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Integrating benthic macroinvertebrate biomonitoring, river ecology and urban wastewater management: A case study-based critical review of the Narmada River, Central India

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Abstract
River ecosystems are increasingly affected by urban wastewater, hydrological modification, habitat disturbance and competing demands for freshwater resources. Effective river conservation therefore requires an assessment framework that integrates physicochemical water quality, biological responses, biodiversity conservation and wastewater-management performance. The Narmada River, one of the principal river systems of central India, provides an important case for examining these interconnected challenges.
This case study–based critical review synthesises three complementary evidence streams: (i) historical field observations from a two-year investigation of benthic macroinvertebrates and physicochemical parameters at Bargi Dam, Gwarighat and Bhedaghat during November 2015–October 2017, (ii) published research and government reports concerning Narmada River ecology and water quality, and (iii) recent institutional and judicial records relating to river conservation and urban sewage management in Jabalpur. The historical investigation documented 758 benthic macroinvertebrate individuals belonging to 55 families, 18 orders and four phyla. Four biological indices—Saprobic Index, Hilsenhoff Biotic Index, Benthic Index of Biological Integrity and EPT percentage—were used alongside a Water Quality Index to assess ecological condition. The reported results demonstrated spatial variation among sampling locations and non-uniform changes between the two study years.
Recent evidence adds an important management dimension. The Wildlife Institute of India undertook intensive ecological surveys of the Narmada between December 2022 and May 2024 as part of a national river-conservation initiative. Separately, judicial records concerning Jabalpur documented a substantial gap between estimated sewage generation and the quantity treated, alongside proposed sewerage infrastructure expansion. These records identify a need to connect wastewater-treatment performance with direct measurements of receiving-water quality and biological response. The review proposes an integrated river-health framework combining biological monitoring, physicochemical analysis, habitat assessment, wastewater-load accounting and transparent environmental reporting. It argues that infrastructure completion alone cannot demonstrate ecological recovery, improvements must also be verified through receiving-water measurements and standardised biological indicators. The framework may support evidence-based monitoring and conservation planning for the Narmada and other rivers experiencing similar urban and hydrological pressures.

Keywords: Narmada River, benthic macroinvertebrates, river health, biological monitoring, wastewater management, sewage treatment, Water Quality Index, biodiversity conservation, Jabalpur, ecological restoration

Introduction

Rivers are dynamic ecological systems that support freshwater biodiversity, nutrient cycling, fisheries, agricultural production, drinking-water supply and cultural practices. Their ecological condition depends on the interaction of hydrological processes, water chemistry, habitat structure and biological communities. Increasing urbanisation, wastewater generation, land-use change and the modification of river flows can alter these interactions and compromise the long-term sustainability of freshwater ecosystems.
River-health assessment has traditionally relied on physicochemical measurements such as dissolved oxygen (DO), biochemical oxygen demand (BOD), pH, conductivity and total dissolved solids (TDS). These measurements are indispensable for evaluating water quality, identifying potential pollution and assessing compliance with applicable standards. However, they generally describe conditions at the time and location of sampling. Biological communities, in contrast, may integrate the effects of environmental stress across different periods, depending on organismal life histories, habitat stability and the duration of exposure.
Benthic macroinvertebrates are particularly useful for biological assessment because they occupy the riverbed, participate in aquatic food webs and exhibit differing sensitivities to organic enrichment, oxygen depletion, sedimentation and habitat disturbance. Community composition, taxonomic richness and pollution-tolerance metrics can therefore complement conventional water analysis. Rapid bioassessment approaches and multimetric frameworks have established the importance of standardised biological evidence in freshwater monitoring (Lenat & Barbour, 1994; Stoddard *et al*., 2008) [8, 18]. Nevertheless, biological indices are not universal measures of pollution. Their interpretation depends on regional reference conditions, substrate type, hydrological regime, taxonomic resolution and sampling effort. A robust assessment must therefore integrate biological observations with the physicochemical and habitat characteristics that influence community structure. The Narmada River provides a relevant case for such an integrated approach. Flowing

westward across central India, the river supports urban and rural populations, irrigation, fisheries, energy production and important aquatic habitats. Its ecological characteristics are influenced by reservoirs and other hydraulic structures, tributary inputs, riverbank activities and wastewater management. Research on the river has examined water quality, plankton–environment relationships, macrozoobenthic diversity, dam-related ecological effects and broader river-health assessment (Vyas *et al*., 2012; Naskar *et al*., 2020; Gurjar & Vyas, 2024) [1, 5, 11].

Recent research has also broadened the discussion beyond conventional water chemistry. Sarsaiya and Jain (2025) [13] reviewed the quality, quantity, technological developments, management initiatives and challenges associated with the Narmada. Saini *et al*. (2025) [12] assessed ecological sustainability using macrophyte-based indices and physicochemical measurements. These developments highlight the need for a critical synthesis that connects biological monitoring with contemporary urban wastewater management and conservation planning.

The present article adopts a case study–based critical-review approach centred on the Jabalpur stretch of the Narmada. It uses historical field evidence from Bargi Dam, Gwarighat and Bhedaghat, examines recent official reports and judicial records, and identifies practical ways to integrate biological monitoring with river-management decisions.

Rationale and research gap

Three issues motivate this review.

First, historical macroinvertebrate observations provide a biological baseline for understanding conditions during 2015–2017, but they cannot establish the current ecological status of the river without comparable recent sampling.

Second, contemporary wastewater-management records describe sewage generation, treatment capacity, sewer connections and infrastructure plans. These indicators are important, but infrastructure statistics alone do not establish whether the ecological condition of a receiving river has improved.

Third, biological, physicochemical, habitat and administrative information is frequently reported through different monitoring systems. A framework that links these evidence streams may improve the interpretation of river-health trends and the prioritisation of conservation interventions.

The novelty of this review lies in connecting the historical benthic-macroinvertebrate dataset from the Jabalpur stretch with recent wastewater-management records and national ecological-assessment initiatives. It does not claim that the historical and recent datasets form a continuous time series, nor does it attribute current ecological conditions to changes observed during 2015–2017.

Objectives

The review aims to:

1. Re-examine historical physicochemical and benthic macroinvertebrate observations from the Jabalpur stretch of the Narmada.
2. Evaluate the complementary roles and limitations of physicochemical indices and biological metrics in river-health assessment.
3. Review recent official evidence on Narmada conservation, ecological assessment and urban sewage management in Jabalpur.
4. Identify the principal data gaps that prevent direct evaluation of long-term ecological recovery.
5. Propose an integrated, practical framework for future river-health monitoring and management.

Review methodology and evidence base

1. Review design

This article adopts a case study–based critical-review design rather than presenting a new field experiment or a formal systematic review. It combines an existing primary research dataset with peer-reviewed literature and official institutional records.

Three evidence categories were considered:

Category A: Historical field evidence. The author's PhD thesis and related research on physicochemical water quality and benthic macroinvertebrates in the Narmada River at Bargi Dam, Gwarighat and Bhedaghat, covering November 2015–October 2017.

Category B: Scientific literature. Peer-reviewed studies and scholarly chapters addressing Narmada water quality, biological monitoring, macrozoobenthic diversity, macrophyte-based assessment, hydrological modification and river conservation.

Category C: Contemporary institutional evidence. Available Wildlife Institute of India reports, Madhya Pradesh Pollution Control Board resources, Central Pollution Control Board water-quality data, government programme documents and judicial records concerning wastewater management and river conservation.

2. Source identification and selection

Sources were identified through searches of scientific publication records, publisher websites and official government portals. Priority was given to sources with identifiable authors, publication dates, institutional responsibility or traceable document records.

The review focuses on evidence relevant to the interaction between river ecology, biological indicators and urban wastewater management. Sources concerning the broader Narmada basin were included where they provided context for hydrological alteration, biodiversity conservation or management policy.

This is a narrative critical synthesis. It does not claim exhaustive systematic coverage, a preregistered search protocol or quantitative meta-analysis.

3. Treatment of historical data

The historical dataset was interpreted using the values reported in the PhD thesis and associated summary. Reported values are distinguished from new analyses and from the review's proposed management framework.

Where annual summaries and detailed site-specific tables differ, the discrepancy is explicitly identified rather than silently reconciled. No statistical significance, causal relationship or current water-quality condition is inferred without supporting data.

4. Temporal comparability

The 2015–2017 biological observations and the 2022–2024 ecological surveys undertaken through the Wildlife Institute of India initiative represent different study periods and

potentially different methods, sampling locations and objectives. They should not be directly compared as a continuous ecological time series unless comparable site-level data and methods can be verified.
Likewise, sewage generation and treatment figures reported in administrative or judicial documents are treated as management indicators rather than direct measurements of ecological recovery.

5. Analytical framework
The evidence was synthesised across five connected dimensions:
1. Physicochemical water quality.
2. Benthic macroinvertebrate community structure and biological indices.
3. Habitat and hydrological context.
4. Wastewater collection and treatment performance.
5. Biodiversity conservation and institutional monitoring.

This framework provides the basis for the case study, critical discussion and proposed monitoring recommendations.

The historical Narmada biomonitoring case study
1. Study reach and sampling context
The historical investigation covered three locations in the Jabalpur region: Bargi Dam, Gwarighat and Bhedaghat. These locations represent contrasting aquatic and human-use settings.
Bargi Dam represents a regulated, reservoir-associated environment. Gwarighat is an urban riverbank location subject to recreational and religious use. Bhedaghat is characterised by distinctive rocky river habitats and tourism-related activities. These differences are ecologically relevant because flow conditions, substrate composition, organic-matter accumulation and human disturbance can influence benthic organisms independently of water chemistry.
The study was conducted from November 2015 to October 2017. The thesis describes upstream and downstream stations at each location and repeated sampling across winter, summer and rainy seasons.

2. Physicochemical observations
The thesis reports the following annual mean values:

Parameter	2015–2016	2016–2017
Temperature (°C)	25.0	24.1
Turbidity (NTU)	5.9	5.9
pH	7.0	6.9
Conductivity (µS/cm)	631.3	632.1
TDS (mg/L)	751.6	733.4
Dissolved oxygen (mg/L)	6.2	6.1
BOD (mg/L)	4.2	4.1
COD (mg/L)	5.9	5.9
Chloride (mg/L)	30.7	31.1
Total hardness (mg/L)	145.4	146.1

Source: author's PhD thesis. The original observation tables and analytical units should be verified before final publication.

The annual means suggest that several parameters changed only modestly between the study years. TDS and BOD declined, whereas chloride, hardness and conductivity increased slightly. Dissolved oxygen showed a small decrease. These mixed responses caution against describing the entire river as having improved or deteriorated solely on the basis of annual averages.
Seasonal variation was also reported. Turbidity was relatively high at Gwarighat during the rainy season, while chloride showed site-specific differences. Such variation may be influenced by runoff, dilution, sediment mobilisation and local inputs. However, direct source measurements would be required to identify the relative contribution of individual processes.

3. Macroinvertebrate assemblage
A total of 758 benthic macroinvertebrate individuals were recorded, representing 55 families, 18 orders and four phyla. The thesis reported 410 individuals in the first study year and 348 in the second.
The community included members of Platyhelminthes, Annelida, Arthropoda and Mollusca. The organisms occupied different functional and ecological roles within the benthic food web.
The thesis classified 47% of the recorded families as common, 20% as rare, 20% as very rare and 13% as very common. These categories describe the original study's abundance classification rather than a standardised ecological quality scale.
The findings establish a useful historical record of benthic taxonomic richness in the study reach. However, the reduction in total abundance between years cannot by itself be interpreted as ecological deterioration. Abundance may vary with discharge, season, habitat availability, life-cycle timing and sampling efficiency. Relative abundance, taxonomic composition and environmental context must be considered together.

4. Biological index results
The thesis applied four biological metrics: Saprobic Index, Hilsenhoff Biotic Index, Benthic Index of Biological Integrity and EPT percentage. The site-specific summary is reproduced below for historical reference.

Indicator	Bargi: Year I / II	Gwarighat: Year I / II	Bhedaghat: Year I / II
WQI	55.089 / 64.106	76.124 / 51.593	60.641 / 71.066
Saprobic score	5.492 / 5.389	5.507 / 5.402	5.524 / 5.542
HBI	4.835 / 4.444	5.933 / 4.130	5.069 / 4.636
B-IBI	16 / 12	17 / 19	15 / 17
EPT (%)	8.00 / 12.19	9.09 / 14.45	10.98 / 13.16

The thesis contains discrepancies between certain summary values and detailed index tables. All values must be reconciled against the original worksheets before they are used for inferential analysis.
The reported EPT percentage increased at all three locations between the study years. B-IBI decreased at Bargi Dam but increased at Gwarighat and Bhedaghat. Saprobic scores also showed different directions of change among locations.
These results demonstrate why biological metrics should not be interpreted in isolation. Each metric captures a different aspect of community composition or environmental tolerance. Differences among indices may reflect ecological heterogeneity, methodological limitations or different sensitivities to environmental stress.

5. Interpretation of the historical findings

The strongest conclusion supported by the historical dataset is that the Jabalpur stretch exhibited spatial and temporal variability in physicochemical and biological indicators during 2015–2017.

The results do not establish a uniform ecological recovery across the three sites. Nor can they demonstrate the present-day ecological status of the Narmada. Instead, they provide a baseline against which future surveys could be compared if sampling locations, methods, taxonomic resolution and seasonal coverage are standardised.

The dataset's greatest contemporary value is therefore as a historical reference for designing repeatable biological monitoring rather than as a substitute for current field observations.

Contemporary developments: Narmada conservation and Jabalpur wastewater management

1. Ecological assessment by the Wildlife Institute of India

The National River Conservation Directorate entrusted the Wildlife Institute of India (WII) with ecological assessment and conservation planning for selected Indian rivers, including the Narmada. According to the WII project documentation, intensive Narmada surveys were conducted between December 2022 and May 2024 [3, 5]. The programme examined biodiversity, ecological threats, conservation-priority stretches and measures for long-term river conservation.

The importance of this programme lies in its broader ecological scope. River conservation requires consideration of aquatic and riparian biodiversity, hydrological modification, habitat integrity and pollution pressures rather than water chemistry alone.

For the present case study, the WII assessment provides an important contemporary evidence stream. However, its findings cannot be assumed to confirm improvement or deterioration at the historical Bargi Dam, Gwarighat and Bhedaghat stations unless the relevant locations, observations and methods are directly comparable.

2. Contemporary water-quality monitoring

The Central Pollution Control Board (CPCB) publishes river-monitoring data, including measurements for Narmada stations. Its 2022 [3] dataset reports measurements of temperature, pH, conductivity, dissolved oxygen, biochemical oxygen demand and bacteriological indicators at locations across the river. The Madhya Pradesh Pollution Control Board also maintains a Narmada water-quality reporting resource and information on water-monitoring programmes. These monitoring systems offer a foundation for tracking water-quality conditions over time. Nevertheless, chemical monitoring and biological assessment answer different questions. Chemical measurements characterise selected parameters at particular sampling times, whereas biological assessment helps evaluate how resident communities respond to the environmental conditions they experience.

A future integrated monitoring programme should therefore link water-quality observations with standardised macroinvertebrate sampling at matched stations and seasons.

3. Jabalpur's sewage-treatment gap: evidence from 2025–2026 [25]

One of the most significant contemporary developments for this case study concerns sewage generation and treatment in Jabalpur.

In judicial records concerning urban drains and wastewater management, information submitted by the municipal corporation and pollution-control authorities identified an estimated sewage generation of approximately 174 million litres per day (MLD). The records discussed treatment of approximately 76.5 MLD and an estimated untreated flow of around 97.5 MLD into drains. A separate progress report also documented changes in treatment capacity and sewer connections during the reporting period.

Jabalpur Sewage Management

Figures Reported In The 2026 Judicial Record	
Estimated sewage generated 174 MLD	Reported treated quantity 76.5 MLD
Estimated untreated flow 97.5 MLD	Estimated untreated share 56.0%

The percentage is calculated from the reported 97.5 MLD divided by 174 MLD. These are estimates recorded in the relevant proceedings, not independently verified measurements of sewage entering the Narmada itself. The distinction between sewage generated in a city and sewage reaching a particular river station is essential. The judicial record describes drainage pathways through the Pariyat and Hiran river systems before eventual convergence with the Narmada. Accordingly, the estimated untreated urban flow cannot be treated as a measured direct discharge of 97.5 MLD into the Narmada at Gwarighat or any other specific study station.

The same proceedings describe sewerage infrastructure expansion, operation of treatment plants, reuse of treated wastewater and proposed additional infrastructure. These developments are relevant to long-term management, but planned or commissioned infrastructure must be distinguished from verified treatment performance and measured ecological outcomes.

4. AMRUT 2.0 and urban water infrastructure

The AMRUT 2.0 project portal lists sewerage and water-supply projects in Jabalpur, including a sewerage project for the Cantonment area and a proposed water-supply project. The portal records their respective project costs and implementation milestones.

These projects provide an opportunity to strengthen wastewater collection, treatment and reuse. From an ecological perspective, the relevant question is whether the infrastructure reduces untreated wastewater loads reaching receiving waters and whether any resulting improvement is detectable in both physicochemical and biological measurements.

1. The proposed assessment should distinguish four stages:
2. Infrastructure planned or sanctioned.
3. Infrastructure completed and operational.
4. Verified sewage treatment and reduction in pollutant loads.
5. Demonstrated improvement in receiving-water quality and ecological condition.

Only the fourth stage provides direct evidence of environmental improvement.

5. National river-conservation programmes

The National River Conservation Plan supports pollution-abatement measures such as sewage interception, diversion, treatment and riverfront or bathing-ghat improvements. Government reporting also describes the national ecological-assessment initiative involving the Narmada and other rivers. These initiatives create an opportunity to connect infrastructure-based river management with ecological monitoring. Biological assessment could help determine whether improvements in wastewater management are accompanied by changes in benthic community composition, pollution-sensitive taxa and other measures of ecological integrity.

The monitoring framework proposed in this article is intended to complement, rather than replace, the existing responsibilities of environmental and water-management agencies.

Critical synthesis: connecting historical and contemporary evidence

The historical biomonitoring investigation and the contemporary management records describe different but related dimensions of river health.

The 2015–2017 study provides a biological and physicochemical baseline for three locations in the Jabalpur region. Contemporary institutional records describe wider ecological assessment, sewage-treatment infrastructure and wastewater-management challenges. Together, these evidence streams suggest that river conservation requires a monitoring framework that links environmental pressures to measurable ecological responses.

The available evidence does not yet establish whether the macroinvertebrate community at the original sampling stations has improved since 2017. That question requires repeat sampling and a comparison using standardised methods. Similarly, the existence of current infrastructure programmes cannot, by itself, demonstrate recovery of the benthic ecosystem.

This distinction is particularly important because the same biological metric may respond to multiple drivers. Changes in EPT percentage, for example, may be associated with organic pollution, but can also reflect substrate composition, flow conditions, seasonal emergence and sampling effort. A convincing ecological assessment must consider these competing explanations.

Proposed integrated Narmada River Health Monitoring Framework

The following framework is a proposed contribution of this review. It has not been implemented or validated as part of the historical thesis.

1. Pollution-pressure monitoring

Sewage loads, treatment-plant performance, urban drains, runoff and solid waste

2. Physicochemical and microbiological assessment

DO, BOD, COD, pH, conductivity, TDS, nutrients and microbial indicators

3. Biological and habitat assessment

Macroinvertebrate assemblages, EPT metrics, calibrated biotic indices, substrate and flow

4. Integrated river-health evaluation

Site-wise and seasonal comparisons, reference conditions, uncertainty and trend analysis

5. Management response and verification

Prioritise interventions, measure outcomes and revise the monitoring plan

1. Standardised biological monitoring

The three historical stations should be revisited, subject to access and habitat comparability. Additional stations could be selected upstream and downstream of major wastewater inputs. Sampling should be repeated in the principal hydrological seasons using a documented, consistent sampling protocol.

2. Link treatment performance to receiving-water response

Wastewater monitoring should include actual influent and effluent flow, treatment efficiency, bypasses and the quantity of treated water reused or discharged. Receiving-water sampling should be undertaken at appropriately selected upstream and downstream stations, with attention to river discharge and seasonal dilution.

3. Develop regionally appropriate biological benchmarks

The Saprobic Index, HBI, B-IBI and EPT percentage used in the thesis provide a starting point. Their thresholds should be validated against suitable regional reference sites and the ecological characteristics of central Indian rivers before they are used for formal classification.

4. Introduce advanced analytical methods

Where suitable data are available, multivariate analysis can help distinguish patterns associated with water chemistry, habitat conditions and seasonality. Taxonomic verification, GIS-based catchment analysis, remote sensing and molecular identification may complement conventional monitoring.

These methods should be selected according to the research question and data quality rather than added solely to make a manuscript appear technologically advanced.

Major research gaps

The review identifies six priority gaps:

- **Temporal gap:** No directly comparable post-2017 macroinvertebrate dataset has been established here for the three historical stations.
- **Spatial gap:** The relationship between urban drainage pathways and measured ecological conditions at individual receiving-water stations requires further study.
- **Methodological gap:** Differences between the thesis's summary tables and detailed index calculations must be resolved.
- **Reference-condition gap:** Suitable regional reference sites and calibrated biological thresholds are needed.
- **Causal gap:** The contribution of sewage, runoff, habitat modification and hydrological alteration should be evaluated using direct measurements.
- **Governance gap:** Wastewater-treatment statistics, water-quality data and biodiversity observations should be linked through consistent reporting and monitoring periods.

Management recommendations

River management should combine pollution prevention, treatment performance and ecological verification.

First, untreated sewage entering urban drainage systems should be intercepted and treated in accordance with applicable environmental requirements. Second, treatment-plant operation and effluent quality should be monitored independently, with transparent reporting of treatment quantities and discharge pathways. Third, standardised macroinvertebrate surveys should complement water chemistry at matched stations. Fourth, habitat protection and catchment management should be included in restoration planning. Fifth, public participation and riverbank waste management should be supported by measurable environmental targets.

The effectiveness of each intervention should be evaluated against a defined baseline. Where possible, monitoring should include before-and-after observations and appropriate comparison stations, while accounting for seasonality and changes in flow. Such an approach would allow environmental managers to distinguish infrastructure delivery from demonstrated ecological outcomes.

Limitations

This review combines a historical field investigation, published scientific literature and contemporary administrative records. These sources differ in geographic coverage, observation period, methods and purpose.The thesis data cover November 2015–October 2017, while the WII ecological surveys cover December 2022–May 2024 [21]. Contemporary sewage figures refer to urban management estimates and should not be interpreted as direct river-discharge measurements. The review also does not claim a complete systematic search of every relevant publication or government record. Accordingly, the proposed framework is a synthesis and management recommendation, not evidence that current ecological recovery has already occurred. Directly comparable contemporary biological and physicochemical measurements are required to determine the present status of the three historical stations.

Conclusion

The Narmada River case study illustrates why effective river-health assessment must move beyond isolated water-quality measurements or infrastructure statistics. The historical investigation at Bargi Dam, Gwarighat and Bhedaghat documented a diverse benthic macroinvertebrate assemblage and spatially variable physicochemical and biological indicators during 2015–2017. Recent ecological-assessment initiatives and judicial records concerning urban wastewater management provide important contemporary context, but they do not establish the present ecological condition of those historical stations.

The central recommendation of this review is to integrate biological monitoring, physicochemical analysis, habitat assessment and wastewater-treatment performance within a consistent, transparent framework. Such an approach would enable managers to test whether pollution-abatement interventions produce measurable improvements in river ecosystems.

The value of the historical dataset lies in its potential to support standardised repeat surveys. By reconnecting that baseline with current environmental monitoring and independently verified management outcomes, future research can develop a more robust understanding of ecological change and contribute to the long-term conservation of the Narmada River in central India.

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