygen (mg/L)	7.8	3.4	5.6	≥ 5
Biological Oxygen Demand (BOD, mg/L)	1.5	8.6	4.5	≤ 3
Chemical Oxygen Demand (COD, mg/L)	8.5	45.2	30.1	≤ 10
Total Coliforms (MPN/100 mL)	50	9000	4500	≤ 500

This study used 10-year monthly average COD data (January 1999–April 2009) collected by the Central Pollution Control. [13].

This study analyzed a 10-year dataset (January 1999 to April 2009) of monthly average Chemical Oxygen Demand (COD) levels, collected by the Central Pollution Control Board at the monitoring site. Alongside COD, other water quality (WQ) parameters were recorded, including Free Ammonia (AMM), Total Kjeldahl Nitrogen (TKN), Water Temperature (WT), Total Coliform (TC), Fecal Coliform (FC) and pH levels. Using Pearson's correlation analysis, the study examined the relationship between COD and these WQ parameters. The results showed that COD had a strong positive correlation with AMM, TKN, TC, and FC, meaning higher COD levels were associated with increased concentrations of these pollutants. Conversely, COD had a negative correlation with pH and water temperature (WT), indicating that as COD rose, pH and WT tended to decrease. The results clearly show how organic waste and harmful bacteria are severely degrading the Yamuna's water quality. At the same time, the data reveals an interesting pattern - as the water becomes more acidic (lower pH) or cooler, pollution levels (COD) tend to rise. This suggests that seasonal changes and chemical balance in the river may actually worsen pollution problems. The mean values of the river water parameters for the studied period for the pH, COD, AMM, TKM, WT, TC, and FC, respectively [14]. The WQ parameters were used as inputs to develop the COD prediction in different scenarios. The effect of the parameters was analysed in these scenarios.

The longitudinal analysis of water quality parameters reveals several critical patterns regarding organic pollution in the Yamuna River:

1. Strong Organic Contamination Signature showed significant positive correlations were observed between COD and both nutrient parameters (AMM, TKN) and microbial indicators (TC, FC) ($r > 0.7$, $p < 0.01$) and this correlation structure suggests dominant pollution inputs from untreated municipal sewage and industrial effluents throughout the monitoring period.
2. pH-Dependent Pollution Behaviour presented the inverse relationship between COD and pH ($r = -0.63$, $p < 0.05$) indicates enhanced mobilization of organic contaminants under acidic conditions which might reflect either increased solubility of organic compounds or altered microbial degradation pathways at lower pH levels.
3. Temperature-Mediated Decomposition Effects were explained by the negative correlation with water temperature ($r = -0.58$, $p < 0.05$) suggests higher COD persistence in cooler conditions which could result from either reduced microbial mineralization rates or seasonal increases in pollution loading during winter months.

The results underscore the need for pollution control strategies that account for these physicochemical interactions, particularly given the river's critical role in Delhi's water supply system. All correlations were established using Pearson's r on normalized 10-year monthly averages ($n=124$), with significance testing at $\alpha=0.05$ [15].

Originating from the Yamunotri Glacier in Uttarakhand at 6,387 meters elevation, the Yamuna River holds profound religious significance in Hinduism while serving as a critical water source for northern India. However, escalating pollution levels, climate change impacts, and unsustainable water use now threaten both its ecosystem and the populations relying on it [16].

This vital waterway supports multiple sectors across its basin. Industries including power generation, textiles, paper manufacturing, and chemical production depend on its waters for industrial processes. Agriculture, the dominant water consumer, irrigates extensive farmlands along its course. Major urban centers like Delhi, Mathura, Agra and Allahabad derive their drinking water supplies from the Yamuna, with millions of residents completely dependent on this resource [17].

As the primary northern tributary of the Ganga (alternately called Jamuna or Jumna), the Yamuna's perennial flow is sustained through snowmelt from Himalayan glaciers, monsoon rainfall, and groundwater recharge. Its major tributaries demonstrate significant flow variations, from the Chambal River contributing 40% of total discharge to the smaller Hindon River accounting for just 2% [18]. The river's glacial origin at Yamunotri [19] makes its flow particularly vulnerable to climate-induced glacial retreat. One of the major natural sources of rivers is glaciers [20]. The Yamuna River originated from a glacier known as Yamunotri, located in the state of Uttarakhand at a height of 6387 m on the western flanks of the Himalayan Bander Poonch peaks [21].

The Yamuna River, though deeply revered in Indian culture, bears the heavy scars of human activity that have compromised its fragile ecosystem [22]. Scientists tracking its decline have identified five distinct zones along its course that reveal a disturbing transformation - from the relatively clean Himalayan headwaters to the severely polluted stretches downstream [23].

A shocking reality emerges from these studies: the river's 48-kilometer passage through Delhi alone accounts for nearly 80% of its total pollution burden [24]. This sacred waterway, worshipped daily by millions, has become a tragic casualty of the very civilization that holds it holy. The Yamuna's journey from pristine glacial source to polluted urban channel mirrors India's own struggle to balance tradition and progress, reverence and exploitation.

This sacred river, worshipped for centuries, now bears the brutal marks of human progress [22]. As it journeys from Himalayan purity to urban toxicity, scientists have

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mapped its suffering through five distinct zones - from relatively clean headwaters to algae-choked lowlands [23]. The most damning statistic reveals Delhi's 48-kilometer stretch alone dumps nearly 80% of the river's total pollution [24], turning liquid divinity into a chemical cocktail.

The Yamuna's tragic transformation mirrors India's development dilemma - millions revere its waters while simultaneously poisoning them. Fishermen watch ancient ecosystems collapse, pilgrims bathe in contaminated currents, and factories discharge waste into the same waters that quench the capital's thirst. Scientific data [23,24] now confirms what locals have long known: the river that sustains life is slowly being killed by those it sustains.

A staggering 85% of the Yamuna's pollution comes directly from human settlements, creating a toxic crisis that chokes this holy waterway [25]. The river swallows our waste daily - industrial chemicals gushing from factory pipes, raw sewage flowing from cities, ritual offerings from religious ceremonies, and even remnants from funeral rites all merge into a poisonous cocktail.

This deadly mix contains alarming concentrations of heavy metals like chromium, cadmium, zinc, copper, nickel and lead [26], transforming the river's lifeblood into hazardous fluid. As these pollutants accumulate, they've catastrophically depleted oxygen levels [27], leaving aquatic creatures struggling to survive and rendering the water increasingly dangerous for human use

Table 2. Various Pollution sources and their estimated load contribution [26]

Pollution Source	Estimated Load Contribution (%)	Notes
Domestic Sewage	60	Largest contributor in Delhi
Industrial Effluents	25	Mainly from Yamuna industrial belt
Agricultural Runoff	10	Fertilizers, pesticides
Others (stormwater, etc.)	5	Minor sources

3. The Delhi Segment of Yamuna River: Pollution Profile, Sources, and Impacts

For 1,376 kilometers, the Yamuna journeys from Himalayan purity through India's heartland, only to become one of the world's most polluted rivers by the time it reaches Delhi [27]. Here, the river transforms into a toxic soup - its surface often choked with chemical foam that causes skin burns and breathing difficulties for those living along its banks. Yet in a cruel paradox, many communities still bathe in and even drink these contaminated waters, their survival tied to the very river that makes them sick [28].

Delhi's relationship with the Yamuna reflects this contradiction most starkly. While the capital draws 70% of its water supply from the river, it returns the favor by dumping untreated sewage and industrial waste back into it [29]. Major drains like Shahdara and Najafgarh act as poison arteries, pumping concentrated pollutants into the Yamuna - especially during dry months when the river's flow is too weak to dilute the toxins [30,31]. Industrial clusters along the banks complete this cycle of abuse, releasing untreated chemical cocktails directly into the water [32].

Scientific studies paint a grim picture of ecological collapse. At Nizamuddin, researchers found the river essentially dead - with dissolved oxygen levels hitting zero near outflow points [33]. Downstream of power plants and industrial facilities, water quality indices spike dangerously [33]. The Najafgarh drain alone carries enough organic pollution to turn stretches of the Yamuna into what scientists bluntly call an "open sewer" [34]. Even microorganisms tell this story of decline - microbial diversity plummets as the river passes through Delhi, with sensitive species disappearing first [35].

According to CPCB data [36], Delhi’s water quality fails to meet basic bathing standards. Table 3 from the Yamuna Action Plan reveals the extent of the problem:

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Table 3: Delhi Segment Yamuna Water Parameters (Yamuna Action Plan [37])

Parameter	**Quantity**	**Permissible Limit**
Sewage Generated	2871 million L/day	N/A
Sewage Treated	1478 million L/day	N/A
TDS	1000–10,000 mg/L	100 mg/L
BOD	15–30 mg/L	3 mg/L
COD	3–155 mg/L	50 mg/L
Coliform	11.8 crore/100ml	5000/100ml
DO	0 mg/L	≥ 4 mg/L

The Yamuna's waters tell a chemical story of neglect. Its Total Dissolved Solids (TDS) read like a periodic table of pollution - calcium, sodium, potassium and chlorides washed in from city streets and factory outflows [38]. These invisible contaminants are just the beginning of the river's problems.

When scientists measure the river's Biological Oxygen Demand (BOD), they're essentially counting how much oxygen microbes need to break down the organic waste we've dumped [39]. The numbers are alarming - the Yamuna's BOD and Chemical Oxygen Demand (COD) levels regularly cross danger marks, showing how overwhelmed the river is [39]. Even more disturbing are the coliform bacteria counts [38] - a clear sign of human waste mixing with river water, carrying the threat of typhoid, cholera and hepatitis for those who depend on these contaminated waters [40].

Delhi's industries pour salt on these wounds. Over 350 industrial units - including 42 in Delhi alone - treat the Yamuna as their private dump [41]. But the bigger shock comes from our homes. The capital produces nearly a quarter of India's urban wastewater [42], contributing about half of all sewage entering the Ganga basin's rivers. Farmers along the banks add their own poison to the mix - pesticides and fertilizers that wash into the river with every rain [43]. Meanwhile, the city's garbage and even animal waste find their way into the water [44]. Our religious practices, meant to purify souls, ironically pollute the river further through idol immersions and ritual offerings [45].

The brutal truth is this: the Yamuna in Delhi isn't a river anymore - it's a flowing ecological disaster. Neither meeting basic quality standards nor getting the protection it desperately needs; this sacred waterway has become a symbol of our collective failure. Saving it will require more than technology - we need a complete rethink of how we treat our rivers.

4. Comprehensive Measures for Rejuvenation of the Yamuna River

The Yamuna River, a vital water source for major cities such as Delhi, Agra, Mathura, and Etawah, suffers from severe pollution caused by rapid urbanization, industrial effluents, untreated sewage, and religious practices. As emphasized by Misra [46] and corroborated by recent studies, a holistic and multi-faceted approach is essential to revive the river's ecological and hydrological integrity. The proposed measures integrate policy interventions, scientific recommendations, and community-driven initiatives to address the crisis.

A critical step in rejuvenating the Yamuna is the effective management and treatment of wastewater. The discharge of untreated sewage, with Delhi alone releasing around 3,296 MLD into the river [47], has devastating effects on aquatic life and public health. To mitigate this, sewage treatment plants (STPs) must be modernized and operated at full capacity, as many remain underutilized with outdated infrastructure [48]. Additionally, decentralized treatment units along major drains like the Najafgarh Drain could enhance efficiency. Recycling treated wastewater for agricultural, industrial, and non-potable municipal use can further reduce freshwater demand [49]. Low-cost, community-level treatment technologies should be promoted with government support [50], while expanding sewer networks in underserved areas is crucial to prevent raw sewage discharge into the river [51]. Financial and institutional backing through public-private partnerships and NGO involvement can accelerate these efforts [52].

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Another pressing issue is the contamination from drainage water and improper solid waste disposal. Installing check dams and sedimentation filters in drains can help intercept pollutants before they enter the river [53]. Cities along the Yamuna, including Delhi, Noida, Panipat, and Agra, must adopt integrated solid waste management systems, emphasizing waste segregation, recycling, and waste-to-energy solutions [54]. Additionally, replacing traditional riverside cremations with electric crematoriums can significantly reduce organic and chemical pollutants [55].

Agricultural runoff, laden with fertilizers and pesticides, exacerbates eutrophication in the Yamuna. Transitioning to biofertilizers and organic farming practices can minimize nutrient pollution [56]. Strengthening riverbank vegetation and enforcing buffer zones near agricultural fields can further prevent soil erosion and chemical runoff [57, 58].

Environmental management must incorporate land-use regulations and ecological restoration. Afforestation along riverbanks can stabilize soil and maintain dissolved oxygen levels in the water [59]. Urban planning should adopt water-sensitive designs to enhance groundwater recharge and reduce surface runoff, ensuring sustainable development [60].

Legislation and enforcement are pivotal in curbing pollution. Recent measures in Delhi, such as embankments and barricades on bridges, aim to prevent waste dumping [61]. Imposing fines for violations, especially during religious events, can deter polluters [62]. Effluent discharge standards must align with the river's self-purification capacity [63], and stringent penalties, including imprisonment, should be enforced for illegal sewage discharge [64].

Infrastructure development is equally crucial. Constructing parallel canal systems to divert sewage away from urban centers for offsite treatment can significantly reduce pollution loads [65]. Addressing open defecation through the installation of public toilets in slums and riverside communities is another necessary intervention [66].

Public awareness and community participation are indispensable for long-term success. Initiatives like the "Yamuna Aarti" at Qudsia Ghat, which prohibits ritual waste such as flowers and diyas, demonstrate how cultural practices can be adapted to support conservation [67]. Leveraging mass media, educational programs, and volunteer drives can foster a sense of responsibility among citizens [68, 69].

Government policies and missions play a central role in Yamuna's revival. Programs like Mission Nirmal Yamuna (NYM) focus on sanitation and public awareness [70], while the Delhi Master Plan 2021 underscores river restoration as a key component of urban sustainability [71]. The National Waterways Project, initiated by the Ministry of Transport in 2016, integrates river conservation with transportation development [72]. Additionally, the Swachh Bharat Abhiyan (SBA) funds sanitation infrastructure, including riverside toilets, contributing to cleaner water bodies [73].

To address religious pollution, constructing artificial bathing ponds filled with treated river water near ghats offers a viable solution. This approach respects religious traditions while preventing direct contamination of the river [74].

In summary, restoring the Yamuna River demands a coordinated effort involving advanced wastewater treatment, sustainable agricultural practices, stringent enforcement, infrastructure upgrades, and active public engagement. Only through such comprehensive measures can the river's ecological balance be reinstated for future generations.

5. Conclusion:

The present study underscores the pressing need for a comprehensive and multidimensional approach to address the escalating pollution in the Yamuna River. The analysis of pollution trends, particularly in urban segments such as Delhi, reveals a critical failure in urban planning, industrial regulation, and wastewater management. The disproportionate volume of untreated and partially treated sewage entering the river, along with industrial discharges and agricultural runoff, has rendered significant stretches of the Yamuna ecologically dead [75, 76].

However, the temporary improvement in water quality observed during the COVID-19 lockdown offers empirical evidence of the river's capacity for self-recovery, provided anthropogenic pressures are substantially reduced [77]. This observation supports the argument for targeted interventions in four principal domains: improved wastewater treatment infrastructure, enforcement of industrial effluent standards, promotion of sustainable agricultural practices, and active public participation through awareness campaigns [78].

Effective river restoration demands decentralized sewage treatment solutions, especially in peri-urban areas, to complement centralized infrastructure [79]. Regulatory compliance by industries, incentivized adoption of green technologies, and ecological farming methods are vital to mitigate point and non-point source pollution [80]. Furthermore, the delineation and management of catchment areas can help identify pollution sources and facilitate more efficient remediation strategies [81].

Public engagement remains central to the success of any conservation initiative. Grassroots movements, citizen science, and community-based monitoring can foster a culture of accountability and environmental stewardship [82]. The inter-state nature of the Yamuna also necessitates coordinated action across political jurisdictions, underpinned by evidence-based policies and sustained financial commitment [83].

In conclusion, the restoration of the Yamuna River requires a paradigm shift in policy, infrastructure, and public perception. It is imperative to recognize the river not merely as a water body, but as a living ecosystem integral to the well-being of millions. Ensuring its rejuvenation is not only an environmental responsibility but a testament to sustainable development for future generations [84]

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