

ADVANCED REVIEW

Four Decades of Ganga Rejuvenation: Evidence, Outcomes, and Road Ahead

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ABSTRACT

The Ganga River has undergone four decades of successive restoration efforts, from the Ganga Action Plan (GAP-I, 1985) through the ongoing Namami Gange Mission (2014–present). This review synthesizes scientific and policy literature from 1985 to 2025, examining pollution sources, water quality dynamics, and institutional performance. Municipal sewage remains the principal pollution source (~70% of total pollution load); however, treatment capacity has expanded markedly from 1192 MLD in 2011 to over 8200 MLD today. Industrial pollution management has also improved through real-time monitoring of > 2800 grossly polluting industries and enhanced regulatory compliance. These interventions have resulted in improved water quality, including reductions in BOD at 43 monitoring locations, improved DO at 32 locations, and reduced fecal coliform levels at 25 locations (up to September 2023). A performance assessment using a six-dimensional composite scoring framework reveals that the Namami Gange program achieved an effectiveness score of 7.8/10, compared to a 3.2/10 score for the National Ganga River Basin Authority, reflecting improvements in financial management, real-time monitoring, and ecological focus. Nevertheless, future river restoration progress can be accelerated by strengthening sewerage connectivity, sludge management, advanced monitoring systems, enhanced ecological conservation, and environmental flow management to secure the long-term sustainability and resilience of the Ganga river.

1 | Introduction

In India, the Ganga, or Mother Ganga, is revered as a deity and one of the subcontinent's most sacred rivers, serving as a foundational pillar of Indian civilization, spirituality, culture, and economy. (K. D. Alley 2002; Dwivedi et al. 2018; Mishra and Upadhyay 2021; Sati 2021) Originating from the Gangotri Glacier in the central Himalayas of Uttarakhand, the river

flows across the Indo-Gangetic plains before discharging into the Bay of Bengal (Figure 1). Spanning over 2525 km and draining around 26.3% of India's land, the Ganga basin supports over 600 million people, 45% of the population, and supplies water to more than 37% of India's inhabitants (Singh and Singh 2020; Srinivas et al. 2020). Hydrologically, the basin is of exceptional national importance, with an estimated hydroelectric potential of 20,711 MW (Nexdigm 2024). Economically, the Ganga

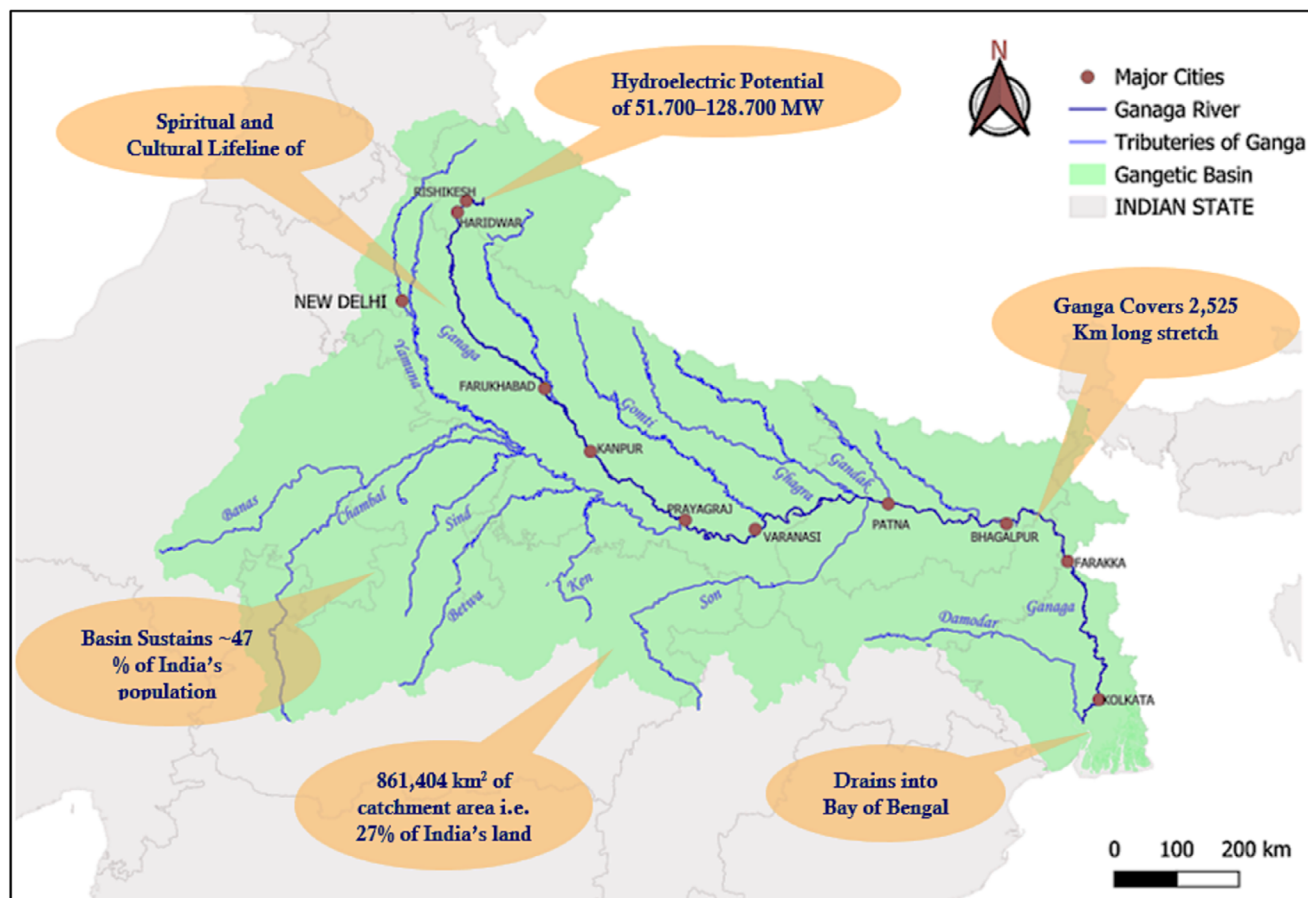


FIGURE 1 | An overview of the Gangetic basin, depicted with the tributaries from origin to outfall in the Bay of Bengal.

river basin underpins roughly 40% of India's GDP, with agriculture serving as its principal driver (IFC 2023; Mishra and Upadhyay 2021; Balkrishna et al. 2024).

Beyond its material and economic importance, the Ganga has a unique historical and cultural identity. Ancient scriptures and historical accounts consider that the river's water (Gangajal) has medicinal and reviving properties, likely due to bacteriophages and bioactive compounds from medicinal flora in the upper reaches (Dwivedi et al. 2026; Kochhar 2020). Millions of devotees engage in ritual bathing and ceremonies along its banks, viewing the river as a symbol of purity and spiritual liberation (K. D. Alley 2002). Over centuries, the Ganga has nurtured iconic religious and cultural centers like Gangotri, Devprayag, Haridwar, Prayagraj, and Varanasi, strengthening its role as both a vital lifeline and sacred heritage of India (Sati 2021; Singh, Tiwari, Sharma, et al. 2022; Singh, Tiwari, and Singh 2022).

Despite its cultural and spiritual importance, the Ganga faces challenges from rapid urbanization, industrial expansion, and population growth, which have intensified water withdrawals, altered natural flow regimes, and threatened its ecological integrity. (Simon and Joshi 2022; Rai et al. 2024; Sinha and Ghosh 2012). Water-quality degradation is mainly driven by untreated wastewater, improper solid waste disposal, and diffuse pollution, threatening aquatic ecosystems and public health. In response, several government initiatives have been launched to address these challenges. First, the Ganga Action Plan (GAP-I)

was launched in 1985 as India's first large-scale river restoration in 25 towns across Uttar Pradesh, Bihar, and West Bengal. Building on this foundation, GAP II was initiated in 1993, extending efforts to 60 towns and major tributaries such as the Yamuna, Damodar, Gomti, and Mahananda. Subsequently, the National River Conservation Plan (NRCP) was introduced in 1995 to expand the scope to additional rivers such as the Betwa, Mandakini, and Ramganga. (MoEF 2004, 2009; Balkrishna et al. 2024). A further paradigm shift occurred with the establishment of the National Ganga River Basin Authority (NGRBA) in 2009, which promoted a basin-scale management framework through scientific inputs, inter-agency coordination, and stakeholder participation (The World Bank 2015).

Despite substantial public investment and localized improvements, earlier programs failed to achieve their intended basin-scale objectives. Limited community awareness and engagement, ambiguities in policy frameworks, uneven state-level commitment, and fluctuating administrative support constrained their effectiveness (Sanghi and Kaushal 2014; Tare et al. 2003; K. D. Alley 2016; IIT Consortium 2011; Dwivedi et al. 2018). The Ganga River Basin Management Plan (GRBMP) reported that the 11 basin states generated approximately 12,051 MLD of sewage, with nearly 6334 MLD discharged untreated. By 2014, urban centers with populations over 50,000 near the river had treatment capacity for only about 900 MLD of the nearly 2900 MLD of sewage generated. Persistent challenges related to the inadequate O&M funding, a shortage of skilled personnel,

irregular power supply, mechanical failures, and stormwater ingress hinder effective treatment, resulting in underutilized capacity (CPCB 2019; The World Bank. 2023). Creating 900 MLD over three decades was an institutional and infrastructural achievement, but variable performance highlighted the need for better governance, sustainable funding, and performance-focused management. These lessons guide subsequent phases of Ganga restoration effort.

Industrial pollution significantly stresses water quality in the Ganga River, mainly from effluents of sugar, chemical, textile, tannery, and pulp-and-paper industries classified as grossly polluting industries (GPIs) (Srinivas et al. 2020). Nevertheless, municipal sewage continues to account for the largest share of the overall pollution burden, followed by industrial discharges ($\approx 20\%$) and agricultural runoff ($\approx 10\%$) (Mahendra and Vinay 2025; Sigdel et al. 2023). Persistent issues like treatment gaps, incomplete sanitation coverage, open defecation, solid-waste dumping, delays in infrastructure expansion, and limited public awareness have historically compounded pollution pressures (Comptroller and Auditor General of India 2017).

The limited outcomes of GAP I and GAP II, and the NRCP, coupled with deterioration in water quality at several locations, catalyzed the launch of the Namami Gange program in 2014. Replacing the National Ganga River Basin Authority (NGRBA), the program adopted a more comprehensive basin-scale management framework, supported by an investment of approximately ₹20,000 crore (Singh and Singh 2020; Comptroller and Auditor General of India 2017). While this shift represents a major institutional and financial commitment, important questions remain regarding the magnitude and distribution of pollution loads, the relative contribution of dominant sources, and the broader socio-economic and environmental outcomes of past and ongoing interventions.

While several studies have examined individual phases of Ganga restoration efforts independently, a comprehensive, evidence-based performance assessment integrating pollution dynamics, institutional evolution, and socio-economic and ecological outcomes across all major programs from 1985 to 2025 has not been undertaken. This review addresses this gap by applying a multi-dimensional composite scoring framework to systematically evaluate program effectiveness and budget efficiency across four decades, thereby providing a structured evidence base for adaptive river governance.

1.1 | Methodology

This work follows the approach of narrative systematic reviews of environmental, academic, and governance literature (Bilotta et al. 2014). The study reviews literature from 1985 to 2025 using databases like Scopus, Web of Science, Google Scholar, and PubMed, focusing on terms like ‘Ganga’, ‘water quality’, ‘Namami Gange’, ‘sewage treatment’, and ‘environmental flow’. It includes 49 peer-reviewed papers, 37 government reports, and 10 policy documents, supplemented by data from National Institute of Hydrology (NIH), IITs, CPCB, and NMCG. This review uses secondary data, with no primary sampling, covering five mainstem states over the period. Water quality data from CPCB and

NMCG was selected based on strict adherence to BIS/IS:3025 and APHA standards. Studies with explicit QA/QC protocols were prioritized. Program performance was assessed using composite scores and budget metrics derived from implementation outcomes, as detailed in the [Supporting Information](#). Programs were evaluated on six dimensions: infrastructure, finance, coordination, monitoring, participation, and ecology, each scored 0–10. The average score indicated implementation quality, with 0–3 as limited, 4–5 partial, 6–7 substantive, and ≥ 8 as comprehensive performance. Criteria are grounded in documented implementation outcomes reported by CPCB, NMCG, CAG, the World Bank, and peer-reviewed studies, the resulting dimension scores and composite indices ultimately reflect the authors’ expert judgment based on this body of evidence.

1.2 | Novelty and Contribution of This Review

The present review makes three distinct contributions to the existing literature. First, to the authors’ knowledge, it is the first synthesis to quantitatively evaluate institutional performance across all major Ganga restoration programs using a six-dimensional composite scoring framework encompassing infrastructure development, financial management, institutional coordination, monitoring systems, public participation, and ecological focus. Second, the review integrates budget efficiency analysis, normalized to 2024 values using an inflation rate of 7%, enabling a time-adjusted comparison of program performance per unit of financial investment. Third, by examining the Namami Gange program through the lens of ecosystem services (Arth Ganga), environmental flows (E-Flow Gazette Notification), and emerging contaminants, this review extends the scope of existing assessments beyond conventional water-quality parameters to encompass the socio-ecological dimensions of river restoration (Figure 2).

2 | Ganga River Pollution Sources

2.1 | Municipal Wastewater

Municipal wastewater is the dominant source of pollution in the Ganga River, accounting for nearly 70% of the total pollution load (Figure 3) (NMCG, 2020–2021). This load originates from a linear chain of urban settlements along the river corridor, comprising 29 large cities, 23 medium towns, and 50 smaller urban centers distributed across five basin states (NMCG, 2020–2021). Rapid population growth, coupled with persistent gaps in sewerage coverage and treatment capacity, has remained a central challenge over multiple decades (Chaudhary and Walker 2019).

Comparative assessments of water quality before and after the implementation of the Ganga Action Plan (GAP) indicated that conditions in several river stretches, particularly in the middle reaches, showed limited improvement (Tare et al. 2003; Sigdel et al. 2023; Comptroller and Auditor General of India 2017). Following the integration of GAP II into the National River Conservation Plan (NRCP) in 2000, these structural constraints continued to influence outcomes (IIT Consortium 2011; MoEF 2009). By 2011, wastewater generation had reached 2923.3 MLD, whereas installed treatment capacity stood at

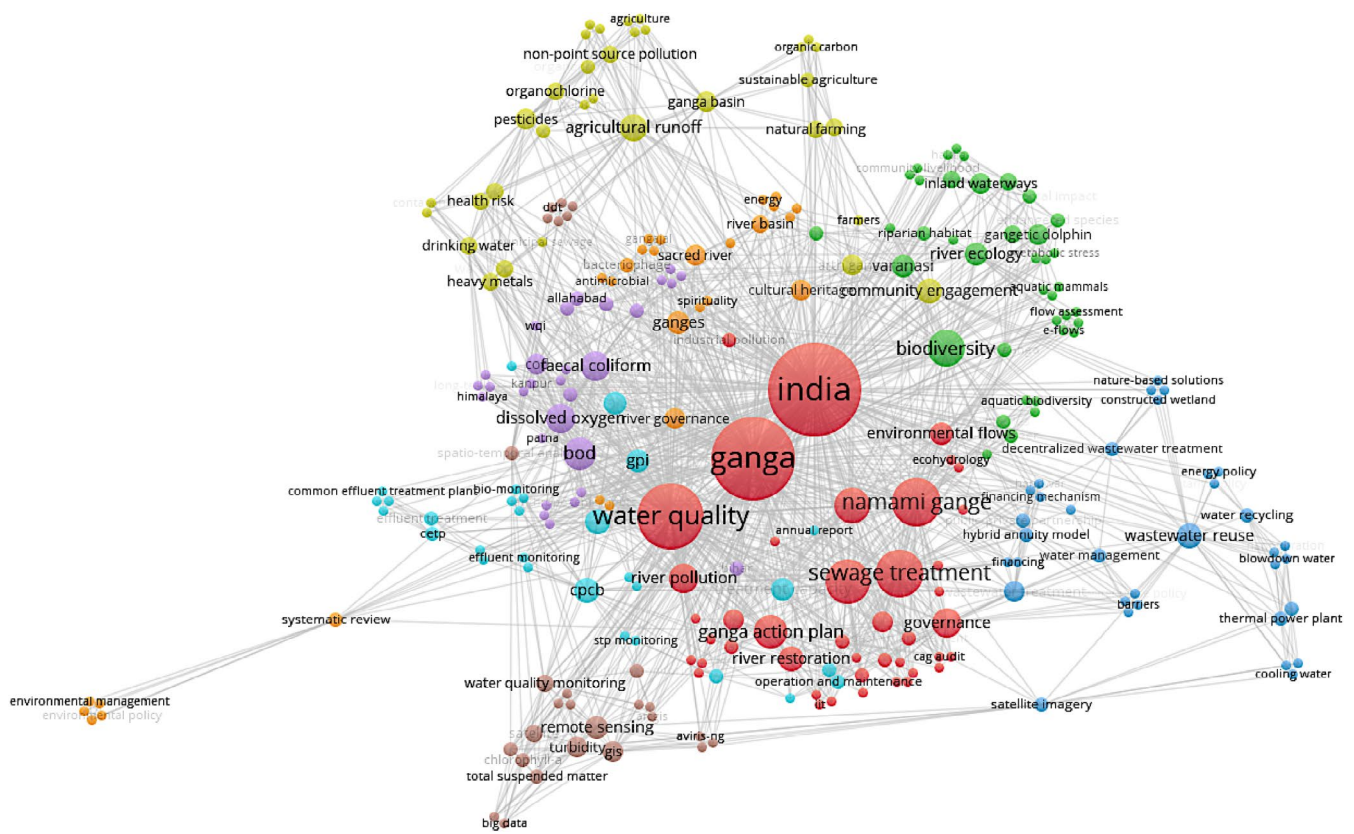


FIGURE 2 | Keyword co-occurrence network of the manuscript generated using VOS viewer. Node size reflects keyword frequency; edge thickness indicates co-occurrence strength between keywords. Colors denote distinct thematic clusters. The five dominant clusters represent: Water Quality and Pollution Parameters (red), Governance and Policy (red-pink), Ecology and Biodiversity (green), Agriculture and Non-point Sources (yellow), and Technology and Monitoring (teal/blue).

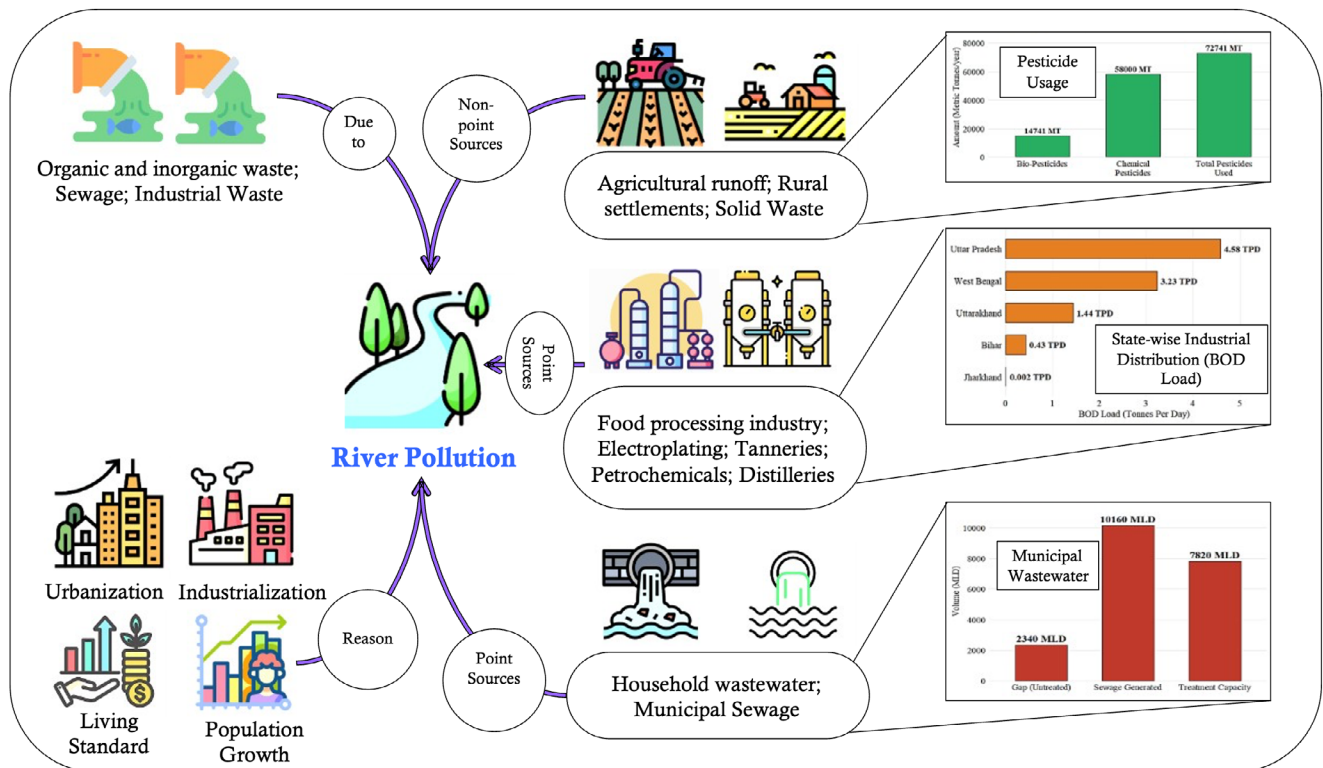


FIGURE 3 | Various sources of pollution in the Ganga River. (Clip art source is [Flaticon.com](https://www.flaticon.com/)).

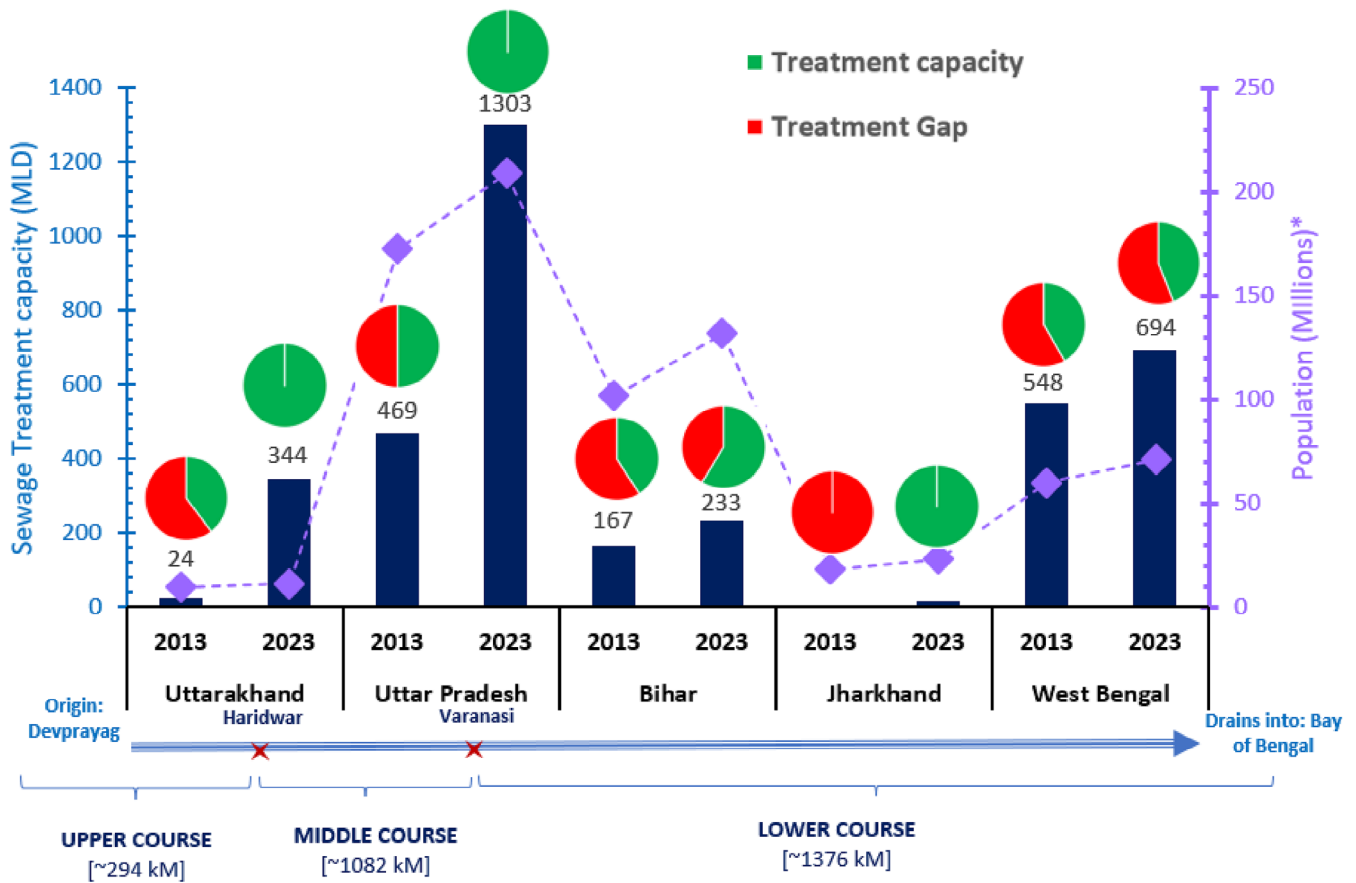


FIGURE 4 | Decadal change in population, sewage generation, installed treatment capacity, and treatment gap in Five Ganga states (Class I and Class II towns) between 2013 and 2023 (CPCB 2013; CPCB 2023a, 2023b).

1192.4 MLD, corresponding to a deficit of approximately 45% (CPCB 2013). Notably, West Bengal, Uttar Pradesh, and Bihar together accounted for more than 1400 MLD of this capacity shortfall, underscoring the spatial concentration of sanitation challenges along the Ganga corridor (Figure 4).

Historically, the effectiveness of sewage management along the Ganga has been constrained by underutilization of existing sewage treatment plants (STPs), prolonged delays in commissioning new facilities, and rapid demographic expansion in riverine cities. As a result, in 2017, only about 30% of the generated sewage was treated, with the remaining 70% discharged untreated into the river system (National Mission for Clean Ganga 2017). These limitations manifested as elevated microbial contamination downstream of Rishikesh, where total coliform concentrations exceeded the prescribed limit of 500 MPN/100 mL and remained persistently high through downstream urban centers. The detection of pathogenic organisms, such as *Salmonella*, in cities like Kanpur and Varanasi further underscores direct public health concerns (CPCB 2017). Water quality assessments at Varanasi during 2019–2021 documented total coliform concentrations ranging from 4364–6202 MPN/100 mL across seasons, far exceeding permissible limits and indicating sewage contamination in the middle reaches (Singh, Chaudhary, et al. 2025; Singh, Singh, et al. 2025).

More recent assessments, however, indicate a substantial scaling-up of treatment infrastructure across the basin (Ministry

of Jal Shakti 2024b). Operational treatment capacity has now reached approximately 7820 MLD, corresponding to nearly 77% of the total 10,160 MLD of sewage generated (Ministry of Jal Shakti 2025). To bridge the remaining gap, an additional ~1996 MLD of capacity is currently under construction. Under Namami Gange 2.0, significant milestones have been achieved, most notably the completion of the 564 MLD facility at Okhla, along the Yamuna river in Delhi, which is now operational as the largest sewage treatment plant in Asia (Dhanya 2025a). Collectively, these investments signal a paradigm shift from incremental capacity creation to large-scale, system-wide strengthening of urban wastewater management along the Ganga basin.

In the upper reaches of the Ganga, water quality remains comparatively favorable. A long-term assessment spanning 1971–2020 by Kumar et al. (2021) indicated that, at most monitoring locations, water quality generally met acceptable drinking-water abstraction limits. Nonetheless, phosphate concentrations in the range of 0.04–0.09 mg/L have been reported, likely reflecting a combined influence of natural geological weathering and diffuse fertilizer runoff from agricultural activities (Jain et al. 2021).

The middle reaches of the river, historically the most environmentally stressed segment, experienced the greatest pressure. Comparative analyses of pre- and post-GAP conditions along the Kannauj-Kanpur stretch revealed localized improvements, yet persistent pollution remained evident. Prior to GAP

implementation, biochemical oxygen demand (BOD) ranged from 1.63–7.18 mg/L, whereas during the post-GAP period, certain locations, such as Jajmau, recorded elevated BOD values reaching 16.1 mg/L (Tare et al. 2003). At the Yamuna–Ganga confluence in Prayagraj, water quality index (WQI) values ranged from 86.2–157.7, corresponding to poor overall water quality (Sharma et al. 2014). Further downstream, studies have documented declining dissolved oxygen (DO), increasing chemical oxygen demand (COD), and fecal coliform concentrations ranging from 5000–6000 MPN/100 mL near Patna, substantially exceeding permissible limits (Kumari and Narayan 2018). The downstream stretches, particularly in West Bengal, highlighted the scope for improvement in managing domestic wastewater, as reflected in elevated organic levels (Dutta et al. 2020).

The experiences of downstream urban centers such as Patna and Kolkata indicate a structural shift in the nature of the challenge, from infrastructure development to infrastructure performance. Increased operational efficiencies, consistent maintenance, and full utilization of existing treatment infrastructure will add value in ongoing river restoration initiatives (Kumar et al. 2021). With climate change projected to exacerbate water-quality pressures in the mid-century period (2040–2060), and climate-change assessments for the Himalayan region highlight increasing vulnerability of water resources, ecosystems, and human settlements, underscoring the need to integrate basin-scale restoration with climate-resilient development pathways (Matta et al. 2025), future river-restoration efforts must prioritize operational excellence, adaptive governance, and climate-responsive basin management to ensure long-term gains (Santy et al. 2022).

2.2 | Industrial Sources

Industrial discharges contribute a comparatively smaller share of the total pollution load in the Ganga River, approximately 20%, yet their elevated toxicity warrants focused regulatory attention (Kumar et al. 2021; Mahendra and Vinay 2025). Industrial activity is unevenly distributed across basin states. Uttar Pradesh accounts for the largest industrial footprint, with 687 units consuming about 693 MLD of fresh water and generating approximately 269 MLD of wastewater. This is followed by Uttarakhand, where 42 units consume around 224 MLD and discharge 127 MLD; Bihar, with 13 units consuming 91 MLD and discharging 17 MLD; and West Bengal, where 22 units consume 116 MLD and generate 87 MLD of effluent (CPCB 2013). In aggregate, industries within the basin consume roughly 1123 MLD of water and discharge about 500 MLD wastewater, approximately 45% of their intake, with the pulp and paper, sugar, and chemical sectors representing the largest contributors (CPCB 2013). More recent official reporting under the Namami Gange program reiterated that a large number of grossly polluting industries (2706 GPIs inspected across seven states, including Uttar Pradesh, Uttarakhand, Bihar, Jharkhand, West Bengal, Delhi, and Haryana) remain subject to compliance actions to control industrial effluent discharge, underscoring continued regional concentration of industrial pollution sources in the basin (Press Information Bureau 2023).

Recent assessments indicate a substantial increase in the identification and registration of grossly polluting industries (GPIs),

rising from 1080 in 2021 to 4246 in 2024 (National Mission for Clean Ganga 2023). This increase largely reflects improved industrial mapping, monitoring coverage, and regulatory scrutiny rather than a proportional rise in pollution-generating activity. Haryana and Uttar Pradesh now host the largest clusters of textile units, while West Bengal and Uttarakhand continue to be important centers for pulp and paper industries, apart from Uttar Pradesh (Ministry of Jal Shakti 2024b). Major contributing sectors include distilleries, tanneries, paper, textile, and sugar industries (National Mission for Clean Ganga 2021a, 2021b). Figure 5 shows the sector-wise distribution of GPIs in the river Ganga basin.

To further understand industrial discharge patterns at the operational scale, a recent investigation of 153 GPIs across four northern states examined physico-chemical characteristics, spatial distribution, and multivariate structure of industrial effluents released through both tapped and untapped drains (Singh, Chaudhary, et al. 2025; Singh, Singh, et al. 2025). The study indicates notable variability in pollutant loads, with evidence of both organic and inorganic pollution profiles across different locations. It also points toward the presence of certain industrial clusters that may have a relatively higher contribution to overall river contamination. These insights suggest the potential value of adopting more focused, cluster-based management and regulatory approaches to enhance the effectiveness of pollution control strategies.

At the collective-treatment level, eight common effluent treatment plants (CETPs) provide a combined installed capacity of 59.3 MLD (CPCB 2021a, 2021b), supporting clusters of small and medium enterprises. Statutorily, all industrial units are required to operate effluent treatment plants (ETPs) under the Environment (Protection) Act, 1986. Compliance assessments over time highlight both challenges and progressive tightening of oversight. While earlier inspections found that most CETPs required performance upgrades, subsequent evaluations show incremental improvements, with four of nine CETPs achieving full compliance by 2023 (CPCB 2023a, 2023b), indicating a gradual strengthening of operational controls.

At the individual industry level, inspection data similarly reflect increasing regulatory engagement. Of the 1080 GPIs assessed in 2022, 725 were found compliant, while enforcement actions, including closures and corrective notices, were initiated for noncompliant units (CPCB 2023a, 2023b). Importantly, the expansion of continuous online monitoring represents a major regulatory advance (Singh, Tiwari, Sharma, et al. 2022; Singh, Tiwari, and Singh 2022). As of 2024, 2805 of the 4246 GPIs have been integrated into the CPCB's Online Continuous Effluent Monitoring System (OCEMS), substantially enhancing transparency, real-time compliance tracking, and enforcement capability (CPCB 2024).

The marked increase in registered GPIs from 1080 in 2021 to 4246 in 2024 requires careful interpretation. As noted in the text, this increase primarily reflects improved regulatory mapping and monitoring coverage rather than a proportional increase in actual pollution-generating activity. However, the expansion of the OCEMS network to 2805 GPIs also reveals previously unquantified point sources, suggesting that earlier

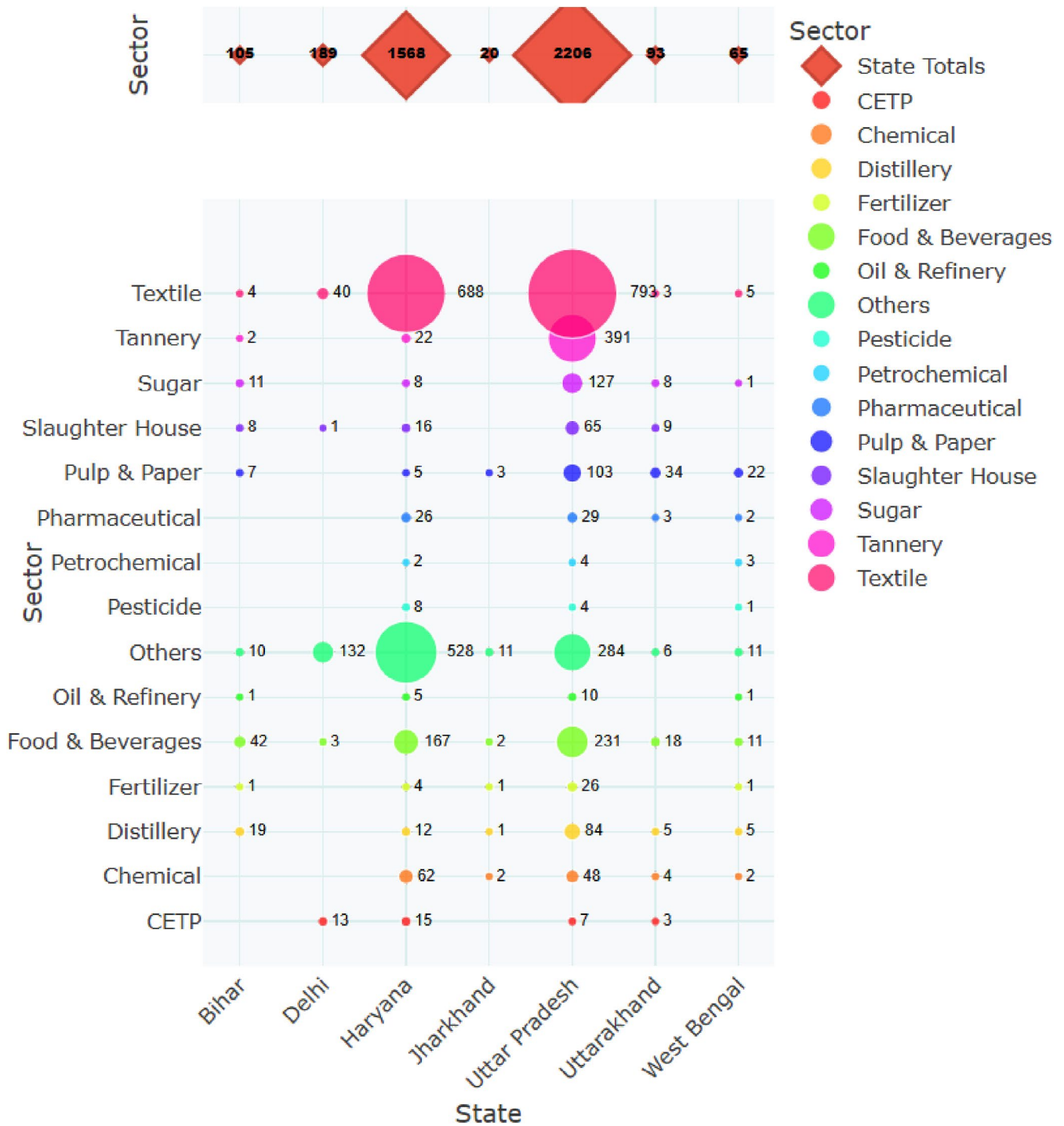


FIGURE 5 | Sector-wise distribution of GPIs in the river Ganga basin (Source: Namami Gange Annual Report 2023–24).

pollution load estimates, based on a fraction of the operating industrial base, likely underrepresented the true industrial contribution to basin-wide water quality degradation. This systematic expansion of monitoring coverage has important implications for retrospective assessments of pre-2020 water quality data.

2.3 | Agricultural Runoff

Agricultural runoff is the dominant nonpoint source of pollution, transporting nutrients, pesticides, and sediments into the

river, and interacting with regulated flows and localized industrial discharges to influence ecological processes. Numerous studies have clearly established the pathways by which pesticides migrate from croplands to surface waters via surface runoff, leaching, and storm-driven wash-off (Kumari et al. 2007). Between 2012 and 2017, pesticide use within the Ganga basin was estimated at approximately 72,741 MT, accounting for nearly 27% of national consumption, underscoring the basin's agricultural intensity (Shah and Parveen 2021). Earlier assessments reported annual pesticide usage of around 9000 MT, while the NGRBA estimated consumption at about 21,000 MT

in 2011, reflecting improved reporting and spatial coverage over time. Insecticides dominate the chemical profile ($\approx 80\%$), followed by herbicides ($\approx 15\%$) and fungicides ($\approx 2\%$) (DPPQS 2022; Shah and Parveen 2021).

Historically, organochlorine insecticides were extensively used until the early 1990s, after which organophosphate formulations became more prevalent; by 2014, this overall usage pattern remained broadly consistent. Commonly applied compounds include butachlor, endosulfan, mancozeb, monocrotophos, paraquat, phosphamidon, quinalphos, and isoproturon. Persistent organic pollutants (POPs), such as DDT and lindane, merit particular attention due to their environmental persistence, long-range transport potential, and tendency to bioaccumulate (Sah et al. 2020). India historically applied nearly 25,000 MT of chlorinated pesticides annually, with DDT accounting for about 40% of total pesticide use; cumulative consumption since 1985 is estimated at approximately 350,000 MT. Agricultural runoff, disposal of legacy pesticide-containing waste, and atmospheric deposition are the principal pathways through which these compounds may enter the environment (Sah et al. 2020; Khan et al. 2021).

Achieving a clean and ecologically stable Ganga river increasingly depends on reducing reliance on chemical pesticides, scaling up organic and sustainable farming practices, and strengthening regulatory controls on agrochemical use. Systematic identification of pollution hotspots through integrated ecological and public health assessments can enable more targeted, cost-effective interventions. Such a transformation in agricultural practices is inherently long-term and requires sustained collaboration among farmers, policymakers, extension agencies, and local communities (Syafudin et al. 2021; Haseena et al. 2017). Recent work in the Ramganga sub-basin demonstrated the application of GWQI, HPI, and HEI indices to assess groundwater contamination and related health risks from Zn, Fe, Cd, As, Cr, and Pb, revealing predominantly good-to-excellent water quality but localized zones of poor status and elevated risk (Kumar et al. 2024). Moreover, recent trends indicate a gradual yet meaningful transition toward more sustainable pest-management approaches. Between 2015 and 2021, while overall pesticide production increased by 36.4%, chemical pesticide consumption declined by 3.1%, alongside a substantial 44.9% increase in the use of bio-pesticides (DPPQS 2022). This shift toward bio-based alternatives not only supports agricultural sustainability but also represents a critical step toward reducing diffuse pollution pressures and enhancing the long-term ecological resilience of the Ganga river.

3 | Past Ganga Rejuvenation Programs

3.1 | Ganga Action Plan

The Ganga Action Plan (GAP) Phase I, launched in January 1986, marked India's first large-scale, government-led initiative to restore a polluted river system. Implemented across 25 Class-I towns in Uttar Pradesh, Bihar, and West Bengal, the program was supported by an initial budgetary allocation of ₹452 crore (Balkrishna et al. 2024; Dwivedi et al. 2018). GAP-I

was conceived primarily as a sewage management intervention, focusing on infrastructure to intercept and treat municipal wastewater before discharge into the river. While GAP-I established an important institutional and technological foundation, its outcomes fell short of original expectations. Over an implementation period of nearly 15 years, total expenditure increased to ₹901.71 crore, yet only about 39% of the targeted sewage treatment capacity was realized (Das and Tamminga 2012; MoEF 2004). Subsequent evaluations identified that these limitations arose largely from systemic and operational challenges inherent to a first-generation river restoration effort (K. D. Alley 2016). Key constraints included limited baseline environmental data and planning approaches that were insufficiently aligned with on-ground realities. In several cases, sewage treatment plants were sited without comprehensive environmental impact assessments, including on productive agricultural land. In addition, gaps in reliable information on wastewater quantity and quality constrained accurate process design, leading to facilities that were often undersized or mismatched to actual load conditions (Das and Tamminga 2012; IIT Consortium 2011; MoEF 2009).

Building on the lessons of GAP Phase I, the Ganga Action Plan Phase II (GAP-II) was launched in 1993. The paradigm expanded to include river-restoration efforts for the major tributaries, the Yamuna, Gomti, Damodar, and Mahananda, sited across 60 towns (Haberman 2006). Subsequently, the National River Conservation Plan (NRCP), initiated in 1995, expanded the scope further by subsuming GAP-II and extending interventions to other major rivers across the country. Within the Ganga basin, the NRCP encompassed eight rivers: the Ganga, Yamuna, Gomti, Damodar, Mahananda, Betwa, Mandakini, and Ramganga (MoEF 2009). While this broadened mandate marked an important paradigm shift toward basin-level coverage, implementation continued to face challenges in inter-institutional coordination, mobilizing financial resources, and building technical capacity at the state, urban, and local body levels. A Ministry of Environment and Forests review acknowledged that, despite substantial investment, the environmental outcomes of GAP and NRCP were positive but fell short of their full potential (MoEF 2009; Mishra and Upadhyay 2021).

A comprehensive evaluation by a consortium of seven IITs systematically examined the performance of GAP-I and GAP-II and identified several structural and operational constraints that limited their effectiveness (IIT Consortium 2011). Key issues included delays in project execution, ambiguities in funding mechanisms, technological mismatches, insufficient provision for operation and maintenance of created assets, and weak monitoring and evaluation frameworks. In addition, limited coordination between state agencies and urban local bodies, along with overlapping institutional mandates at the local level, constrained effective implementation. These assessments highlighted the need for clearer institutional roles, stronger inter-agency coordination, and dedicated mechanisms to ensure long-term asset sustainability. The findings also underscored the importance of citizen engagement and local ownership in sustaining infrastructure performance, insights that have since informed the design of more integrated and participatory river-restoration frameworks (Mishra and

Upadhyay 2021). On this basis, GAP-I and GAP-II achieved composite effectiveness scores of 1.3/10 and 1.7/10, respectively, reflecting high nominal project completion but limited operational performance, weak monitoring, and negligible ecological or community focus.

3.2 | National Ganga River Basin Authority

Recognizing the limitations of the earlier GAP phases, the Government of India (GoI) established the National Ganga River Basin Authority (NGRBA) in 2009 under Section 3(3) of the Environment (Protection) Act, 1986, with the Prime Minister as Chairperson (Balkrishna et al. 2024). Backed by an allocation of approximately US\$1 billion and supported by the World Bank, NGRBA represented a significant escalation in financial commitment and policy intent (The World Bank 2015).

Conceptually, NGRBA marked a major advancement over GAP by adopting a basin-wide management framework aligned with international best practices. Its mandate extended beyond sewage infrastructure to include strengthening the water-quality monitoring network from Gangotri to the Bay of Bengal; assessing pollution loads and compliance of grossly polluting industries; evaluating STP and CETP performance; analyzing seasonal pollution from major drains; reviewing analytical quality control practices of SPCBs; applying remote sensing and GIS for water-quality mapping; and conducting bio-monitoring from Haridwar to Diamond Harbor to assess ecological health. The paradigm shift toward this holistic approach was meant to directly address several conceptual gaps identified in earlier programs.

However, the transition from vision to implementation proved challenging. NGRBA operated without a fully institutionalized operational framework, leading to fragmented roles and limited coordination among ministries, states, and urban agencies. The lack of a unified implementation roadmap led to project-specific decision-making, resulting in delays and technical inconsistencies in the preparation of detailed project reports. Although scientific inputs, such as the Indian Institute of Technology (IIT)-led Ganga River Basin Management Plan, were available, their integration into project execution remained limited, leading to an emphasis on city-centric interventions rather than basin-scale solutions (Ministry of Jal Shakti 2024a).

Operational constraints were further compounded by procedural and financial sequencing issues, including fund releases before project readiness, delays in land acquisition and statutory clearances, and gaps in sewer network connectivity, which affected asset utilization. Enforcement of industrial pollution controls also progressed unevenly, with incomplete CETPs and variable compliance. In the absence of an integrated, real-time monitoring platform, decision-making relied on fragmented datasets, limiting the effectiveness of adaptive management. Consequently, key pollution indicators, such as BOD, COD, and fecal coliforms, showed limited basin-wide improvement during this phase (Ministry of Jal Shakti 2024a). The NGRBA phase scored 3.1/10, indicating an important conceptual shift toward basin-scale management and ecological considerations, but only partial implementation on the ground, particularly

in infrastructure delivery, monitoring systems, and public participation.

4 | Namami Gange: A Paradigm Shifts in River Rejuvenation Strategy

The Namami Gange program, launched in June 2014, is the most comprehensive effort to restore the Ganga river system. Approved with ₹20,000 crore and increased to ₹42,500 crore over 15 years, it is a long-term investment focused on sustainability. (Dhanya 2025b). Unlike earlier initiatives, Namami Gange introduced annuity-based payment mechanisms and explicit provisions for operation and maintenance over a 17-year cycle, directly addressing a critical limitation of the GAP era: insufficient post-construction asset sustainability (Ministry of Jal Shakti 2024b).

Several innovations distinguish Namami Gange from previous efforts, underpinning a paradigm shift. Notably, it implements a basin-scale management approach from the NGRBA that was difficult to execute. Its design, based on the comprehensive Ganga River Basin Management Plan by seven IITs (IIT Consortium 2011), offers a strong scientific foundation for prioritizing interventions across the basin. This evidence-based framework allows integrated consideration of hydrology, ecology, and socio-economics, shifting from fragmented city projects to coordinated basin-wide governance (Ministry of Jal Shakti 2024a; Balkrishna et al. 2024).

The Namami Gange program shifted from just pollution control to ecological restoration, recognizing that river health involves water quality, hydrology, biodiversity, sediment, and ecosystem services (Balkrishna et al. 2024). This holistic approach emphasizes not only sewage treatment but also maintaining environmental flows, conserving habitats, protecting biodiversity, and engaging communities. A key innovation was introducing context-specific public-private partnership (PPP) models for sewage infrastructure, notably adapting the Hybrid Annuity Model (HAM) with International Finance Corporation (IFC) and World Bank experts, tying payments to performance benchmarks for sustained treatment (K. D. Alley 2023; IFC 2019; Parajuli and de Souza 2023). This incentivized long-term plant performance. The program also piloted revenue mechanisms, like selling treated wastewater to IOC for industrial cooling at Mathura, saving about 20 million liters of freshwater daily and improving financial sustainability (Parajuli and de Souza 2023).

The Namami Gange Program integrated real-time monitoring and digital governance, filling gaps in earlier efforts. Platforms like PRAYAG enable continuous water-quality tracking along the river, improving data transparency and pollution detection (ESRI India 2024). This technology-driven framework supports evidence-based decisions by providing high-frequency, objective data. It also adopted a participatory, community-centered approach, engaging riparian populations through initiatives like Ganga Praharis and Ganga Doots. Building on lessons from top-down models, it recognizes that river revival depends on active community involvement, fostering local stewardship, social legitimacy, and a distributed monitoring network that complements regulation. The program has made measurable progress

despite ongoing challenges. Infrastructure-wise, it has expanded sewage treatment capacity by 3586 MLD as of February 2024, with 134 projects completed. Overall, 303 of 466 projects, costing around ₹17,763 crore, have been completed and operational (G Ashok 2024).

Monitoring data from the CPCB and NMCG show significant improvements in water quality in parts of the Ganga from 2014 to 2022 (Table 1). Analysis from 97 manual and 76 real-time stations indicates median dissolved oxygen (DO) levels are acceptable along most of the river. BOD levels have decreased, with improvements at 43 locations for BOD, 32 for DO, and 25 for fecal coliforms (G Ashok 2024). Sections previously classified as Priority I–IV pollution zones (BOD > 6 mg/L) recovered notably. Areas like Haridwar–Sultanpur, Buxar–Bhagalpur, and parts of Kannauj–Varanasi shifted from Priority categories to “Not Polluted,” with BOD below 3–5 mg/L. No stretch was in Priority I–IV in 2022, indicating basin-wide progress in pollution control. As per the discussion, compared to GAP I and II and NGRB, Namami Gange achieved a composite effectiveness score of 7.8/10, with strong performance across infrastructure, financial management, monitoring systems, and ecological focus, and markedly higher budget efficiency (0.224 score units per ₹1000 crore in time-adjusted expenditure) than preceding programs (Figure 6 and Supplementary file).

The ecological benefits of the Namami Gange Program are emerging, with biodiversity surveys indicating increased Gangetic dolphin sightings across several river stretches, reflecting localized reductions in pollution and improvements in flow (Himanshu 2025). While these trends should be interpreted cautiously due to methodological constraints and hydrological variability, they signal early ecological response. Interventions such as riparian afforestation, wetland rejuvenation, hatchery-supported fisheries, and biodiversity centers exemplify a shift toward system-scale ecological restoration that aligns with global standards. Industrial effluent regulation has also improved, with over 900 polluting industries now monitored in

real-time, replacing earlier episodic inspections. This enhances transparency, compliance, and regulatory action (Namami Gange 2024). Table 2 shows target vs. achieved goals under the Namami Gange initiative, while Table 3 and Figure 6 compare earlier Ganga restoration efforts with the Namami Gange program, showing progress across administrative, technological, financial, and social areas.

Building on these advances, a set of interconnected system-level factors continues to shape the trajectory of river restoration. Addressing remaining gaps in the sewerage network offers significant potential to enhance the utilization and performance of newly commissioned treatment infrastructure. Managing environmental-flow pressures, linked to upstream diversions and basin-wide water demands, will be central to sustaining dilution capacity and ecological resilience during lean seasons. Diffuse agricultural inputs, primarily nutrients and pesticides, underscore the importance of complementary measures beyond the core program scope to support source-level pollution control. At the urban scale, strengthening municipal capacity in asset management, operation, and maintenance can further consolidate performance gains. In parallel, inherent hydrological variability, including monsoon-driven dilution effects, highlights the need for seasonally informed assessment frameworks to improve long-term water-quality evaluation and trend interpretation.

5 | Impact Evaluation of Rejuvenating the Ganga Under National Mission for Clean Ganga

The Arth Ganga model, announced at the first National Ganga Council meeting in 2019, marks a strategic shift toward integrating river conservation with economic development (Indian Express 2022; National Mission for Clean Ganga 2022a, 2022b). Building on established ecosystem-services concepts, the model explicitly links river rejuvenation with economic value creation, including reclaimed-water reuse for thermal power generation

TABLE 1 | Water quality improvements across Ganga stretches (2014–2022) under the Namami Gange program, with percentage changes relative to 2014 baseline (CPCB 2023a, 2023b; G Ashok 2024; Ministry of Jal Shakti 2024b).

Stretch/State	Parameter	2014 Baseline	2022 value	Change	Pollution category shift
Haridwar–Sultanpur (Uttarakhand)	BOD (mg/L)	> 3 (Priority IV)	< 3	Improving	Priority IV → No PRS
Kannauj–Varanasi (Uttar Pradesh)	BOD (mg/L)	> 6 (Priority II–III)	3–5	~30%–50% reduction	Priority II → Improved
Buxar–Bhagalpur (Bihar)	BOD (mg/L)	> 6 (Priority V)	3–6	~20%–40% reduction	Priority V → Improved
Triveni–Diamond Harbor (West Bengal)	BOD (mg/L)	> 3 (Priority III)	< 3 (partial)	Improving	Priority III → Improved
Multiple stations (<i>n</i> = 43)	BOD	Elevated	Reduced	Improvement recorded	—
Multiple stations (<i>n</i> = 32)	DO	Below standard	Improved	Improvement recorded	—
Multiple stations (<i>n</i> = 25)	Fecal coliforms	Elevated	Reduced	Improvement recorded	—

Note: Exact baseline and current values vary by monitoring station; refer to CPCB (2023a, 2023b) and G Ashok (2024) for station-level data. Abbreviation: PRS = Polluted River Stretch.

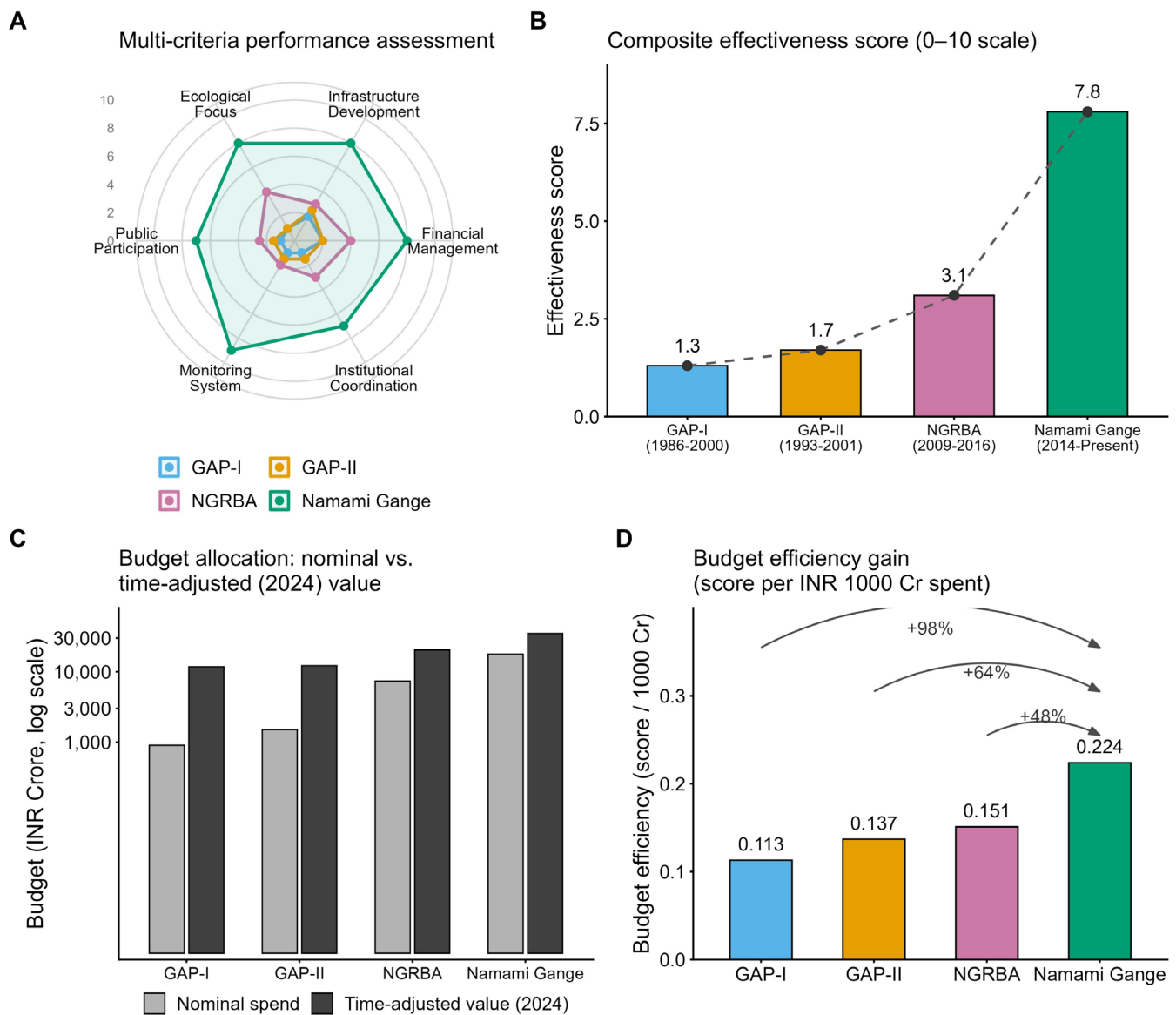


FIGURE 6 | Multi-criteria performance, budget allocation, and efficiency across four decades of Ganga restoration programs. (A) Radar plot of performance scores (0–10) for GAP-I, GAP-II, NGRBA, and Namami Gange across six dimensions: Infrastructure Development, Financial Management, Institutional Coordination, Monitoring System, Public Participation, and Ecological Focus. (B) Composite effectiveness scores (0–10) for each program, calculated as the mean of the six dimension scores. (C) Nominal budget allocations versus time-adjusted budgets (2024 values, log scale) for each program, based on reported expenditure and program duration. (D) Budget-efficiency ratios, expressed as composite effectiveness score per ₹1000 crore of time-adjusted expenditure, with arrows indicating the relative efficiency gains from GAP-I through Namami Gange. All scores and efficiency metrics reflect the authors' synthesis and interpretation of documented implementation outcomes and institutional evaluations.

and expanded inland waterway transport, with an aspirational contribution of up to 3% of India's GDP from activities within the Ganga basin (National Mission for Clean Ganga 2022a, 2022b, 2022c).

The framework is structured around four core objectives: (i) promotion of Zero Budget Natural Farming within a 10-km corridor on both sides of the river to reduce chemical inputs; (ii) continued expansion and upgradation of sewage treatment infrastructure for municipal and industrial wastewater (K. D. Alley 2016); (iii) enhancement of local livelihoods through handicrafts, organic markets, river-based tourism, river-guide training, medicinal-plant cultivation, afforestation, and inland waterway transport; and (iv) strengthening cultural and tourism assets through ghat

revitalization, pilgrimage circuits, river cruises, and the development of museums and galleries (National Mission for Clean Ganga 2022a).

5.1 | Socio-Economic Costs and Benefits From Agricultural Interventions

The Arth Ganga framework promotes sustainable agriculture through capacity building, market linkages, and infrastructure development, facilitating the transition of over 1.2 lakh hectares to natural farming (NMNF 2025). Regional initiatives, such as organic corridors in Bihar (Bihar State Biological Mission 2023), TEEBAgriFood and SARG Vikas Samiti programs in

TABLE 2 | Targets versus achievements in infrastructure development, monitoring, and capacity enhancement under Namami Gange (Ministry of Jal Shakti 2024b; G Ashok 2024; CPCB 2024).

Component	Target	Achieved (as of 2024)	Achievement (%)
Sewage Treatment Capacity	~10,160 MLD	~7820 MLD operational	~77%
STP Projects sanctioned	466	303 completed and operational	65%
New capacity under construction	~1996 MLD	In progress	—
Grossly Polluting Industries monitored (CPCB's OCEMS)	All 4246 GPIs	2805 integrated	~66%
Real-time water quality stations	173 (97 manual +76 RTDAS)	173 operational	100%
River surface cleaning sites	11 locations	11 operational	100%
Riverfront/Ghat development projects	Ongoing	Progressive completion	—

Uttarakhand (UNEP 2025; SARG Vikas Samiti 2025), and decentralized farmer training for organic branding in Uttar Pradesh (Times of India 2022), collectively address input affordability, soil health, and climate resilience. These efforts are reinforced by the national distribution of over 24 crore Soil Health Cards (Ministry of Agriculture and Farmers Welfare 2025) and the development of 75 eco-tourism hubs and Sahakar Ganga Grams to strengthen rural livelihoods and market access (Press Information Bureau 2022).

5.2 | Wastewater Reuse

Wastewater recycling initiatives primarily target industrial users, particularly thermal power plants, where cooling towers account for substantial water consumption (Jain et al. 2021; Lohrmann et al. 2019). This approach aligns with national policy advisories (Ministry of Power 2016) and municipal regulations mandating decentralized treatment (K. D. Alley 2023). However, the successful commercialization of sludge-based agricultural products requires overcoming persistent socio-economic barriers, such as social stigma, information gaps, and low perceived returns among farmers (Friedrichsen et al. 2021; Singh, Tiwari, Sharma, et al. 2022; Singh, Tiwari, and Singh 2022). Ensuring the wider adoption and long-term viability of these reuse systems also depends heavily on strengthening the financial sustainability of urban local bodies and implementing robust utility pricing reforms (Breitenmoser et al. 2022).

5.3 | River Infrastructure

Inland navigation and connectivity are being enhanced through the Jal Marg Vikas Project, which has established operational multimodal terminals at Varanasi, Sahibganj, and Haldia (IWAI 2023). The concurrent development of 62 community jetties aims to support local ecotourism, heritage circuits, and rural livelihoods (Ministry of Ports, Shipping, and Waterways 2022). While National Waterway-1 projects substantial economic revenues from expanded cargo and passenger movement, realizing this potential sustainably requires comprehensive environmental impact assessments (EIAs) to mitigate risks to riverbed

stability and aquatic habitats, balancing economic expansion with ecological integrity (Aggarwal et al. 2020; Dey et al. 2019; Dharmadhikary and Verma 2021).

5.4 | Wastewater Infrastructure

A key strength of the NMCG program lies in its sustained expansion and modernization of wastewater treatment infrastructure. Newly commissioned STPs in cities such as Haridwar, Kanpur, Prayagraj, Varanasi, and Patna are collectively adding over 2700 MLD of treatment capacity, while upgrades and rehabilitation of underperforming facilities are expected to add an additional ~300 MLD. In parallel, decentralized and modular treatment systems using technologies such as MBBR and SBR have been deployed in smaller towns, housing complexes, universities, and rural settings (K. D. Alley 2023). These efforts are supported by the development of complementary sewage pumping stations and underground sewer networks that divert wastewater from open drains to treatment facilities. Where direct drain discharges persist, nature-based solutions, including phytoremediation, bioremediation, and constructed wetlands, are being piloted as adaptive interventions. In addition, riverfront development around major ghats is improving public amenities by enhancing bathing platforms, sanitation facilities, lighting, signage, and regulated vending spaces, thereby contributing to both environmental management and public engagement.

5.5 | Biodiversity Conservation, Fisheries, Tourism, and Ecosystem Services

Biodiversity conservation is integral to the basin's ecological restoration, shifting the focus beyond mere pollution abatement. Flagship river ranching programs have facilitated the upstream release of Hilsa, Mahseer, and millions of native carp fingerlings to re-establish migratory connectivity disrupted by barrages and to support sustainable local fisheries (Ministry of Jal Shakti 2020; Ministry of Fisheries, Animal Husbandry and Dairying 2021). Collectively, these interventions enhance provisioning, regulation, and support of ecosystem services, which are fundamental to the river's overall resilience (Kumar et al. 2021; Srinivas et al. 2020). Sustaining

TABLE 3 | Comparative analysis of Namami Gange program with previous Ganga rejuvenation initiatives (Balkrishna et al. 2024; ESRI India 2024; G Ashok 2024; Himanshu 2025; IFC 2019; IIT Consortium 2011; John and Manuela 2023; Ministry of Jal Shakti 2024c; MoEF 2009; Mishra and Upadhyay 2021).

Parameter	GAP Phase I (1985–2000)	GAP Phase II (1993–2001)	NGRBA (2009–2016)	Namami Gange (2014–Present)	Rationale
Funding model	100% Central funding (₹462 crore)	Initially 70:30 Center-State; later 100% Central (₹1498 crore)	World Bank loan (\$1 billion) + government funding	100% Central funding as a central sector scheme (₹20,000–22,500 crore)	Namami Gange eliminates the state financial burden that caused delays in GAP II. Non-lapsable corpus ensures funds remain available.
Approach	Town-centric, point pollution focus on 25 Class-I towns	Extended to tributaries but is still fragmented	Basin-level approach conceptualized	Integrated River Basin Management covering the entire Gangetic basin	A holistic approach addresses root causes rather than symptoms. Previous plans failed due to a fragmented approach in select cities without comprehensive planning.
Administrative authority	Ministry of Environment and Forests; Central Ganga Authority under PM as chair	Same as Phase I with NRCD	NGRBA under the Environment Protection Act, 1986; PM as Chair	Department of Water Resources, River Development and Ganga Rejuvenation; NMCG as a statutory authority	The shift to the Water Resources ministry provides developmental leverage. Previous placements under the Environment Ministry had limited inter-ministerial coordination, resulting in “faulty execution, delays, and cost overruns.”
Financing mechanism	Grant-in-aid, year-end lapse	Grant-in-aid with state sharing issues	World Bank loan with conditionalities	Hybrid Annuity Model (HAM): 40% during construction, 60% as performance-based annuities over 10 years	HAM ensures long-term O&M support, preventing plant abandonment. GAP I, II plants became non-functional due to the lack of an O&M provision. Performance-based payments ensure accountability, unlike previous grant systems.
Coverage	3 states (UP, Bihar, West Bengal)	7 states, including tributaries	5 mainstem states	Entire Ganga basin across all states with tributary integration	Comprehensive coverage addresses pollution at source. GAP’s limited coverage meant “pollution load of Ganga not fully covered.”

(Continues)

TABLE 3 | (Continued)

Parameter	GAP Phase I (1985–2000)	GAP Phase II (1993–2001)	NGRBA (2009–2016)	Namami Gange (2014–Present)	Rationale
Project completion rate	259/261 projects (99%), but only 39% of sewage treatment targets met	652/764 projects (85%) by 2014	Limited implementation; the conceptual stage mostly	Progressive implementation with monitoring systems	Previous high completion rates are misleading, as “most did not function either fully or partially.” Focus shifted from mere construction to functional operations.
Sewage treatment capacity created	865 MLD against 1340 MLD needed (65%)	Extended capacity but underutilized	Minimal addition	Targets the full pollution load with a phased approach	Addresses the utilization gap. GAP suffered from “sewers laid not connected to STPs and STPs installed having no sewage to treat or electricity to run.”
Operation and maintenance	No provision: states are responsible	State responsibility for funding issues	Unclear provisions	10-year minimum O and M provision with HAM model	Critical for sustainability. “UP and Bihar were not able to provide uninterrupted electricity for running facilities” under GAP, rendering investments useless.
Public participation	Minimal; top-down approach	Limited awareness campaigns	Conceptualized but not implemented	Major focus: involving States, ULBs, PRIs, and riverbank communities	Essential for sustainability. GAP’s failure was attributed to “absence of public awareness and participation” and being “a completely bureaucratic exercise, top-down, end-of-pipe interventions.”
Monitoring systems	Manual monitoring; limited data	Conventional monitoring with gaps	Conceptual monitoring framework	> 100 real-time water quality monitoring stations; online effluent monitoring for GPIs	Real-time data enables prompt action. Previous plans had “a lack of local technical experts for monitoring” and no systematic data collection, causing planning failures.
Industrial effluent control	Regulations existed, but weak enforcement	Limited enforcement	Regulatory framework strengthened	Mandatory real-time online effluent monitoring stations for all Grossly Polluting Industries	Enforceable tracking system. Under GAP, “few industries did not adhere to pollution control norms,” releasing toxic substances unchecked.

(Continues)

TABLE 3 | (Continued)

Parameter	GAP Phase I (1985–2000)	GAP Phase II (1993–2001)	NGRBA (2009–2016)	Namami Gange (2014–Present)	Rationale
Ecological focus	Narrow pollution abatement	Same as Phase I	Ecological flows conceptualized	Comprehensive: e-flows mandate (Oct 2018), biodiversity conservation, afforestation	Recognizes the river as an ecosystem. Previous plans focused only on sewage treatment, ignoring “minimum ecological flows, sustainable access and river ecology.”
Biodiversity programs	Minimal; soft-shelled turtles mentioned	Limited scope	Conceptualized	Dedicated programs: Golden Mahaseer, Dolphins, Ghariyals, Turtles, Otters	Species-specific conservation. GAP’s limited focus on biodiversity failed to comprehensively address ecosystem degradation.
Afforestation component	Not significant	Limited	Not implemented	30,000 ha for aquifer recharge, erosion control, and ecosystem health	Addresses watershed degradation. Previous plans overlooked catchment area protection, resulting in continued pollution from non-point sources.
Coordination mechanism	Poor inter-ministerial coordination	Continued coordination issues	Multiple ministries involved conceptually	Active coordination: Environment, Urban Development, Shipping, Tourism, Rural Development	A multi-sectoral approach is essential. GAP’s “lack of coordination resulted in faulty execution, delays, and cost overruns.”
Timeline and phasing	1986–1990 (extended to 2000)	1993–2001 (merged with NRCP)	2009–2020 target	Entry-level (immediate), Medium-term (5 years), Long-term (10 years); 2014–2026	Realistic phasing with milestones. GAP “postponed deadlines from 1990 to 2000, then 2001,” showing poor planning. Namami Gange has strategic milestones.
River surface cleaning	Not prioritized	Not significant	Not implemented	Active at 11 locations for floating solid waste	Immediate visible impact. Previous plans ignored surface pollution, creating a perception of inaction.

(Continues)

TABLE 3 | (Continued)

Parameter	GAP Phase I (1985–2000)	GAP Phase II (1993–2001)	NGRBA (2009–2016)	Namami Gange (2014–Present)	Rationale
Sanitation integration	Limited to Class-I towns	Extended but uncoordinated	Conceptualized	Ganga Gram initiative: 1674 Gram Panchayats for toilet construction; IIT village adoption	Addresses open defecation at the source. GAP failed to tackle “control of non-point pollution from human defecation” systematically.
Knowledge base	Weak data foundation	Limited research	World Bank-supported knowledge center planned	Ganga Knowledge Center, 7 IIT consortium, comprehensive research programs	Evidence-based planning is critical. GAP suffered from “lack of data on water use and wastewater generation, ensuring plans failed miserably.”
Financial transparency	Audit revealed 39% target achievement; ₹901.71 crore spent against ₹687.88 crore released	Multiple instances of financial mismanagement	World Bank oversight mechanisms	Non-lapsable fund, performance-based contracts, transparent monitoring	Accountability mechanisms prevent fund misuse. CAG audit found “many instances of financial mismanagement” in GAP.
Community engagement	Minimal grassroots involvement	Limited	Public participation framework conceptualized	Active involvement: Ganga Vriksharopan Abhiyan, Ganga Gram Swachta Sammelan, awareness campaigns	Community ownership is essential. “Improper mass awareness and involvement of Ganga users” was the key GAP failure reason.
Funding sustainability	Year-end lapse; no continuity	State contribution issues	Loan-based with repayment burden	Clean Ganga Fund with tax benefits for contributions; non-lapsable corpus	Multiple funding streams reduce dependency. GAP suffered from “limited funding and poor coordination,” leaving “much of the plan incomplete.”

TABLE 4a | For Upper Ganga river basin (origin to Haridwar).

Seasons	Months	(%) Percentage of monthly average flow observed during each of preceding 10 daily periods
Dry	November–March	20
Lean	October, April and May	25
High Flow	June to September	30

TABLE 4b | For river Ganga below Haridwar up to Unnao.

Barrage	Minimum flow releases immediately downstream of barrages (in cumecs) during non-monsoon (October to May)	Minimum flow releases immediately downstream of barrages (in cumecs) during monsoon (June to September)
Bhimgoda	36	57
Bijnor	24	48
Narora	24	48
Kanpur	24	48

these ecological and economic dividends requires strict industrial regulations, guaranteed environmental flows, and the integration of traditional ecological knowledge into basin governance frameworks (Singh, Tiwari, Sharma, et al. 2022; Singh, Tiwari, and Singh 2022; Srinivas et al. 2020; Kumar et al. 2021).

6 | Maintaining Environmental Flows (E-Flow) in the Ganga River and Its Tributaries

Environmental Flows (E-Flows) have emerged as a central scientific and policy instrument for restoring river health, defining the quantity, timing, and variability of flows required to sustain key ecological processes such as habitat stability, sediment transport, channel morphology, and floodplain connectivity.

6.1 | Gazette Notification on E-Flows of Ganga River

The Government of India notified minimum E-Flow requirements for the River Ganga in a Gazette Notification on 9 October 2018, to protect its ecological health. These norms cover the Upper Ganga Basin from glacier-fed headwaters and tributaries up to Devprayag and Haridwar, along the main stem to Unnao, and include all projects, with exemptions for small projects that

do not affect natural flow. Non-compliant projects had to meet standards by 15 December 2019, as notified on 14 September 2019. The notified E-Flow requirements, summarized in Tables 4a and 4b, represent a significant step toward institutionalizing flow-based river restoration in India.

The Central Water Commission (CWC), designated as the nodal authority and data custodian, oversees environmental flow (E-Flow) norms for the River Ganga. Its responsibilities include supervising, monitoring flows, providing regulatory oversight, reporting compliance to authorities, and making emergency reservoir operation decisions. CWC submits quarterly flow and compliance reports to NMCG. Eleven key projects, Maneri Bhali Stage I & II, Tehri, Koteshwar dams, Vishnuprayag HEP, Srinagar HEP, Pashulok Barrage/Chilla HEP, Bhimgoda, Bijnor, Narora, Kanpur barrages, are critical flow-control points. Project authorities must install sensor-based systems for continuous data collection. To standardize monitoring and compliance assessment, the Standard Operating Procedures (SOPs) for minimal E-Flow monitoring in Ganga were approved by NMCG (F. No. 5/46/2017-Hyd (NE), dated 24 January 2020).

6.2 | Other E-Flow Assessments and Implementations in Ganga Tributaries

6.2.1 | Ramganga River

Environmental flow (E-Flow) assessment for the Ramganga River was conducted through a multi-institutional collaboration involving GIZ-IEWP Action Phase II, NMCG, CWC, WII, CIFRI, and NIH. This effort resulted in a national guidance document for E-Flow assessment and implementation in India (Nale et al. 2020), which supports the standardization of E-Flow practices. The guidance recommends three established approaches: the Hydraulic Rating-cum-Habitat Simulation Method, PHABSIM, and MesoHABSIM, with method selection based on data availability, river characteristics, ecological and socio-economic relevance, and resource constraints, enabling context-specific application.

6.2.2 | Yamuna River (Hathnikund to Okhla Barrage)

Pursuant to directions of the Hon'ble National Green Tribunal, NMCG commissioned NIH to assess E-Flows for the Yamuna River between Hathnikund and Okhla barrages. An integrated hydrologic-hydrodynamic framework was applied, combining HEC-RAS simulations at 13 representative locations with SWAT-based flow series. Monthly E-Flow releases were determined to maintain a minimum depth of 0.60 m, explicitly accounting for natural flow variability, with May as the reference low-flow month. Recommended E-Flows ranged from 22.81 cumecs in January to 219.82 cumecs in August. The study also proposed supporting measures, including improved irrigation efficiency in WYC/EYC commands, regulation of groundwater abstraction, enhanced recharge, upstream monsoon storage, and strengthened wastewater treatment.

6.2.3 | State-Level E-Flow Orders and Expansion

In February 2021, the Government of Uttar Pradesh directed maintenance of E-Flows in the Ramganga River downstream of Harewali Barrage at 4 cumecs. In September 2024, E-Flows for the Gomti River at Hanuman Setu, Lucknow, were notified at 40.56 cumecs (non-monsoon) and 65.70 cumecs (monsoon). Complementing these actions, NMCG has sanctioned new R&D studies for E-Flow assessment in nine major Ganga tributaries, including the Chambal, Sone, Damodar, Tons (NIH Roorkee), Ghaghra, and Gomti (IIT Roorkee), and Kosi, Gandak, and Mahananda (IIT Kanpur), reflecting systematic basin-scale expansion.

7 | Remote Sensing Application in Water Quality Assessment of the River Ganga

Water quality in large river systems such as the Ganga has traditionally been monitored using in situ sampling and laboratory analysis, which provide accurate but spatially and temporally limited information (Ansari and Kumar 2022). Remote sensing offers a complementary, basin-scale approach for observing key parameters such as turbidity, chlorophyll-a (Chl-a), total suspended matter (TSM), and colored dissolved organic matter (cDOM), with recent advances in machine-learning models further enhancing retrieval capabilities (Chen et al. 2022; Krishnaraj and Honnasiddaiah 2022). However, applications to highly dynamic rivers like the Ganga remain constrained by sensor limitations and the lack of region-specific calibration datasets. Recent studies using multi-sensor satellite data, including Sentinel-1, demonstrate the potential to capture long-term spatio-temporal variability in optically active constituents across representative Ganga reaches (Muduli et al. 2021). Continued development of region-specific remote-sensing models is therefore essential for reliable, large-scale water-quality monitoring in the Ganga River (Chander et al. 2019).

8 | Toward Sustainable River Restoration

A critical determinant of success for river-rejuvenation initiatives is effective collaboration between government agencies and the public. Experience indicates that infrastructure investments achieve greater effectiveness when supported by sustained public participation, strong inter-agency coordination, and systematic monitoring frameworks. Strengthening cooperation between implementing agencies and monitoring institutions, supported by transparent data sharing and community engagement, is essential to ensure that treated water meets safety and reuse standards.

Wastewater reuse and sludge management (treatment and utilization) remain a key operational focus area, where improving the accuracy of city-level sewage generation estimates and enhancing treatment performance can yield substantial benefits. Strengthening sewage collection and ensuring comprehensive treatment, particularly by minimizing the discharge of untreated domestic wastewater, are central to sustaining improvements in river health. In parallel, optimizing river regulation

through dams and barrages to better reflect natural flow regimes can enhance habitat connectivity and support aquatic species, including the Gangetic dolphin, otters, freshwater turtles, wetland birds, and native fish populations. However, sustaining these populations requires more than flow regulation and needs the active preservation of physical habitat integrity. Future interventions must therefore prioritize the protection of critical riverine features such as deep pools, stable sandbanks, and riparian wetlands from channelization and encroachment. This ensures that the river retains the structural diversity necessary to support complex life cycles, preventing a scenario where improved water quality fails to translate into biodiversity recovery due to habitat loss.

Emerging contaminants, such as microplastics, pharmaceuticals, personal care products, hormones, and hydrocarbons, have been detected in river water and sediments. Their identification underscores the opportunity to further strengthen wastewater treatment systems and advance targeted research on removal technologies, as conventional treatment processes can be enhanced to address these classes of pollutants more effectively. To complement physicochemical water quality monitoring, future governance frameworks should institutionalize systematic bio-monitoring and the use of ecological health indices. Integrating these biological indicators will provide a more holistic assessment of river health that captures the impacts of altered flow regimes and habitat fragmentation, which standard chemical parameters may overlook.

Moving forward, sustained improvements in Ganga water quality will benefit from stronger enforcement of environmental regulations across the industrial, municipal, and agricultural sectors, alongside investments in cleaner, decentralized wastewater treatment systems for peri-urban and non-sewered areas. Expanding and modernizing sewage treatment infrastructure, ensuring complete sewage collection, and promoting sustainable riverfront development can collectively reduce pollution pressures while supporting eco-friendly tourism and recreation. Industrial pollution ingress has also disrupted the functioning of sewage treatment plants. Therefore, small-scale and household industries should be relocated to designated industrial zones equipped with advanced CETPs. More emphasis must be placed on robust operation and maintenance of pumping stations and sewage treatment plants, supported by strict regulatory enforcement and stringent penalties for non-compliance. Adequate standby equipment and spares should be mandatorily maintained to ensure uninterrupted operation during breakdowns. Further, STP operation must be explicitly linked to sludge generation, handling, and safe disposal, with sludge management treated as an integral performance criterion rather than a downstream afterthought.

Ultimately, the rejuvenation of the Ganga is a long-term, multi-dimensional endeavor that depends on inclusive, multi-stakeholder engagement. Active participation of local communities, urban institutions, religious organizations, civil society, and the international community, combined with comprehensive, long-term monitoring and adaptive management, will be essential to sustain progress. While complex, restoring the Ganga is both achievable and vital for ecological integrity and the livelihoods of millions who depend on the river.

9 | Conclusions

Four decades of Ganga restoration have led to a transition from fragmented GAP initiatives to integrated Namami Gange basin-scale management, yielding measurable gains: treatment capacity has expanded sevenfold (from 1192 to 8200 MLD) and real-time monitoring has been established for 2805 industries. Namami Gange achieved 7.8/10 effectiveness versus NGRBA (3.2) with the highest budget allocated and utilization efficiency (0.224). The institutionalization of environmental flows and Arth Ganga's integration of organic agriculture, wastewater reuse, and biodiversity conservation demonstrate socio-ecological co-benefits. Sustaining restoration requires strengthening sewerage connectivity, optimizing treatment plant operations and maintenance, relocating industries to zones with advanced CETPs, integrating sludge management as a performance criterion, applying remote sensing for water quality assessment, reducing agricultural pesticide loads, protecting critical habitats, ensuring flow-resilient management, and fostering multi-stakeholder engagement. Collectively, the evidence indicates that sustained alignment of ecological processes, institutional capacity, and socio-economic incentives can elevate the Ganga's recovery from incremental gains to enduring river health.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article, as no new data were created or analyzed in this study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.