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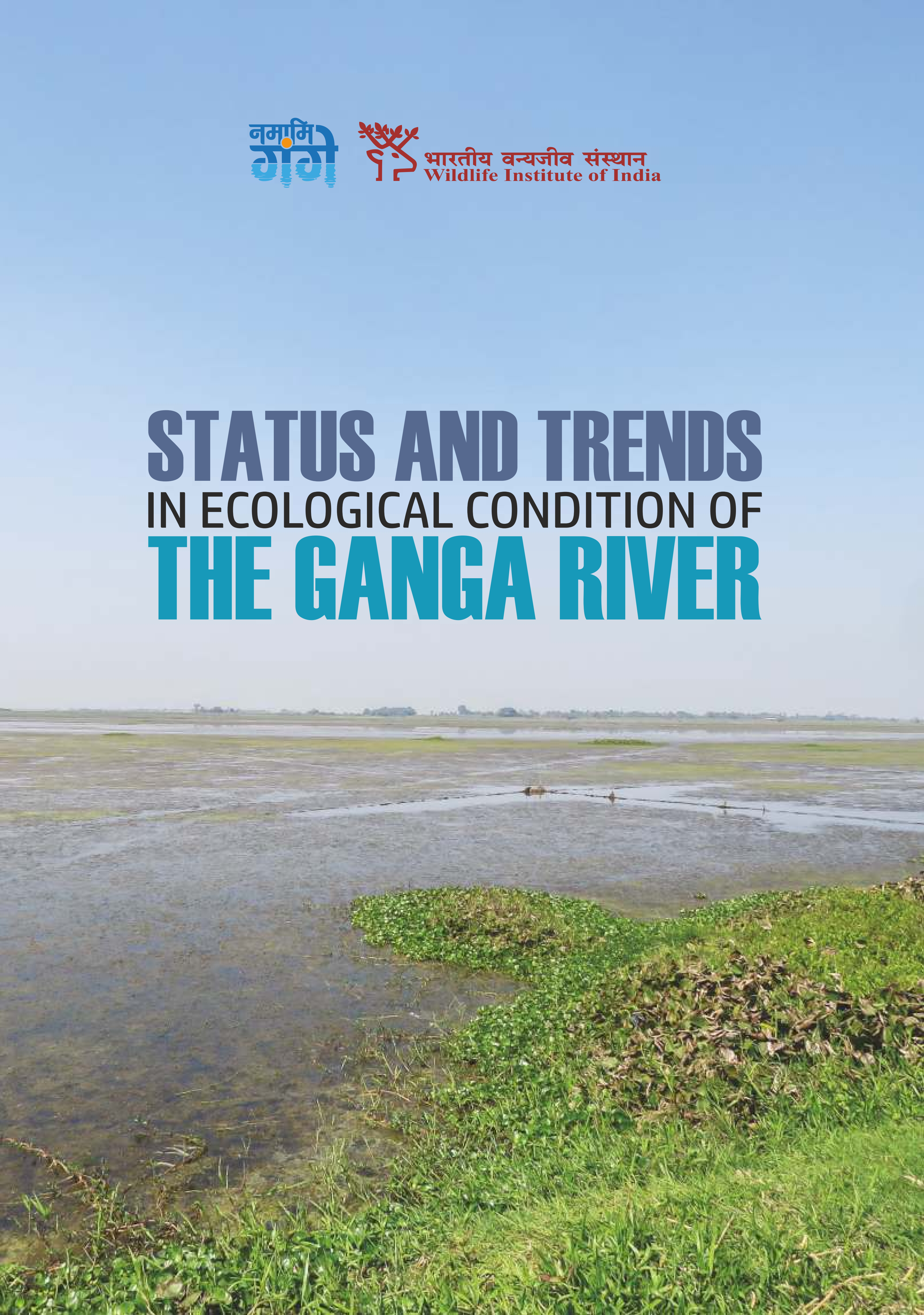
भारतीय वन्यजीव संस्थान
Wildlife Institute of India

STATUS AND TRENDS
IN ECOLOGICAL CONDITION OF
THE GANGA RIVER



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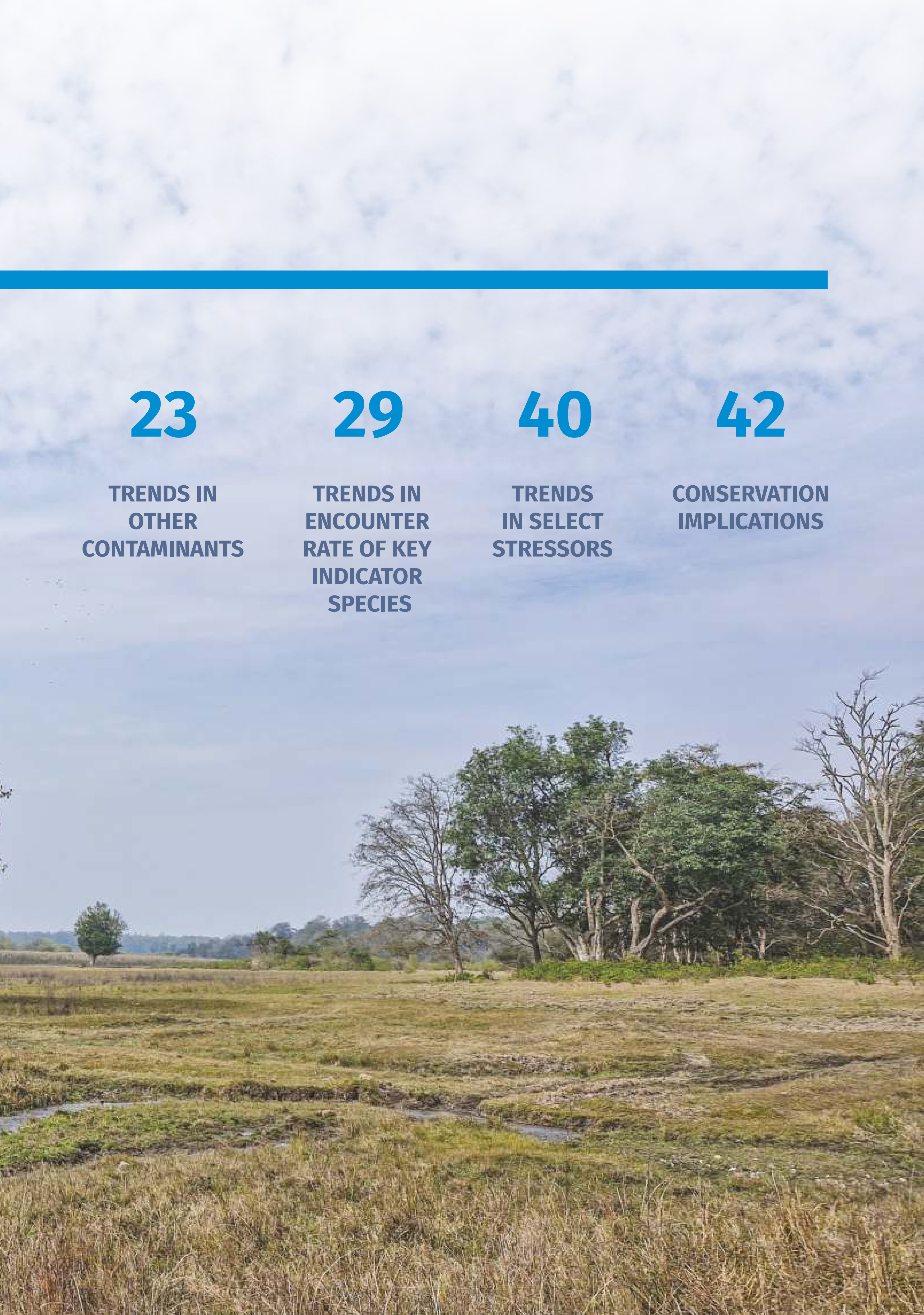

EXECUTIVE

The Ganga River is India's one of the most iconic and ecologically significant rivers. Over the time, it has transitioned into a stressed river under mounting anthropogenic pressures and possible climate change impacts. Recognising the urgency of intervention, the Government of India initiated the Namami Gange programme by setting up of National Mission for Clean Ganga (NMCG) - a flagship initiative - with the overarching aim to restore the river's ecological health, ensuring adequate ecological flows, and rebuilding the relationship between the Ganga and the communities that depend on it.

The *Namami Gange* programme encompasses comprehensive interventions including sewage treatment infrastructure development, industrial effluent management, riverfront development, maintaining ecological flows, rural sanitation, afforestation, biodiversity conservation, and community participation. Various national and state- level agencies are involved in this programme. For pollution abatement, a total of 292 sewerage infrastructure projects with a treatment capacity of 6540.225 MLD have been undertaken for pollution remediation in the Ganga River Basin (as on 1st April 2025). Of these, 157 STPs with a capacity of 3687.265 MLD are operational, while 102 STPs with a capacity of 2185.877 MLD are under progress, and 33 STPs with a capacity of 667.083 MLD are under tendering. To improve the flow of the Ganga River, the e-flow requirement was notified in October 2018. Along with this, the floodplain connectivity is being enhanced through conservation and protection of the wetlands, afforestation of the Ganga River through the scientific plan developed by the Forest Research Institute, Dehradun. Sustainable agriculture is being promoted in the 5 km corridor along the Ganga River by involving multiple agencies. River-people connect is being strengthened along the principles of *Jan Bhagidari*, and a cadre of volunteers, Ganga Prahari, has been established by the WII for conservation of the Ganga River. The ICAR-Centre Inland Fisheries Research Institute (ICAR-CIFRI), was entrusted to assess the fish diversity of the Ganga River and restore the population of Indian Major Carp, through ranching.

In 2016, the Wildlife Institute of India (WII) was entrusted the task of undertaking ecological assessments of the Ganga River and involving communities and other stakeholders in the conservation of the Ganga River. A comprehensive and continuous ecological assessment of the Ganga River since 2017 provided baseline information on the ecological condition of the river during 2017 to 2025. This report presents the condition and trend of the select ecological parameters, vis-à-vis various programmes implemented under the *Namami Gange* programme, at the landscape level

SUMMARY

and also at the reach scale. For the ecological assessment, the Ganga River was divided into 5 km assessment units, known as the Basic Evaluation Units (BEUs), where ecological assessments were conducted. A total of 19 parameters, defining the habitat quality, encounter rate of select aquatic species, contaminants, and anthropogenic stressors, were assessed, and their trends derived. Data generated by other agencies such as Forest Survey of India and relevant published information was also considered. While a detailed assessment report on the current status of the Ganga River and its tributaries is under preparation, this concise report is presenting information on trends of select ecological parameters that affects river health for immediate course correction and redirecting conservation efforts.

The Ganga riverscape spans 57 districts covering approximately 1,89,000 km² area. In view of the afforestation programme taken up by the NMCG during 2016 to 2023 the forest cover across these districts were examined based on forest cover data generated by Forest Survey of India. The analysis showed a modest but consistent upward trend in forest cover between 2017 and 2023, rising from 26,226 km² (13.88%) to 26,481 km² (14.01%) - an overall increase of about 255 km² (0.97%), though this trend was not statistically significant. Very dense forests recorded the strongest increase, followed by Open forests, whereas Moderately dense and Scrub forests shrank, likely due to conversion to agriculture and other land uses. During the same time period depth of the Ganga River and dissolved oxygen (DO) levels improved - all positive signals for improved aquatic habitat quality.

The water quality data examined through primary field sampling suggested that the Nitrate concentrations in river have declined over the assessment period, and the pH levels have remained stable throughout the monitoring period. However, concentrations of Total Dissolved Solids (TDS), salinity, and conductivity are trending upward across the a sampling sites. While these values remain within prescribed threshold limits, their continued rise signals the accumulation of ionic pollutants from diffuse sources - and requires close monitoring to prevent long-term habitat degradation. Concentrations of the legacy contaminants, such as organochlorine pesticides (OCPs), organophosphorus pesticides (OPPs), and heavy metals, declined between 2018 and 2024. Indicating partial recovery yet underscoring persistent anthropogenic contamination requiring continued management.

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The Gangetic dolphin (*Platanista gangetica*) - a flagship indicator species of river health- showed a significant increasing trend in Encounter Rates (ER) over the study period. Among the 414 BEUs surveyed, ER increased in 175 Basic Evaluation Units (BEUs), decreased in 108 BEUs, remained unchanged in 54 BEUs, and no sightings were recorded in 77 BEUs. The dolphin's range also expanded by approximately 245 km along the river, likely driven by improved water depth and reduced fishing pressure. This spatial variability reflects both the progress made in improving river conditions and the persistence of localised threats that require targeted intervention.

The Critically endangered Gharial (*Gavialis gangeticus*) showed an encouraging but statistically inconclusive upward trend ($p = 0.18$). ER increased from 0.013 to 0.021 sightings/km between 2018 and 2024. However, gharials remain restricted to a very small stretch of the river - 384 out of 414 BEUs recorded no sightings at all. The modest increase is thought to reflect ongoing government population augmentation programmes, but long-term monitoring is needed before firm conclusions can be drawn.

Turtles were found across most habitat zones, with the highest densities in the middle stretches, while the upper and extreme downstream stretches had few observations. The ER of hardshell turtles along the Ganga River increased between 2018 and 2020 while the softshell turtles showed a decline. The relative abundance of softshell turtles, experienced a decline between 2018 and 2020. The insignificant changes in ER and relative abundance may be attributed to detection biases or seasonal influences. Softshell turtles are also among the most illegally traded freshwater turtles in India. Long-term monitoring is needed to confirm consistent population changes in the Ganga River.

The breeding waterbirds such as, black-bellied tern (*Sterna acuticauda*), and the river lapwing (*Vanellus duvaucelii*) indicator of local river condition, showed declining trend, whereas the ER of river tern (*Sterna aurantia*) remained static. In case of Indian skimmer (*Rynchops albicollis*), increased ER and colony size along with the reduced occupancy, points out to decline in availability of the suitable habitats for nesting. All four species are sand bar specialists, and the consistent pressure from riverbed mining and cultivation on river islands and sand bars is flagged as the most likely driver of their stagnating or declining numbers, and highlights the need for stronger protection of nesting sites.

Among the noted stressors, ferry and mining intensities showed marked increases between the survey years, rising from 1.39 to 4.85 km^{-1} and from 0.12 to 0.70 km^{-1}, respectively. In contrast, fishing intensity declined from 2.94 to 1.91 km^{-1}, which was not statistically significant. Finer-scale analysis of threat across the surveyed BEUs revealed contrasting patterns. Ferry intensity in the majority of the BEUs recorded an increase (n=326, 78.74%), with only a small proportion showing decreases or no change, and very few with no presence (n=27, 6.52%). Fishing activity showed a predominantly decreasing trend across BEUs (n=244, 58.94%), with a smaller number of BEUs experiencing increases and a small fraction showing no change (n=23, 5.56%). In contrast, sand mining activity was absent in over half of the surveyed BEUs and showed a mixed pattern, with roughly equal proportions of BEUs showing increases, decreases, or no change.

The mixed trends in species encounter rates mirror the broader findings of the report. Water quantity (depth), forest cover enhancement, water quality improvements - rising dissolved oxygen, stable pH, declining nitrate, and sharp reductions in pesticide concentrations - have contributed to habitat recovery for aquatic megafauna like dolphins and gharials. Improved riverscape quality is enabling range expansion or rehabilitation of the historic home range of the indicator species. At the same time, escalating ferry traffic, increasing sand mining intensity and river bed agriculture continue to threaten sensitive species and degrade nesting habitats for waterbirds.

A mixed trend in riverscape quality parameters suggests that while afforestation efforts are yielding results, ecosystem functionality and connectivity remain suboptimal, limiting biodiversity benefits. Riverscape habitat improvements are translating into gains for some species, but riverbed and floodplain-dependent species remain at risk. Regulatory measures, including enforcement of pesticide application regulations, restricted-use classifications, and community awareness campaigns educating farmers on judicious use and alternatives, have shown ground-level impacts. But these efforts need to be upscaled to a larger spatial unit and landscape for measurable positive causal changes in the contaminants in water and sediment.

Infrastructure investments enhanced landscape-scale filtration through riparian buffer zones, constructed treatment wetlands in high-burden catchments, and vegetated filter strips intercepting surface runoff. Natural processes contribute significantly through rapid microbial biodegradation, hydrolysis under alkaline pH conditions characterizing the Ganga River, and photolytic degradation in sunlit surface waters.

The study suggests that immediate priorities must shift from capacity expansion to operational reliability, ensuring all STPs are functional, compliant, and digitally monitored in real time. Equally critical is the complete interception and treatment of high-burden drains in ecologically sensitive stretches. Strengthening these operational and governance mechanisms is essential to consolidate existing gains, address persistent pollution sources, and achieve sustained river health and ecological restoration across the Ganga Basin. The assessment findings point to a clear inflection point in the *Namami Gange* programme. The programme's emphasis on infrastructure development and institutional frameworks has produced measurable outcomes. The next phase should pivot from capacity expansion toward ensuring operational reliability and strengthening ecological management.

The most urgent priorities are:

- Forest and Riparian Management: There is a need to shift from area-based afforestation targets to quality-focused restoration. There is a need to establish and restore continuous riparian corridors, by planting native species.
- Site-specific conservation planning: The variability in outcomes across BEUs confirms that blanket interventions are insufficient. Conservation and management strategies must be tailored to local conditions, threat profiles, and species needs, and thus there is a need to shift from uniform interventions to BEU level planning.
- Continued long-term monitoring: To track the range expansion of indicator species such as Gangetic dolphins and to understand why encounter rates are declining in certain river stretches even though the population is showing an increasing trend, continuous monitoring is called for. Also, to assess the impact of conservation measures such as plantation activities and water quality improvement on species encounter rate and distribution across the riverscape, there is a need to institutionalize long term ecological monitoring framework.
- Sustainable fishery practices: The local communities are dependent on fishery activities. While this is recognised, the mortality caused by fishing nets is one of the main factors affecting the population growth of large macrofauna. Capacity development of the implementing agencies such as Forests and Fisher departments need to be augmented and made sensitive to these underlying issues.
- Stricter regulation of ferries and sand mining: Both activities are intensifying at rates that threaten sensitive aquatic species. Regulation must be consistent, enforced, and data-driven.
- Expanded habitat protection for sand bar-nesting birds: Unlike aquatic megafauna, the island nesting bird species are more sensitive to physical habitat disturbance, highlighting gaps in riverbed and floodplain management.
- Operational compliance of STPs: All treatment plants must be fully functional, compliant with discharge norms, and digitally monitored in real time. Non-functional or under-performing STPs represent the single largest risk to water quality gains.
- Drain interception in sensitive stretches: High-burden drains entering the river in ecologically sensitive areas must be fully intercepted and treated. Partial interception is insufficient.
- Scaling up pesticide regulation: Regulatory enforcement and community awareness on pesticide use have demonstrated ground-level impact. These must now be expanded from targeted areas to the wider river basin to achieve measurable reductions in agricultural contamination.
- Engaging local communities in river conservation: Involving local communities in the Ganga conservation by adopting mass conservation education and awareness programmes and sustainable livelihood development likely to enhance the conservation outcomes in a faster way.

Finally, it is suggested that the ecological monitoring framework must continue and be strengthened. The variability documented in this assessment - across both improvements and deterioration - underscores the value of longitudinal, reach-scale monitoring in guiding adaptive management. The Ganga's recovery is real, but continuous effort needs to be put in place to make the recovery sustainable.

1. INTRODUCTION

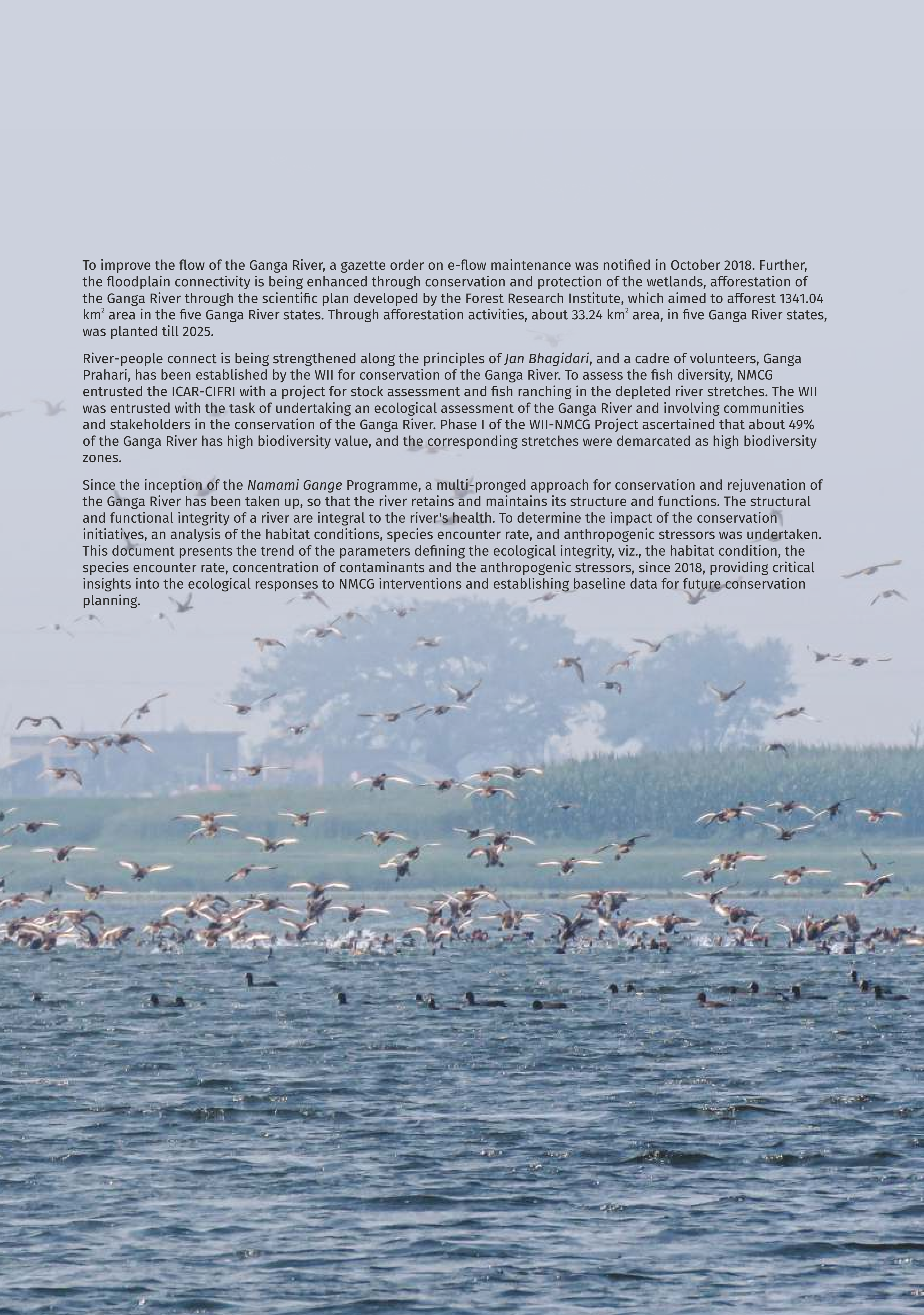
Recognizing the challenges faced by India's most iconic river, the Government of India has been working towards the ecological restoration of the Ganga River since the early 1980s, but the desired results were not achieved. Later, in 2009, a National Ganga River Basin Authority (NGRBA) was set up, through a Government of India notification dated 20th February 2009, with a shift towards an integrated basin-based approach for conservation of the Ganga River. Under NGRBA, the National Mission for Clean Ganga (NMCG) was established in August 2011, which has been implementing the *Namami Gange* Programme since 2014, a flagship programme of the Government of India. The NMCG has been working towards restoring the wholesomeness of the Ganga River by ensuring *Aviral* and *Nirmal* flow of the Ganga River and maintaining its geo-hydrological and ecological integrity. To achieve this, mulitsectoral and multi-agency interventions such as pollution abatement (*Aviral Ganga*), improving ecology and flow (*Nirmal Ganga*), strengthening river-people connect (*Jan Ganga*), facilitating scientific research, mapping, and evidence-based policy formulation (*Gyan Ganga*), connecting livelihood with river conservation (*Arth Ganga*) have been adopted by NMCG.

The *Namami Gange* Programme encompasses comprehensive interventions including sewage treatment infrastructure development, industrial effluent management, riverfront development, maintaining ecological flows, rural sanitation, afforestation, biodiversity conservation, and community participation. For pollution abatement, a total of 292 sewerage infrastructure projects with a treatment capacity of 6540.225 MLD have been undertaken in the Ganga River Basin (as on 1st April 2025). Of these, 157 STPs with a capacity of 3687.265 MLD are operational, while 102 STPs with a capacity of 2185.877 MLD are under progress, and 33 STPs are under tendering. Sustainable agriculture is being promoted in the 5 km corridor along the Ganga River, with the objective of reducing pollution from non-point sources.

To improve the flow of the Ganga River, a gazette order on e-flow maintenance was notified in October 2018. Further, the floodplain connectivity is being enhanced through conservation and protection of the wetlands, afforestation of the Ganga River through the scientific plan developed by the Forest Research Institute, which aimed to afforest 1341.04 km^2 area in the five Ganga River states. Through afforestation activities, about 33.24 km^2 area, in five Ganga River states, was planted till 2025.

River-people connect is being strengthened along the principles of *Jan Bhagidari*, and a cadre of volunteers, Ganga Prahari, has been established by the WII for conservation of the Ganga River. To assess the fish diversity, NMCG entrusted the ICAR-CIFRI with a project for stock assessment and fish ranching in the depleted river stretches. The WII was entrusted with the task of undertaking an ecological assessment of the Ganga River and involving communities and stakeholders in the conservation of the Ganga River. Phase I of the WII-NMCG Project ascertained that about 49% of the Ganga River has high biodiversity value, and the corresponding stretches were demarcated as high biodiversity zones.

Since the inception of the *Namami Gange* Programme, a multi-pronged approach for conservation and rejuvenation of the Ganga River has been taken up, so that the river retains and maintains its structure and functions. The structural and functional integrity of a river are integral to the river's health. To determine the impact of the conservation initiatives, an analysis of the habitat conditions, species encounter rate, and anthropogenic stressors was undertaken. This document presents the trend of the parameters defining the ecological integrity, viz., the habitat condition, the species encounter rate, concentration of contaminants and the anthropogenic stressors, since 2018, providing critical insights into the ecological responses to NMCG interventions and establishing baseline data for future conservation planning.



2. METHODOLOGY

In a riverine ecosystem, the riverscape character, habitat availability, and diversity determine the aquatic community structure. The landscape-level features, such as riparian forest cover, reflect riverbank stability, sediment regulation, and habitat complexity, while reach-scale indicators, such as river channel depth, are an indicator of habitat suitability, as they address the habitat availability and connectivity for riverine biota, especially umbrella species like the Gangetic dolphin. Other reach scale parameters, such as water quality indicators including Dissolved Oxygen (DO), acid-base balance defined by pH, characterize the physiochemical conditions and provide direct insights into microbial water quality, thereby informing the suitability of the chemical environment and potential human health implications. For the trend analysis, species abundance, defined by the encounter rate of Gangetic dolphin, gharial, and select breeding waterbirds, was taken as an indicator of the ecological integrity of the Ganga River along with the anthropogenic stressors that affect the integrity of the river ecosystem.

Primary information for the indicators was collected through riverine assessments conducted in 2018, 2020, and 2024, along the mainstem Ganga River (Figure 1a). Survey strategies included continuous boat surveys in the river and foot transects along the banks were adopted for data collection. A 5 Km segment along the length of the river and 1 Km buffer from the maximum flood line of both banks of the river was considered as the Basic Evaluation Unit (BEU) (Figure 1b).

Riverscape quality was assessed using both landscape and reach scale indicators, wherein forest cover trends were assessed at the district level, which were derived from FSI State of Forest Reports, while channel depth and water quality parameters were measured along the BEUs to characterize in-stream habitat conditions. The key aquatic species, such as the Gangetic dolphin and gharial, prefer deep pools and river channels. Thus, on the basis of the habitat requirement, the depth of the Ganga River was classified into three depth ranges, viz. <4 m, 4 to 7 m and > 7 m. Water quality parameters have scientifically established threshold values used for assessing ecosystem health and determining water suitability for aquatic life. Hence, water quality parameters, such as pH, Dissolved Oxygen (DO), Conductivity, Total Dissolved Solids (TDS), Nitrate, and Salinity, were taken up for assessing the habitat quality suitability for aquatic organisms. The pH should remain between 6.5 and 8.5, as values outside this range stress physiological systems, reduce biodiversity, and increase the mobility and bioavailability of toxic contaminants. Dissolved oxygen (DO) levels must stay above 5 mg/L to support aquatic life, with concentrations below 2 mg/L causing hypoxia that weakens or kills sensitive species. Conductivity in healthy freshwater systems ranges from 150 to 500 µS/cm, supporting good mixed fisheries, while elevated values indicate ionic pollution from industrial, agricultural, or sewage discharges. Total dissolved solids (TDS) affect cellular water equilibrium in aquatic organisms and can serve as toxicant transporters, with elevated levels particularly problematic in agricultural and industrial areas. Nitrate concentrations should remain below 1 mg/L naturally, though untreated wastewater can elevate levels to 30 mg/L; concentrations exceeding 10 mg/L cause eutrophication, hypoxia, and direct toxicity to aquatic animals. Salinity in freshwater ecosystems must stay below 0.5 ppt to support diverse aquatic life, with levels between 0.5-2 ppt inducing osmotic stress in sensitive taxa, values above 2 ppt altering community composition, and concentrations exceeding 5 ppt causing significant mortality in freshwater fish, especially during early life stages. These thresholds were used for assessing improvement in the habitat quality.

Nutrient enrichment through wastewater inflow (Sewage, industrial effluent) was measured and monitored in terms of concentration of pollutants, such as heavy metals (HM), and Organochlorine Pesticides (OCPs), Organophosphorus Pesticides (OPPs) and encounter rate of fishing, sand mining, and ferry intensity. Data on HM, OCPs, OPPs, were compiled from field observations along the study stretch of the Ganga River (Figure 1a). Site-wise and overall means were computed, and temporal trend were evaluated using a log-linear regression model ($\ln Y = \beta_0 + \beta_1 \text{Year}$) to estimate the annual percentage change. Sites were classified as increasing, decreasing, or stable based on slope sign and p-value (< 0.05).

Occurrence and distribution of key aquatic species, including the waterbirds, are influenced by the nature and configuration of the surrounding habitats, and thus these serve as bioindicators. Thus, six species, viz. Gangetic dolphin, gharial, and four species of waterbirds were taken as indicators of river health. Occurrence and encounter rate (ER) data for key indicator species, including gharial (*Gavialis gangeticus*), Gangetic dolphin (*Platanista gangetica*), and four waterbird species, were compiled from ecological assessments conducted in 2018, 2020, and 2024. Ecological assessment was done following standardized protocols, wherein sightings of indicator species and associated anthropogenic stressors were recorded within 414 BEUs. ER was calculated as the number of individuals sighted per kilometer of surveyed river stretch to enable comparison across spatial and temporal scales. The ER values were natural log (ln) transformed before statistical analysis.

Temporal trend for each parameter was evaluated by fitting a linear regression model with ln-transformed parameter as the response variable and survey year as the explanatory variable. Additionally, to understand the finer-scale temporal changes at the BEU level, site-wise and overall means were computed, and temporal trends were evaluated using a log-linear regression model ($\ln Y = \beta_0 + \beta_1 \text{Year}$) to estimate the annual percentage change. Sites were classified as increasing, decreasing, or stable based on slope sign and p-value (< 0.05).

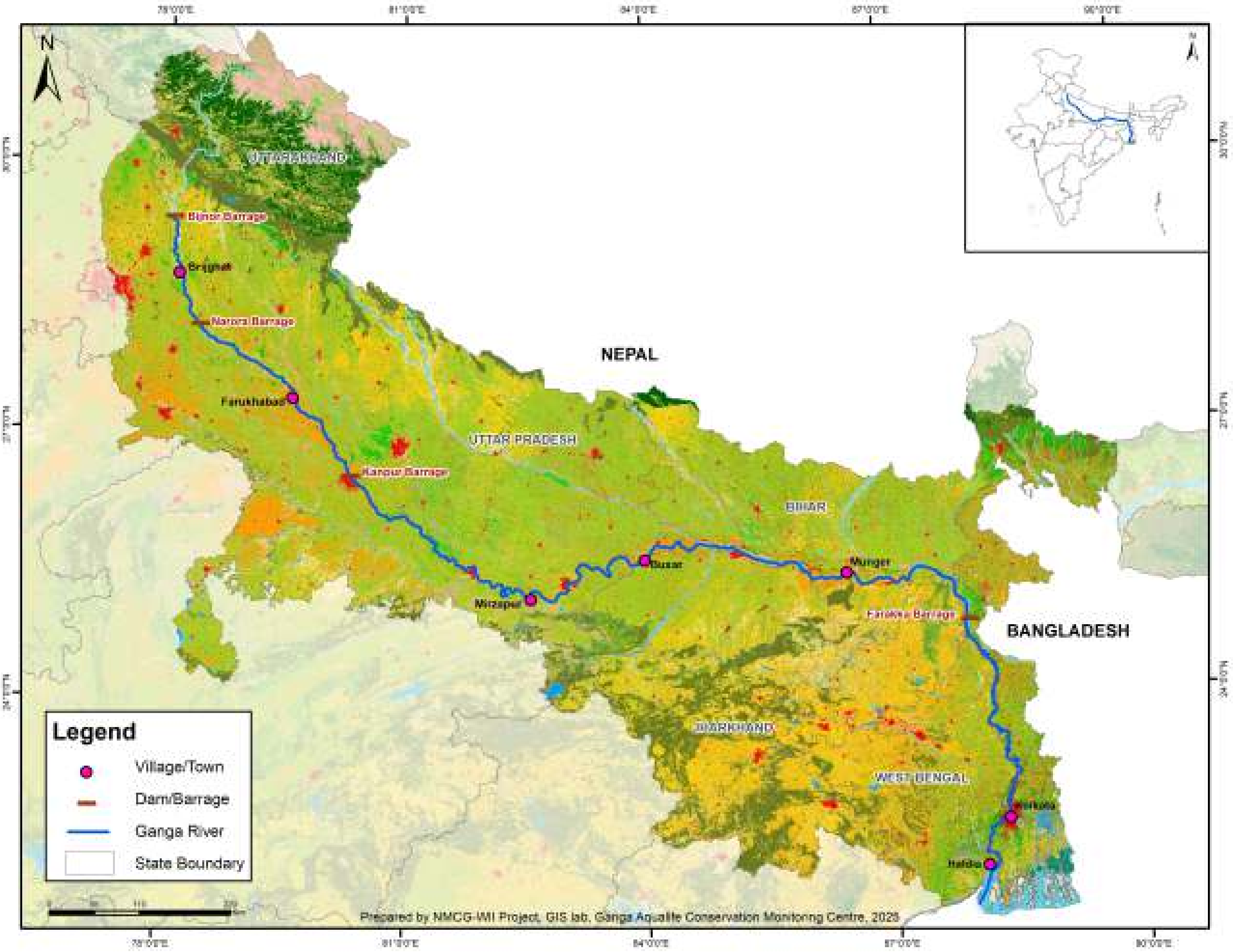


Figure 1a: Sampling locations along the Ganga River

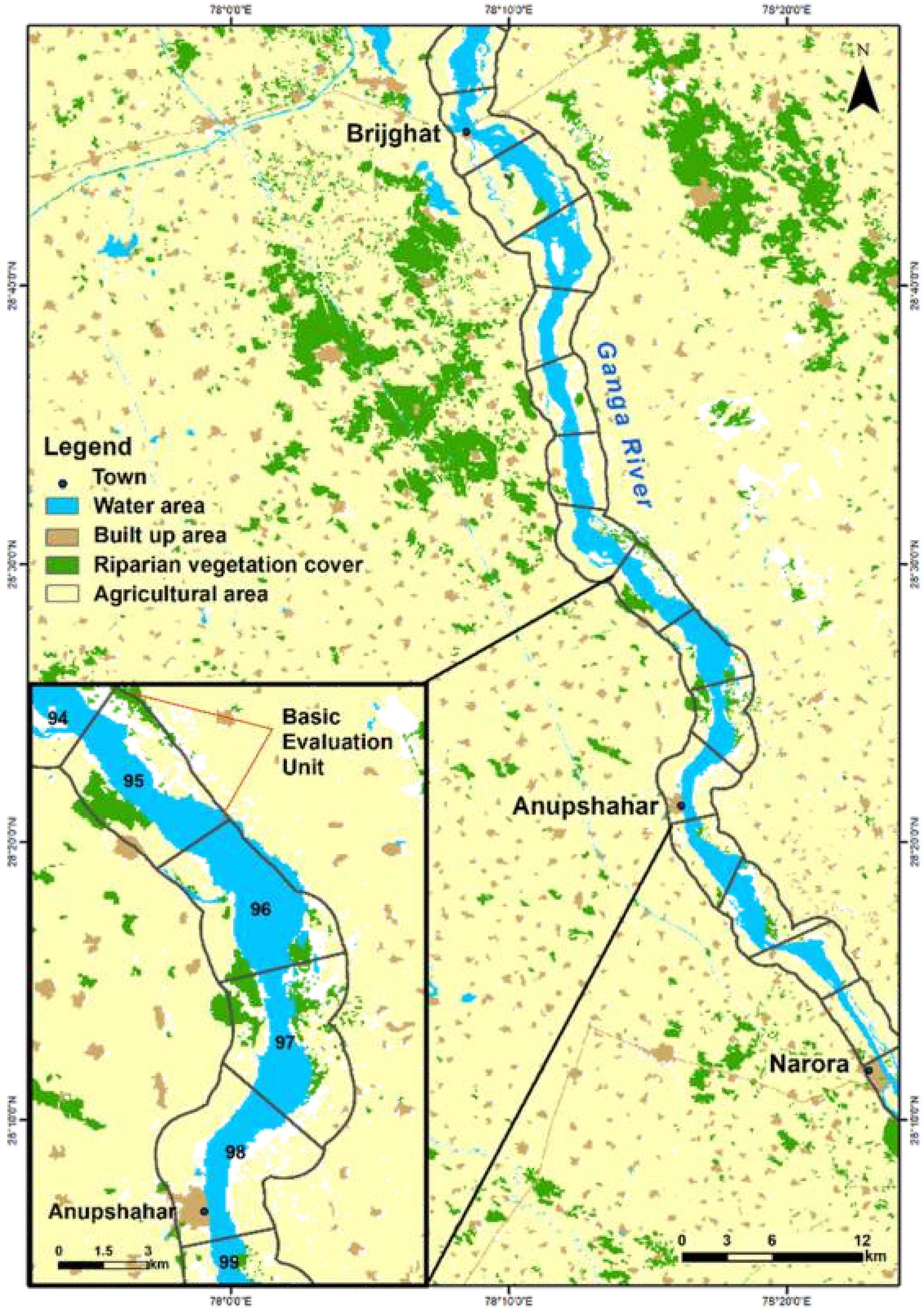


Figure: 1b: Basic Evaluation Unit (BEU) delineated along the Ganga River

Anthropogenic activities are one of the major drivers of ecosystem function degradation. Unsustainable use and extraction of the river's resources lead to loss of river function. Fishing, vessel movement, and sand mining are some of the anthropogenic stressors that negatively influence the river's health. The frequency of these three activities was noted down for each BEU and site-wise, and overall means were computed, and temporal trends were evaluated using a log-linear regression model ($\ln Y = \beta_0 + \beta_1$ Year) to estimate the annual percentage change. Sites were classified as increasing, decreasing, or stable based on slope sign and p-value (< 0.05).

3. TRENDS IN THE RIVERSCAPE QUALITY

3.1. Forest Cover

The riverscape quality influences the instream habitat condition in terms of river flow, sediment transport, nutrient dynamics, and pollutant influx, thus maintaining the biodiversity and ecosystem service value of the river. The Ganga riverscape comprising of 57 districts with an area of ~1,89,000 km^2, of which the forest cover consisted of 26226 km^2 (13.88 %), 26241.7 km^2 (13.88 %), 26146 km^2 (13.83 %) and 26481 km^2 (14.01%) in the year 2017, 2019, 2021 and 2023 respectively (Figure 2a) (FSI, 2017-2023). The analysis of the forest cover data suggests that the cover in the riverscape increased by 254.99 km^2 (0.97%) during the said period, with a rate of increase of 0.14 % annum^{-1} (Figure 2a). The overall rate of increase was prominent in the Very Dense forest (213.77 km^2) (0.74 % annum^{-1}), followed by Open Forest (289.63 km^2) (1.77% annum^{-1}), whereas the Moderately Dense Forest and Scrub forest declined at a rate of 0.30% annum^{-1} and 0.25% annum^{-1}, respectively (Figure 2b). All five states showed an increase in forest cover. The per annum increase was highest in the state of Bihar (0.40% annum^{-1}), followed by Uttar Pradesh (0.28% annum^{-1}), Jharkhand (0.21% annum^{-1}), West Bengal (0.14% annum^{-1}), and Uttarakhand (0.08% annum^{-1}) (Figure 2c).

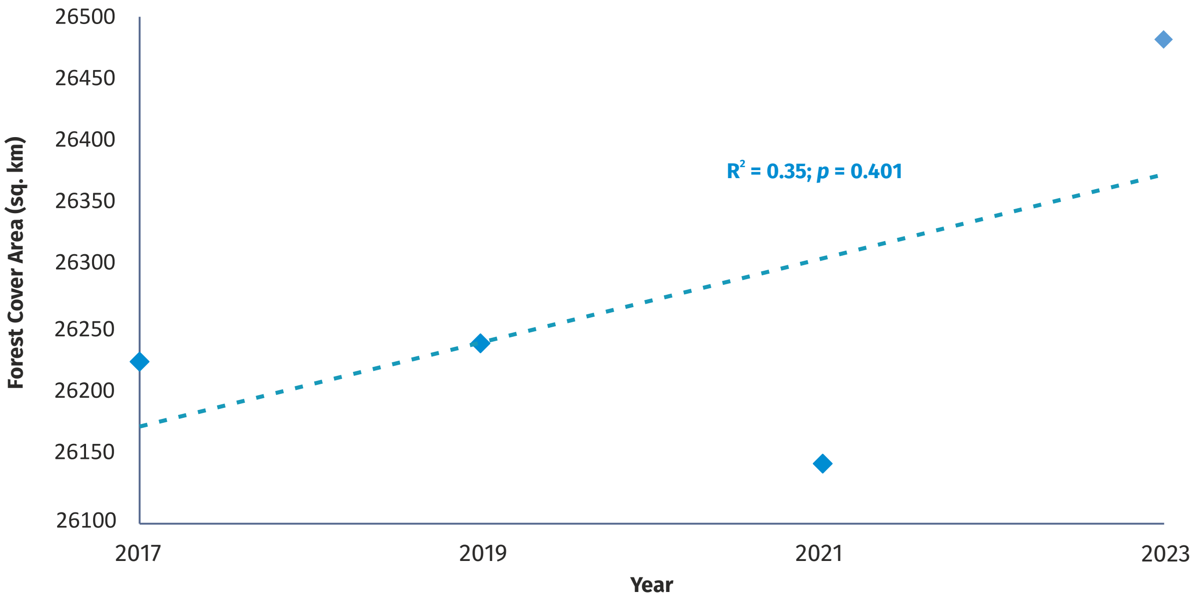


Figure 2a: Overall forest cover in Ganga River districts (Source: FSI, 2017, 2019, 2021, 2023)

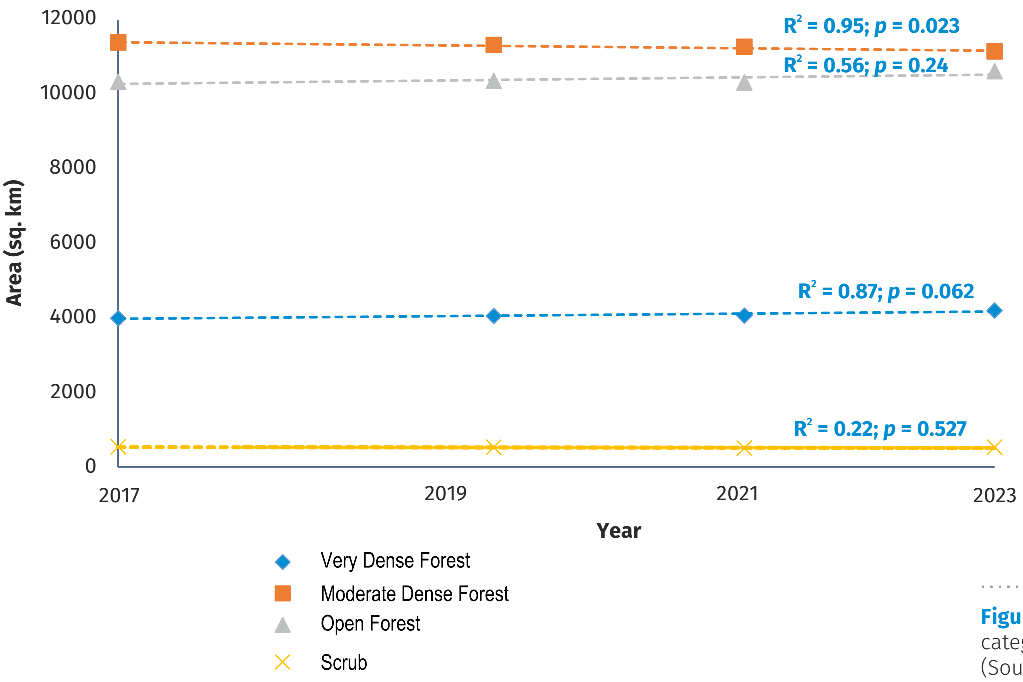


Figure 2b: Change in forest cover categories in Ganga River districts (Source: FSI, 2017, 2019, 2021, 2023)

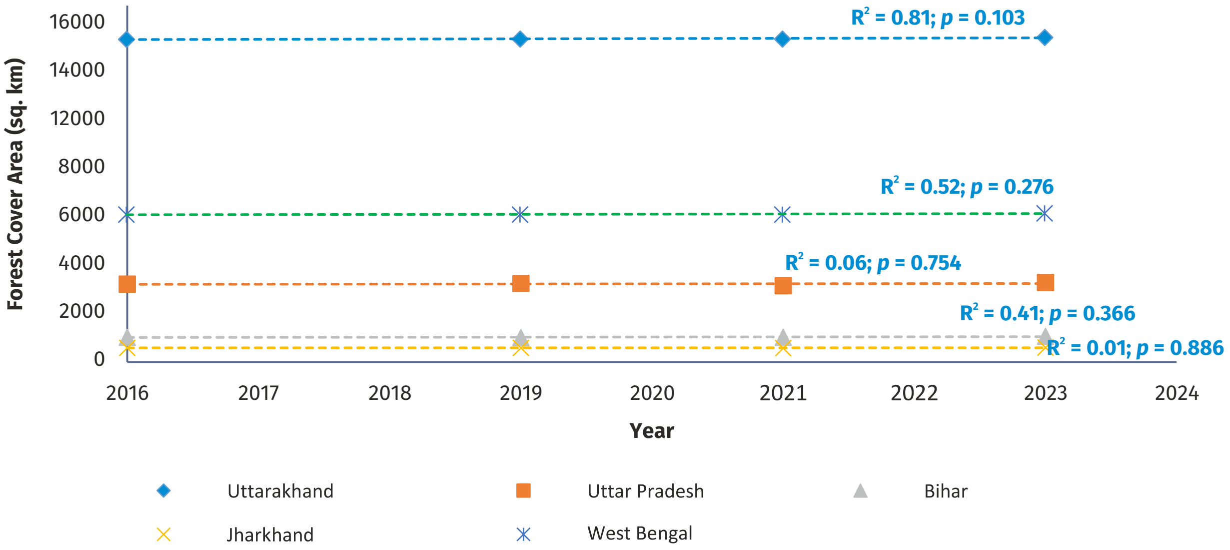


Figure 2c: State wise forest cover in Ganga River districts (Source: FSI, 2017, 2019, 2021, 2023)

3.2. River Depth

Assessment of the depth profile of the Ganga River, between 2018 and 2024, revealed that there has been a gradual decline in shallow stretches (< 4 m) and a relative increase in deeper stretches, particularly the 4 to 7 m category (Figure 3a). The percentage stretches in the 4 - 7 m category increased from 27% in 2018 to 34% in 2024 (Figure 3a). Similarly, the stretches with depth of more than 7 m increased between 2018 and 2024 (Figure 3a). Overall, the length of the Ganga River in the higher depth category saw an increasing trend, but it was statistically insignificant (Figure 3b).

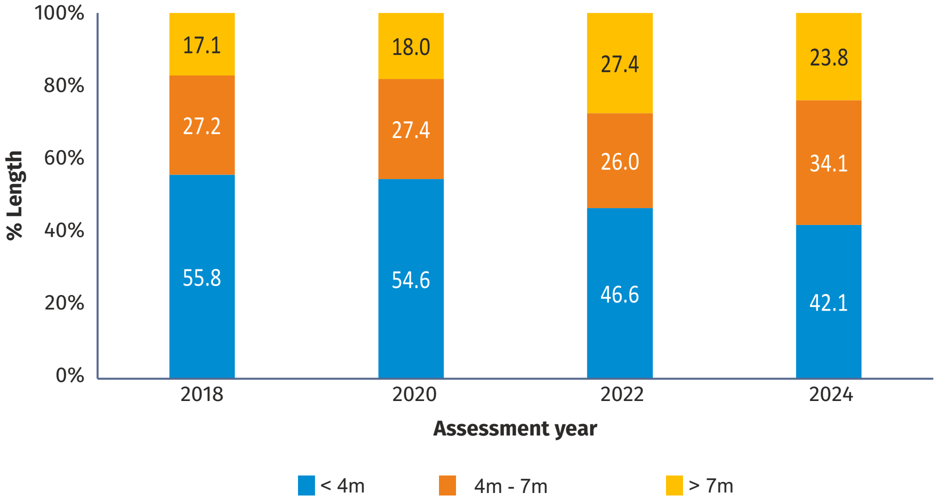


Figure 3a: Percentage distribution of the Ganga River under three depth categories across the sampling years

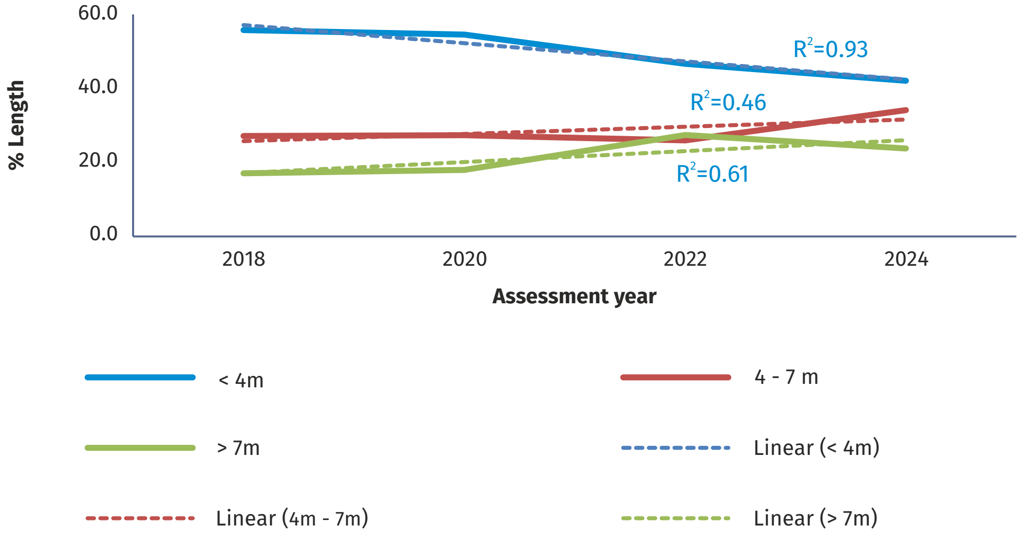
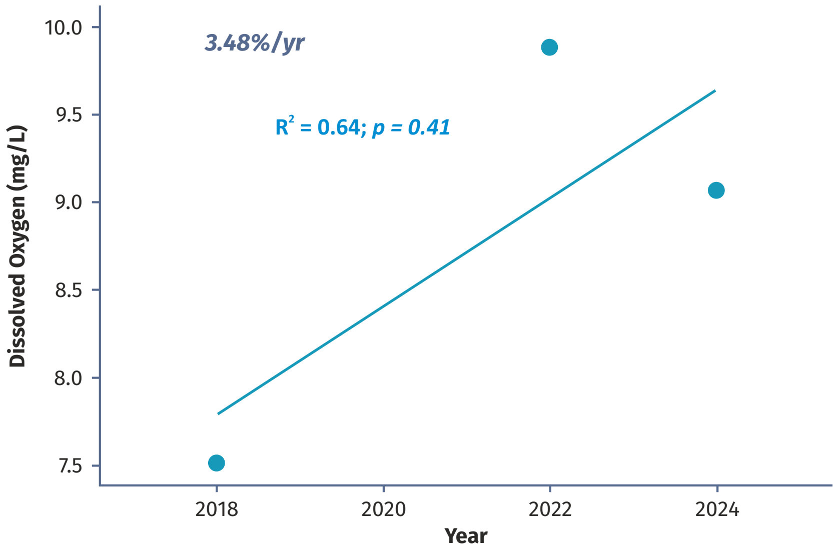


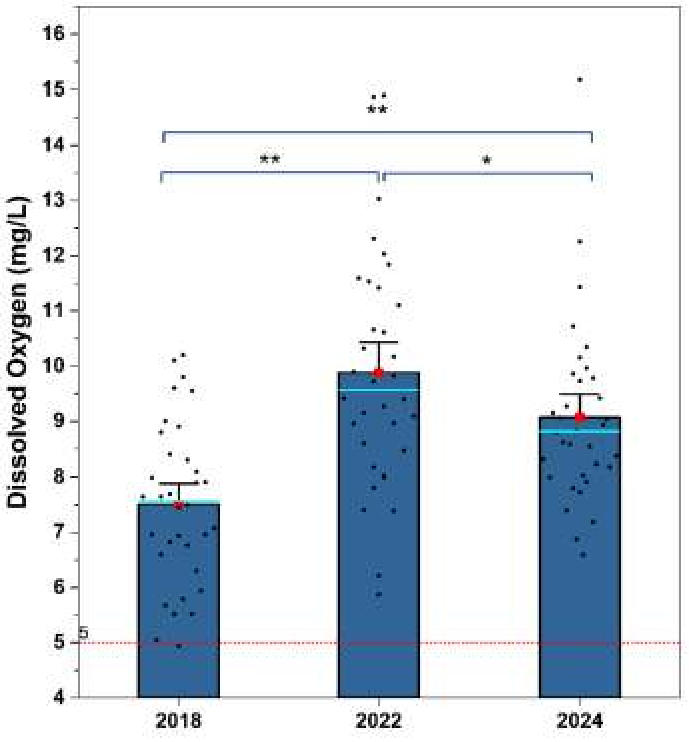
Figure 3b: Temporal trends in river depth categories from 2018 to 2024

3.3. Water Quality

Dissolved Oxygen (DO) exhibited an annual increase (+3.48% yr-¹); however, the trend lacked statistical significance (p = 0.41) (Figure 4a). Nevertheless, DO concentrations exhibited full compliance throughout the sampling years, maintaining concentrations ≥ 5 mg/ L (Figure 4b) at 97% of the locations. DO improved at 10 sites, and deteriorated at 7 sites, while DO in 5 sites remained outside the threshold between the assessment years (no improvement) (Figure 4c).

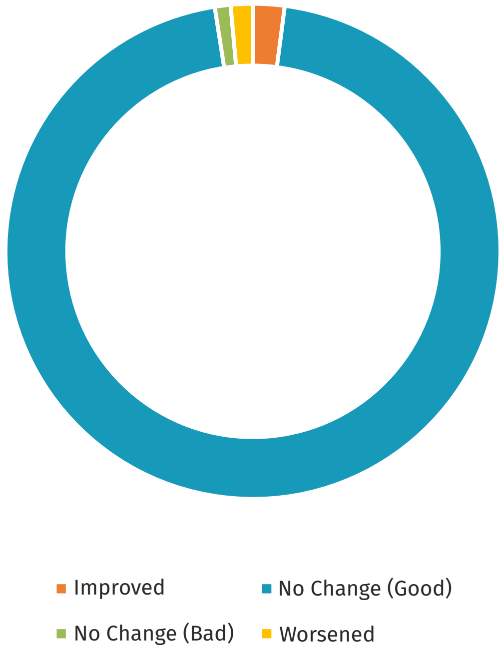


(4a)



Solid line with asterisks indicates statistically significant change, with $p < 0.05$ (*) and $p < 0.01$ (**)

(4b)

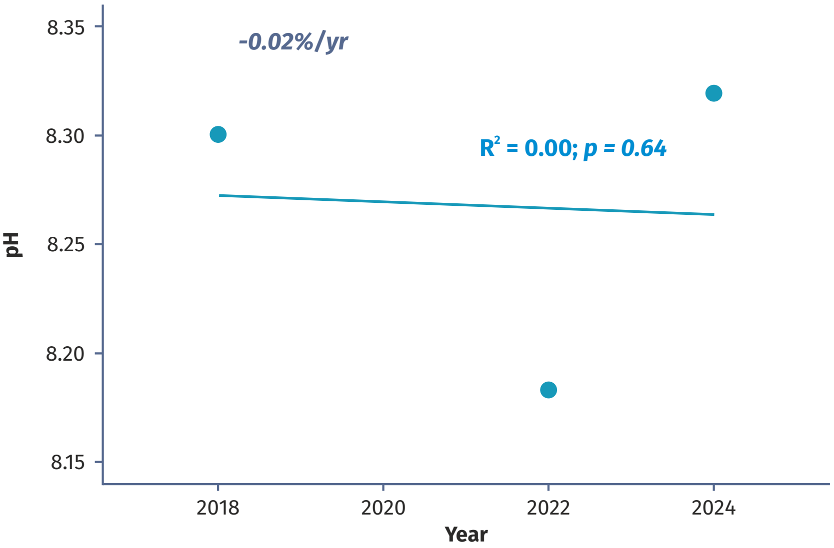


(4c)

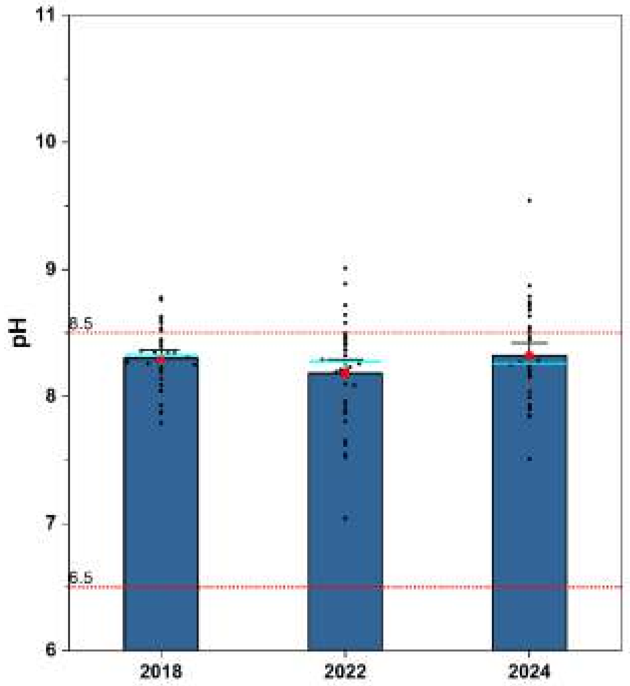
(4d)

Figure 4. *Spatiotemporal assessment of Dissolved Oxygen pollution dynamics in the Ganga River* **(a)** log-linear regression indicating a increasing trend (+3.48% yr-¹, p > 0.05), **(b)** Box plot showing the distribution of Dissolved Oxygen concentrations across sampling years, Red dotted line represents the threshold for aquatic life (≥5 mg/L) **(c)** pie chart depicting site-wise directional changes (%) in Dissolved Oxygen, between 2018 and 2024 phases, and **(d)** Spatial distribution of Dissolved Oxygen trends along the Ganga River.

pH remained largely stable with a negligible and insignificant decline of -0.02% yr-¹ (p = 0.64) (Figure 5a). Overall pH compliance remained within permissible limits (Figure 5b) for 51% of the BEUs. For 33% of BEUs, the pH remained beyond the threshold limit, and for about 15% BEUs, the pH level worsened (Figures 5c and 5d). A large share of BEUs beyond the permissible limit indicates persistent problems despite interventions

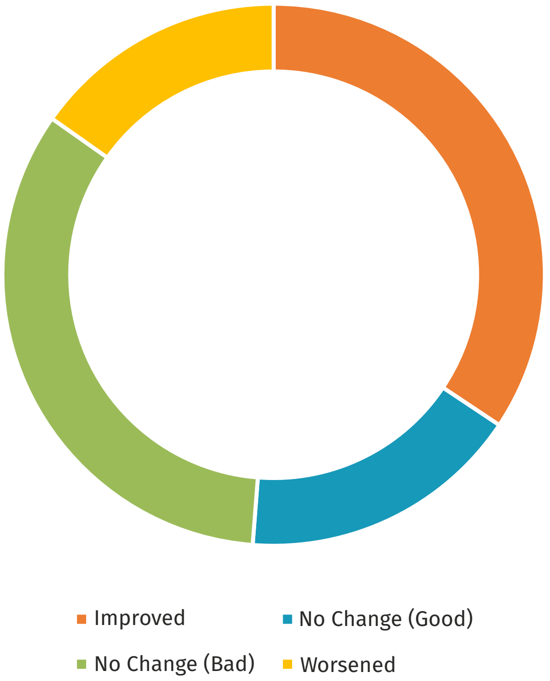


(5a)



Solid line with asterisks indicates statistically significant change, with $p < 0.05$ (*) and $p < 0.01$ (**)

(5b)

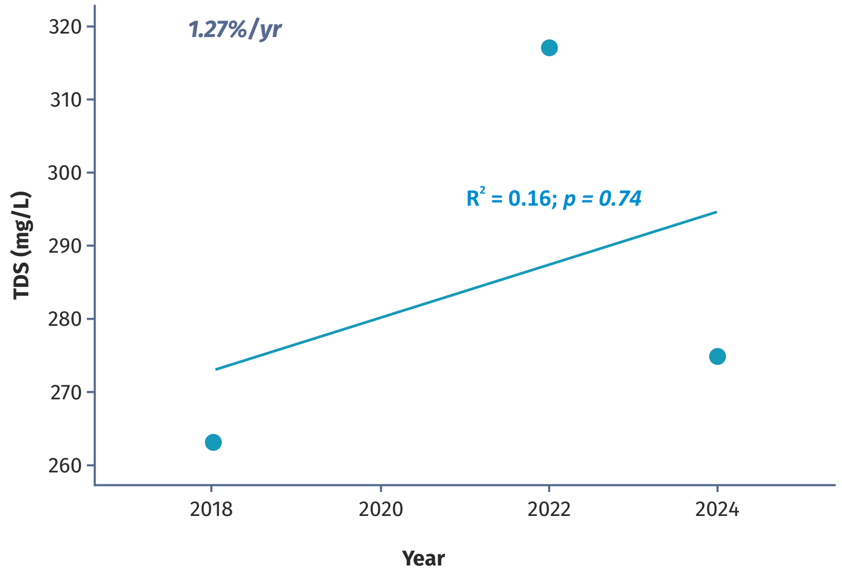


(5c)

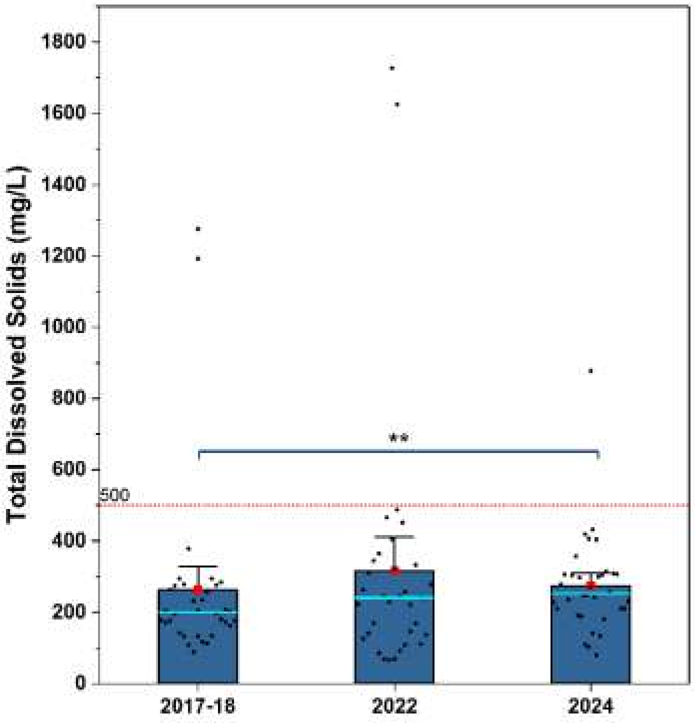
Figure 5. *Spatiotemporal assessment of pH pollution dynamics in the Ganga River* (a) log-linear regression indicating a declining trend (-0.02% yr^{-1}, $p > 0.05$), (b) Box plot showing the distribution of pH concentrations across sampling years, Red dotted line represents the threshold for aquatic life (6.5-8.5) (c) pie chart depicting site-wise directional changes (%) in pH, between 2018 and 2024 phases and (d) Spatial depiction of pH trends along the Ganga River.

(5d)

The concentration of TDS indicates an increasing trend (+1.27% yr^{-1}; Figure 6a), which was statistically insignificant ($p = 0.74$), indicating the absence of detectable temporal change. The TDS across all the years was within the compliance limit for 441 BEUs (90%) (Figures 6b, 6c, and 6d). TDS improved across 13 BEUs, while deteriorating only in 3 BEUs (Figure 6c). About 6% of the BEUs remained non-compliant consistently between the sampling years, mostly in West Bengal due to estuarine influence.

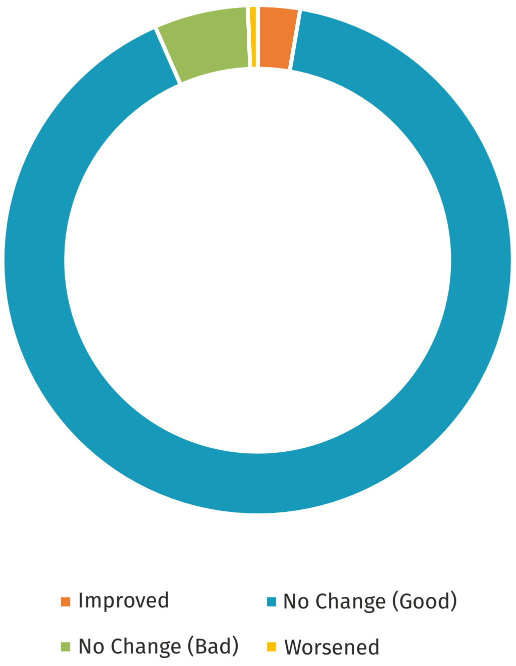


(6a)



Solid line with asterisks indicates statistically significant change, with $p < 0.05$ (*) and $p < 0.01$ (**)

(6b)

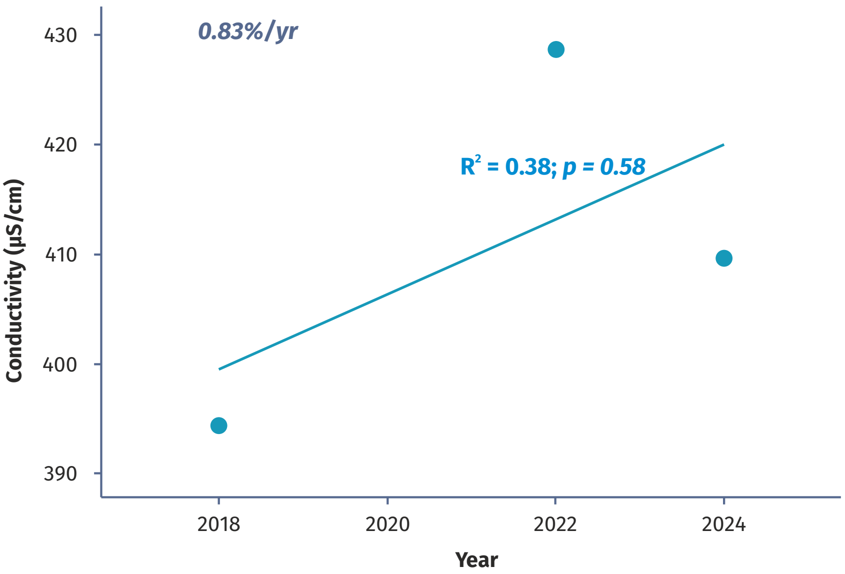


(6c)

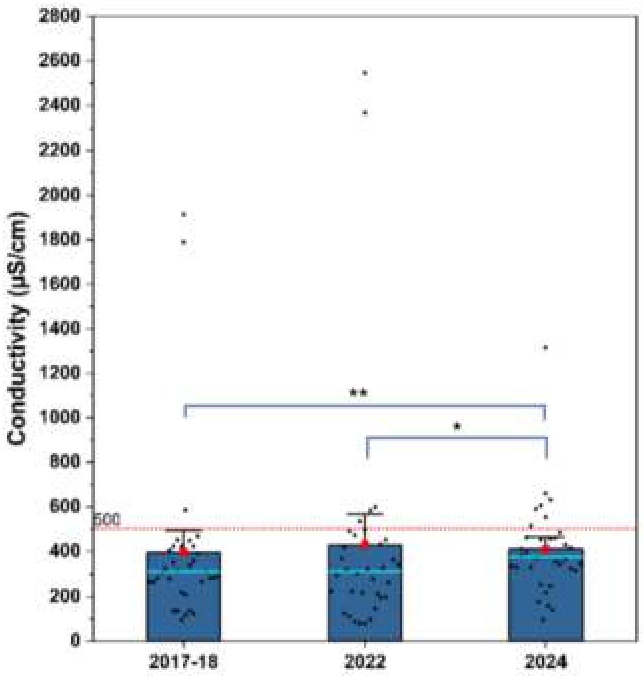
(6d)

Figure 6. *Spatiotemporal assessment of Total Dissolved Solids pollution dynamics in the Ganga River* **(a)** Log-linear regression indicating a increasing trend (+1.27% yr-¹, p > 0.05), **(b)** Box plot showing the distribution of Total Dissolved Solids concentrations across sampling years, Red dotted line represents the threshold for aquatic life (≤500 mg/L) **(c)** Pie chart depicting site-wise directional changes (%) in TDS, between 2018 and 2024 phases, and **(d)** Spatial depiction of TDS trends along the Ganga River.

The conductivity concentrations saw an insignificant (p = 0.58) increasing trend (+0.83% yr-¹; Figure 7a). It remained within the compliance limit for about 58% of the BEUs throughout the sampling years and remained non-compliant for about 33% of the BEUs (Figure 7b). Between the sampling years, the conductivity improved at 27 BEUs, while it deteriorated for 19 sites (Figure 7c). Conductivity non-compliance was primarily observed in midstream stretches (Kanpur-Varanasi), and the tidal influence zone in West Bengal, influenced by urban and agricultural return flows (Figure 7d).



(7a)



Solid line with asterisks indicates statistically significant change, with p < 0.05 (*) and p < 0.01 (**)

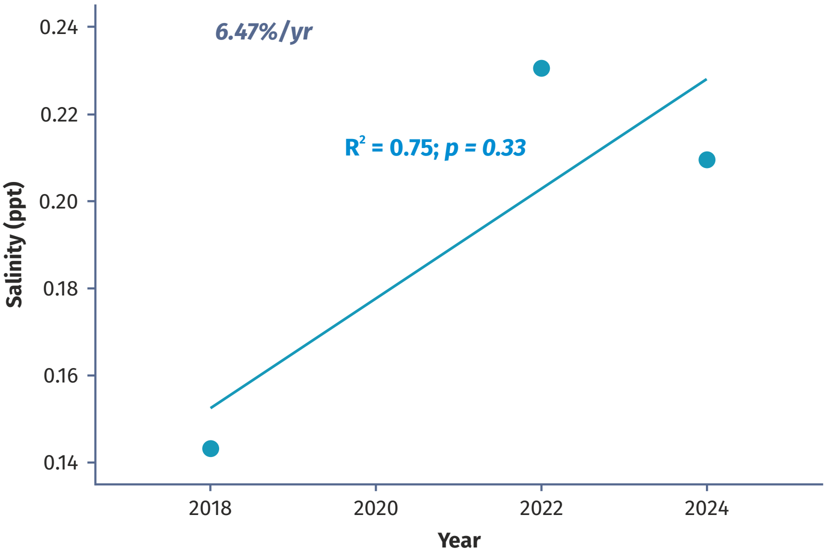
(7b)

(7c)

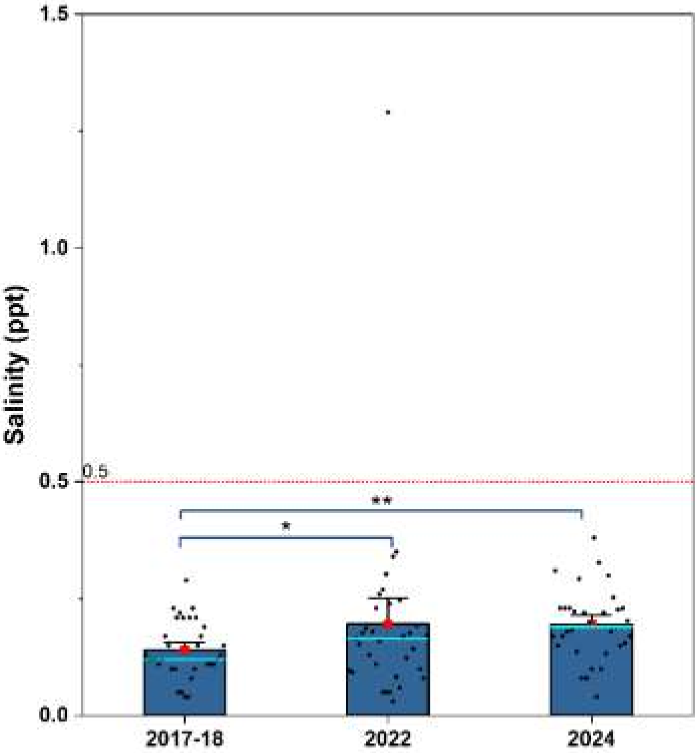
Figure 7. Spatiotemporal assessment of Conductivity pollution dynamics and associated ecological risk transitions in the Ganga River system. **(a)** Log-linear regression indicating an increasing trend (+0.83% yr^{-1}, $p > 0.05$), **(b)** Box plot showing the distribution of Conductivity concentrations across sampling years, Red dotted line represents the threshold for aquatic life (≤ 500 µS/cm) **(c)** Pie chart depicting site-wise directional changes (%) in Conductivity, between 2018 and 2024 phases and **(d)** Spatial depiction of conductivity trends along the Ganga River.

(7d)

The salinity concentrations saw an insignificant (p = 0.33) increasing trend (6.47% yr-¹; Figure 8a). Salinity remained fully compliant (100%), consistently below the freshwater threshold (<0.5 ppt) at all sites (Figures 8b, 8c and 8d).



(8a)



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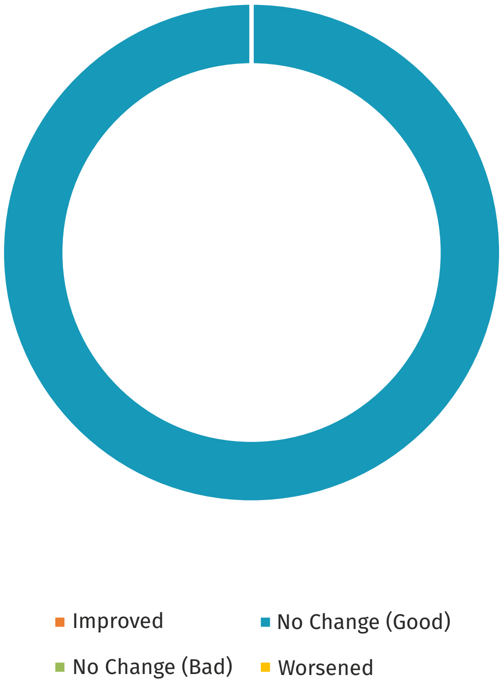
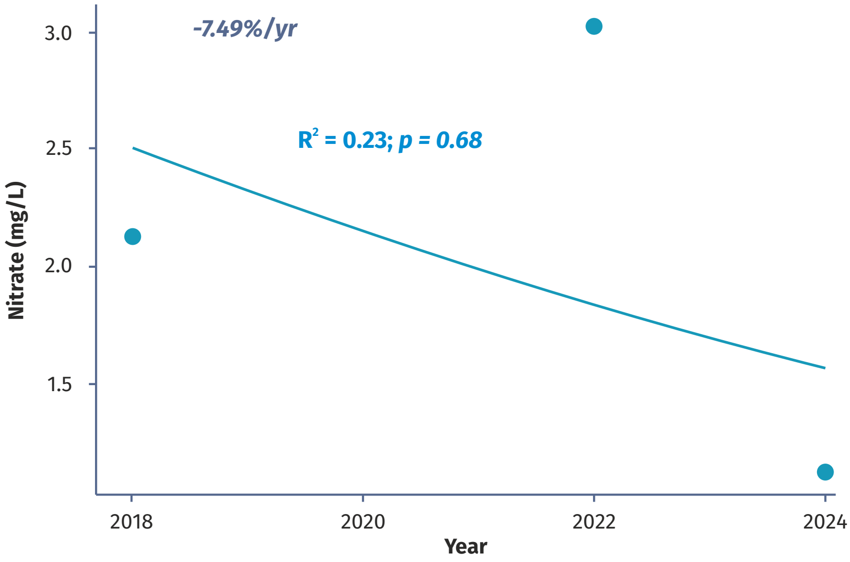


(8c)

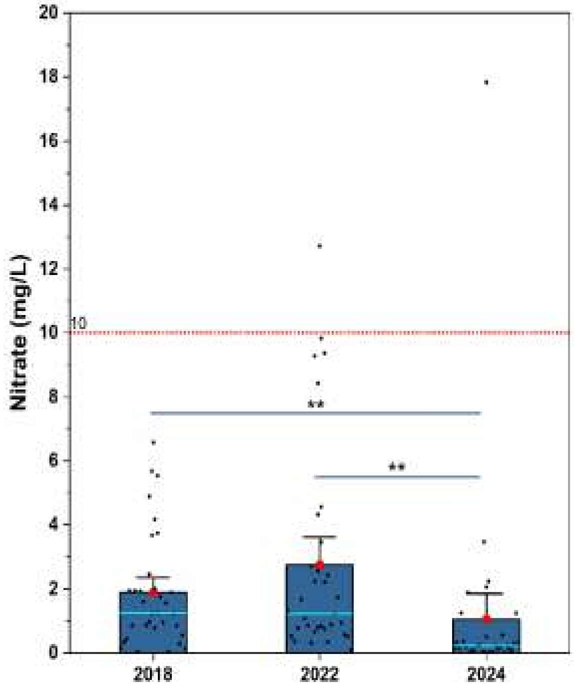
(8d)

Figure 8. *Spatiotemporal assessment of Salinity pollution dynamics in the Ganga River* **(a)** Log-linear regression indicating an increasing trend (+6.47% yr^{-1}, $p > 0.05$), **(b)** Box plot showing the distribution of Salinity concentrations across sampling years, Red dotted line represents the threshold for aquatic life (<0.5 ppt) **(c)** Pie chart depicting site-wise directional changes (%) in salinity, between 2018 and 2024 phases, and **(d)** Spatial depiction of salinity trends along the Ganga River.

Nitrate concentrations exhibited a notable, but insignificant ($p = 0.68$) decreasing trend of -7.49% yr^{-1} (Figure 9a), suggesting reduced nutrient loading. Nitrate levels remained within the threshold value for aquatic life (<10 mg/L) (Figure 9b). Nitrate levels exceeded the compliance limit (<10 mg/L) at Harshil in 2024. The number of sites where nitrate level remained within the threshold for 98% of the BEUs, while for about 2% of the sites (Harshil), the nitrate exceeded the threshold value.

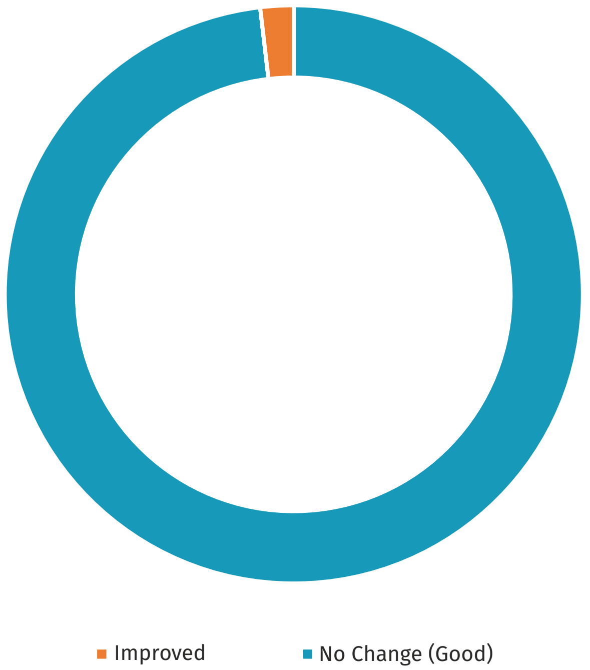


(9a)



Solid line with asterisks indicates statistically significant change, with $p < 0.05$ (*) and $p < 0.01$ (**)

(9b)



(9c)

Figure 9. *Spatiotemporal assessment of Nitrate pollution dynamics in the Ganga River* **(a)** Log-linear regression indicating a declining trend (-7.49% yr⁻¹, p > 0.05), **(b)** Box plot showing the distribution of Nitrate concentrations across sampling years, Red dotted line represents the threshold for aquatic life (< 10 mg/L) **(c)** Pie chart depicting site-wise directional changes (%) in Nitrate levels, between 2018 and 2024 phases, and **(d)** Spatial depiction of nitrate trends along the Ganga River

(9d)

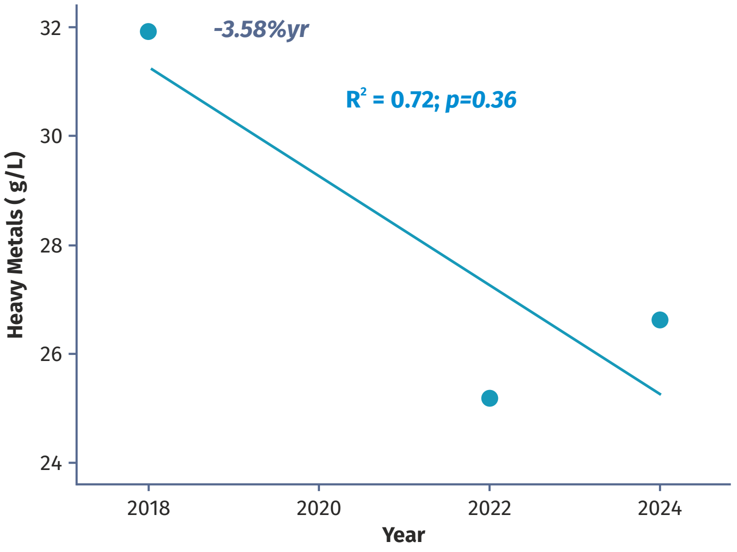
4. TRENDS IN OTHER CONTAMINANTS

There has been a declining trend in the heavy metal concentrations between the assessment years, with an average annual decrease of 3.58% per year, Heavy metal concentration improved in about 35% BEUs. By the end of the assessment year, 65% of the BEUs had heavy metal concentrations within the threshold limit. In about 14% BEUs heavy metal concentration was beyond the threshold (Figures 10a to 10e). Consistent and significant improvements observed in Uttar Pradesh indicate the effectiveness of strengthened enforcement of effluent discharge standards, mandatory online monitoring systems for polluting industries, diversion of tannery effluent to upgraded Common Effluent Treatment Plants, tapping of drains, closure/relocation of non-compliant tanneries/metal processing units, multi-stakeholder engagement, and awareness campaigns. However, the stretches of the Ganga River near Kanpur, Prayagraj, Varanasi, downstream of Patna, Bhagalpur, Sahibganj, and West Bengal need attention (Figure 10e).

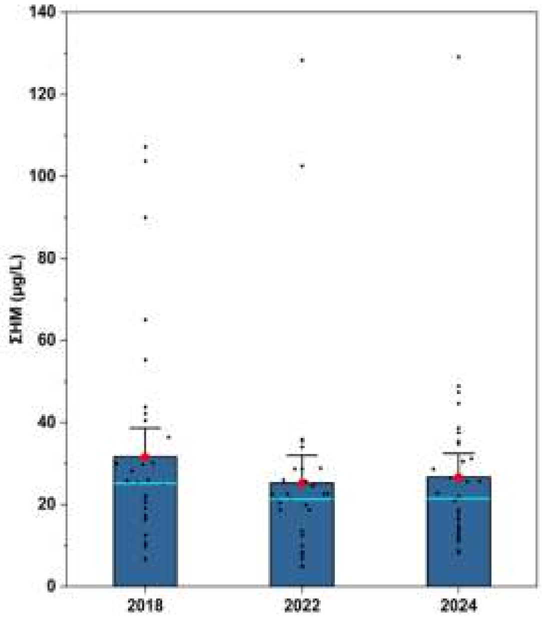
Between Phase I (2018) and Phase II (2024) of the study, high-ecological risk sites decreased by 20%, moderate-risk sites increased by 38% (21% to 59%), and low-risk sites decreased by 3% (26% to 3%) (Figure 10d), demonstrating a significant shift toward moderate ecological risk across the study area, indicating partial recovery yet underscoring persistent anthropogenic contamination requiring continued management. The decrease in high-risk sites suggests successful risk mitigation or environmental improvement interventions. However, the simultaneous decline in low-risk sites and concentration of 59% sites in the moderate-risk category indicates the ecosystem remains vulnerable and requires continued monitoring and management to prevent deterioration back to high-risk status.

Banned legacy organochlorine pesticides (OCP), including DDT, endosulfan, and lindane, which are prohibited under the Stockholm Convention, declined during the monitoring period (2018-2024) (Figure 11a), with an estimated - 52.35% annual reduction rate (Figure 11b), indicating substantial improvement in chemical water quality. OCP concentration improved in about 35% of the BEUs (Figure 11c), which was mainly upstream and downstream of Kannauj, downstream of Kanpur, till Mirzapur, and some stretches near Patna and Bhagalpur. Ecological risk with OCPs exhibited a substantial decline, with high-risk site prevalence decreasing -34% percentage points from 2018 to 2024 (Figure 11d). This substantial decrease reflects the natural depletion of legacy residues accumulated during pre-ban agricultural use. This depletion is mainly driven by environmental processes such as sunlight breakdown, evaporation, and slow decomposition by soil and water microorganisms. The cessation of new inputs following regulatory bans eliminated fresh contamination sources, leaving only the gradual depletion of historical accumulation. Natural attenuation occurs through downstream dilution as contaminated water mixes with cleaner tributary flows, while sediment burial progressively isolates legacy contamination under cleaner deposits, reducing bioavailability. Biogeochemical transformation converts parent compounds to less toxic metabolites, though these may persist for extended periods.

Between 2018 and 2024, a sharp decline, with an annual reduction rate of 52.33% was noted in organophosphorus pesticides (OPP) concentrations (Figures 12a & 12b), indicating substantial improvement in water quality. The boxplot shows significantly lower OPP levels in 2022 and 2024 compared to 2018 ($p < 0.01$), 94% of sites exhibited a decreasing trend (Figure 12a). Ecological risk attributed to OPPs markedly diminished, by -89% percentage points from 2018 to 2024 (Figure 12d). OPP concentration improved in about 59% of the BEUs (Figures 12c and 12e).



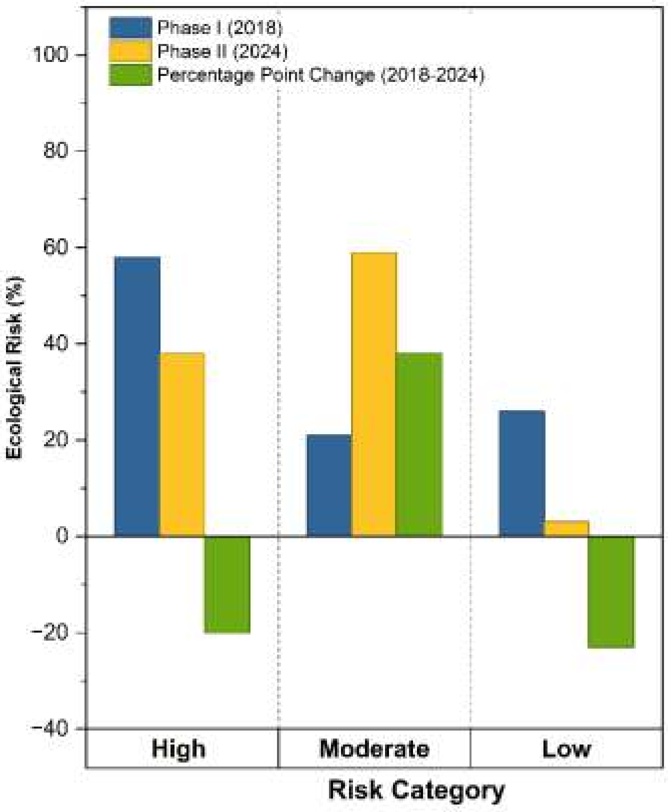
(10a)



Solid line with asterisks indicates statistically significant change, with $p < 0.05$ (*) and $p < 0.01$ (**)

(10b)

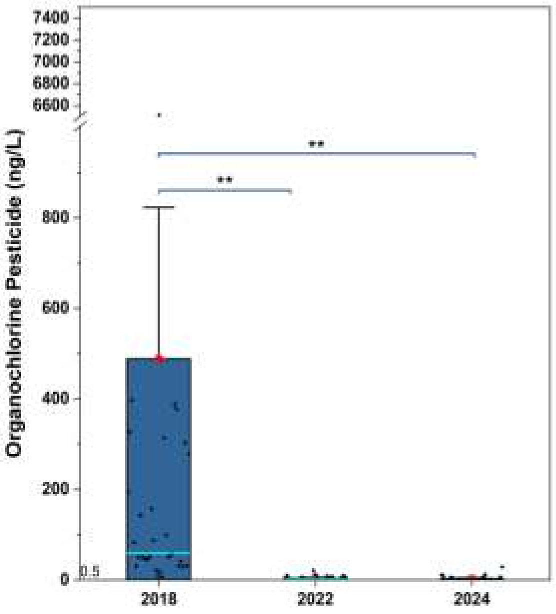
(10c)



(10d)

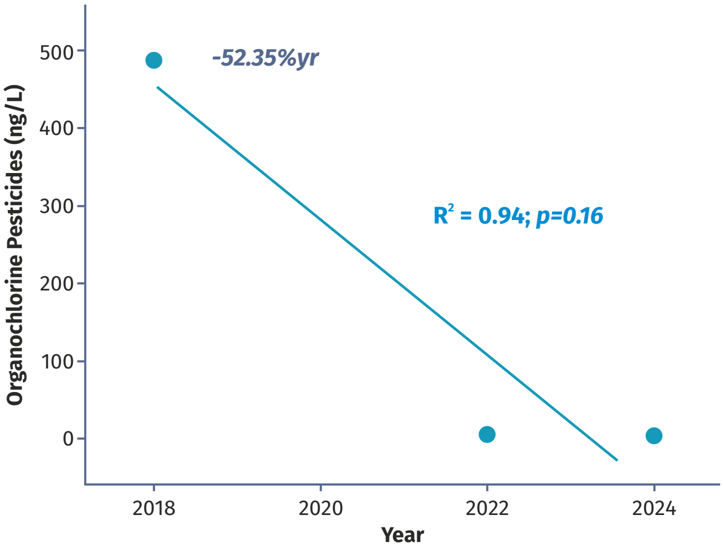
(10e)

Figure 10: *Spatiotemporal assessment of heavy metal pollution dynamics and associated ecological risk transitions in the Ganga River* (a) Box plot showing the distribution of heavy metal concentrations across sampling years, (b) Log-linear regression indicating a significant declining trend (-3.58% yr^{-1}, $p > 0.05$), (c) Pie chart depicting site-wise directional changes (%) in concentration, (d) Comparative analysis of ecological risk categories between 2018 and 2024 phases, and (e) Spatial depiction of trend in heavy metal concentration along the Ganga River.



Solid line with asterisks indicates statistically significant change, with $p < 0.05$ (*) and $p < 0.01$ (**)

(11a)



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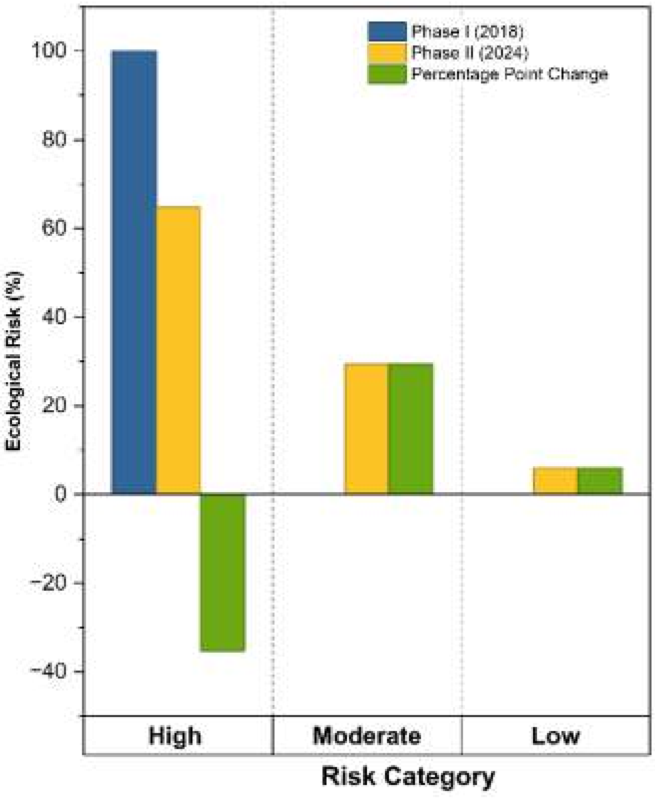
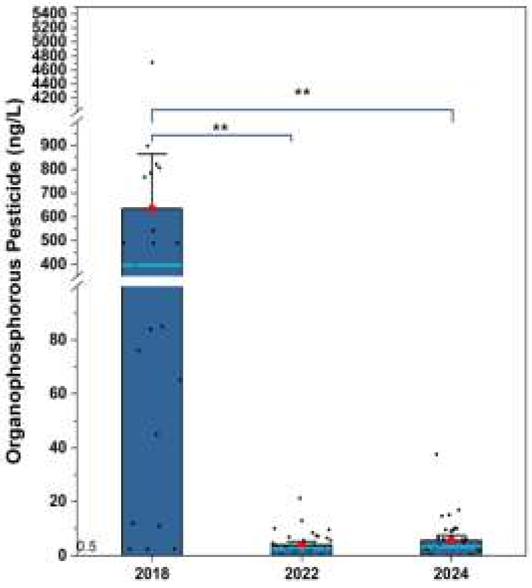


(11d)

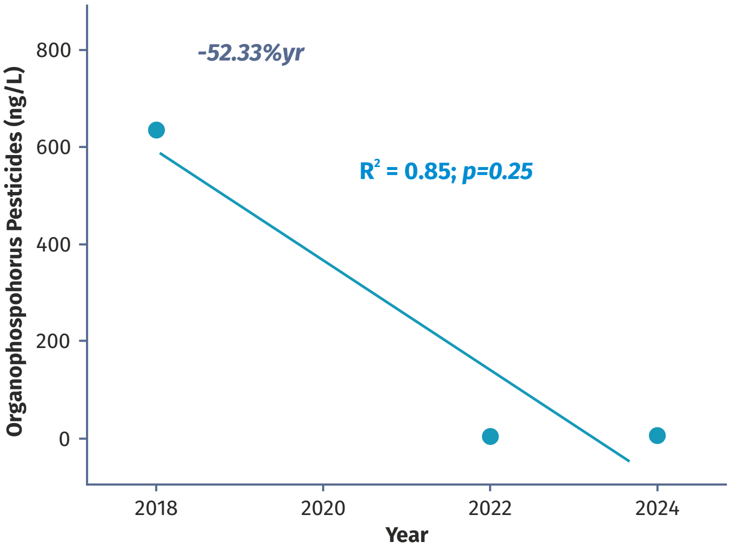
(11e)

Figure 11. *Spatiotemporal assessment of Organochlorine pesticides pollution dynamics and associated ecological risk transitions in the Ganga River* **(a)** Box plot showing the distribution of Organochlorine pesticides' concentrations across sampling years, **(b)** Log-linear regression indicating a declining trend (-52.35% yr⁻¹, p > 0.05), **(c)** Pie chart depicting site-wise directional changes (%) in concentration, **(d)** Comparative analysis of ecological risk categories between 2018 and 2024 phases, and **(e)** Spatial depiction of trend in Organochlorine pesticides' concentration along the Ganga River

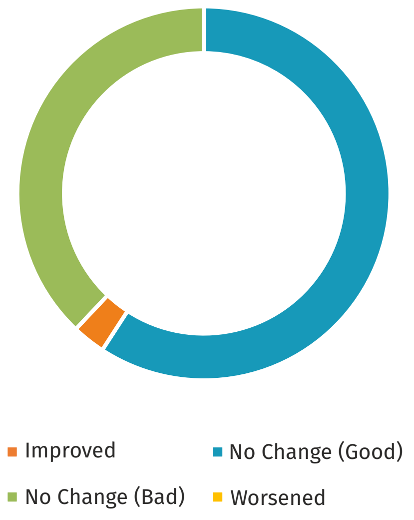


Solid line with asterisks indicates statistically significant change, with $p < 0.05$ (*) and $p < 0.01$ (**)

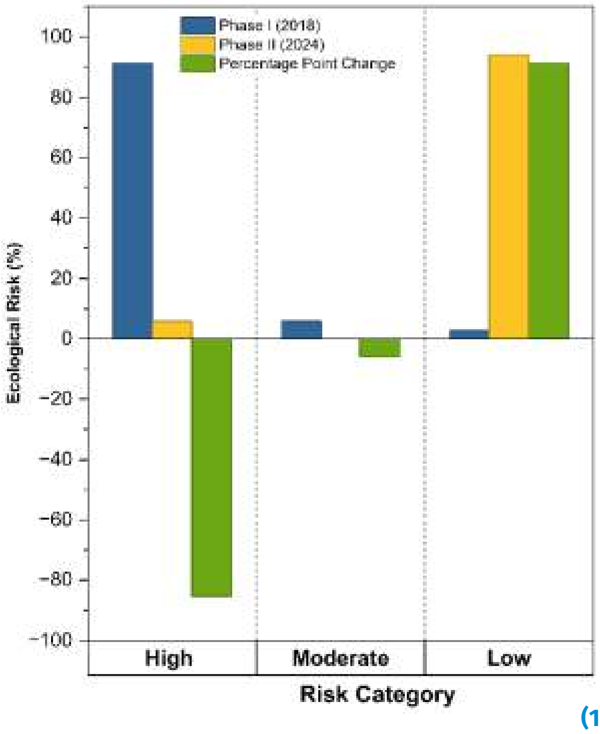
(12a)



(12b)



(12c)



(12d)

(12e)

Figure 12. *Spatiotemporal assessment of Organophosphorus pesticides pollution dynamics and associated ecological risk transitions in the Ganga River system.* **(a)** Box plot showing the distribution of Organophosphorus pesticides'' concentrations across sampling years, **(b)** Log-linear regression indicating a declining trend (-52.33% yr^{-1}, $p > 0.05$), **(c)** pie chart depicting site-wise directional changes (%) in concentration, and **(d)** Comparative analysis of ecological risk categories between 2018 and 2024 phases and **(e)** Spatial depiction of trend in Organophosphorus pesticides concentration along the Ganga River

5. TRENDS IN ENCOUNTER RATE OF INDICATOR SPECIES

5.1. Gangetic Dolphin

Encounter rate of the key aquatic species such as Gangetic dolphin and gharial increased between the assessment years, while it declined and remained stable for the waterbirds. Between 2018 and 2024, the encounter rate (ER) of the Gangetic dolphin showed a significantly increasing trend (p= 0.03; Figure 13). Further, the Gangetic dolphins were found to be occurring in the larger stretch of the Ganga River, indicating an expansion in the range of the Gangetic dolphin, by 245 km, which can be attributed to improved habitat conditions, particularly river depth. ER increased in 175 BEUs, decreased in 108 BEUs, remained unchanged in 54 BEUs, and no sightings were recorded in 77 BEUs (Figures 14a and 14b). The increasing trend in the ER of the Gangetic dolphin indicates apparent positive changes in the overall habitat quality. In 2018, ER was recorded as 0.65 (±0.05 SE) sightings/km, which increased in subsequent years of sampling to 0.77 (±0.06 SE) sightings/km in 2024. The Ganga River harbors a significant population of dolphins in the Ganga basin, with one of the highest ERs. Growing community awareness, improved river depth, and regulation on effluent discharge are perhaps some of the reasons for the increasing trend over the years.

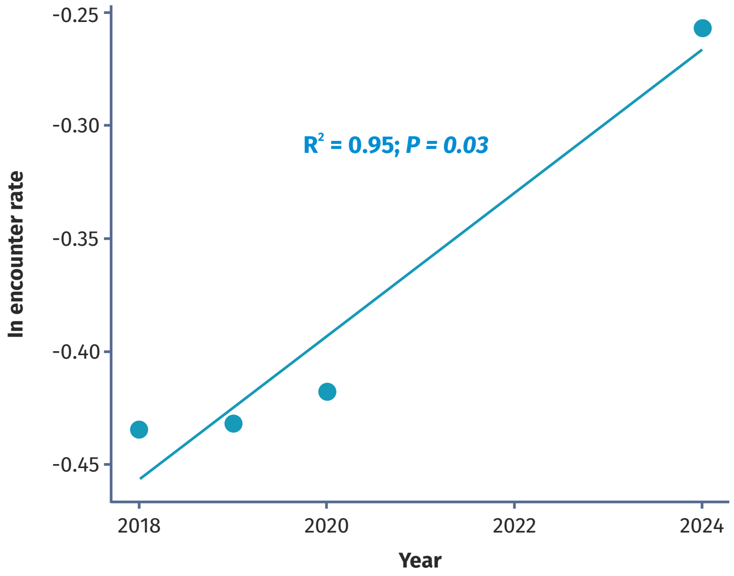


Figure 13: Temporal trend in encounter rate (ER) of the Gangetic dolphin (*Platanista gangetica*) in the Ganga River between 2018 and 2024.

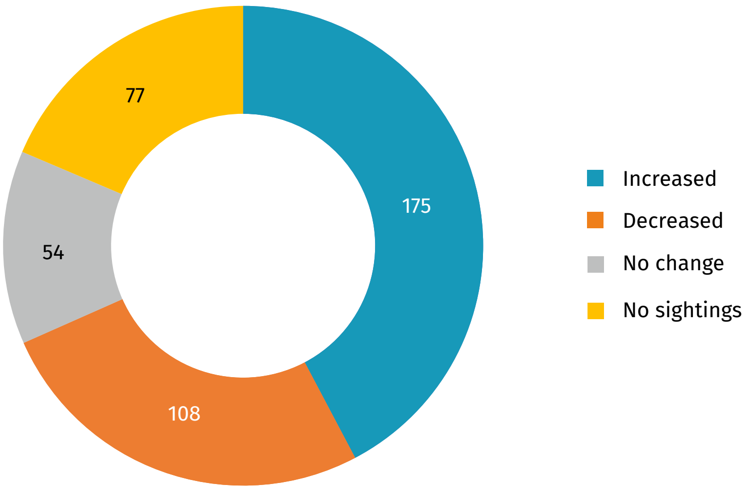


Figure 14a: Number of BEUs in the Ganga River, exhibiting changes in number of individuals of the Gangetic dolphin (*Platanista gangetica*), between 2018 and 2024.

Figure 14b: Spatial depiction of the trend in encounter rate of Gangetic dolphin

5.2. Gharial

The encounter rate of the gharial also showed an upward trend from 2018 to 2024, although this increase was not significant (p = 0.18; Figure 15). Despite the overall positive slope, most BEUs (n = 384, 92.7%) recorded no sightings of gharials during the assessment years. Despite being restricted to a small stretch, the encounter rate increased in 12 BEUs, decreased in 8 BEUs, and remained unchanged in 10 BEUs (Figures 16a and 16b).

Gharials are known to be influenced by several anthropogenic factors. Water depth and fish resources largely influence their distribution. In addition, the availability of sandbars and sand banks, water parameters, availability of fish stock, and predator-related threats regulate the population of gharial. Although the increasing trend in gharial's ER is encouraging, it is not conclusive enough to decipher the statistical significance of the observations. The sighting records of the gharial increased from 0.013 (SE 0.005) sightings/km in 2018 to 0.021 (SE 0.007) sightings/km in 2024. Ongoing continuous population augmentation efforts of the Government might be helping the population increase in the mainstem Ganga and its basin. To derive meaningful and conclusive interpretations, long-term population trend is needed.

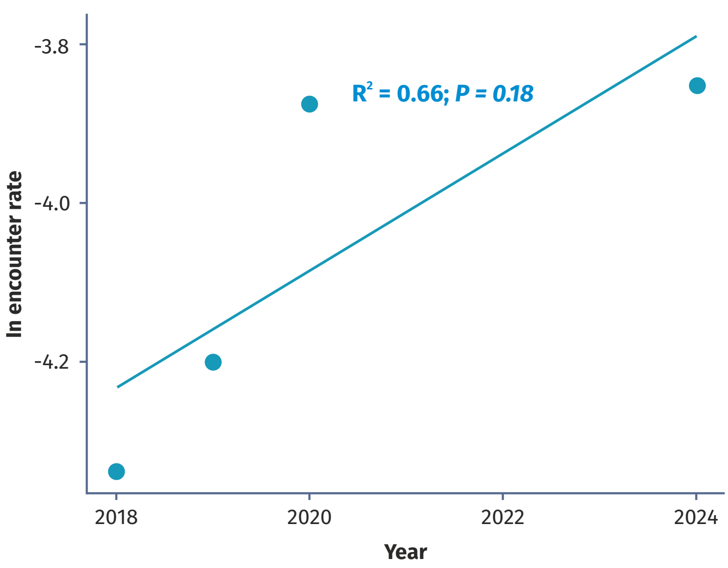


Figure 15: Temporal trend in encounter rate (ER) of the gharial (*Gavialis gangeticus*) in the Ganga River between 2018 and 2024.

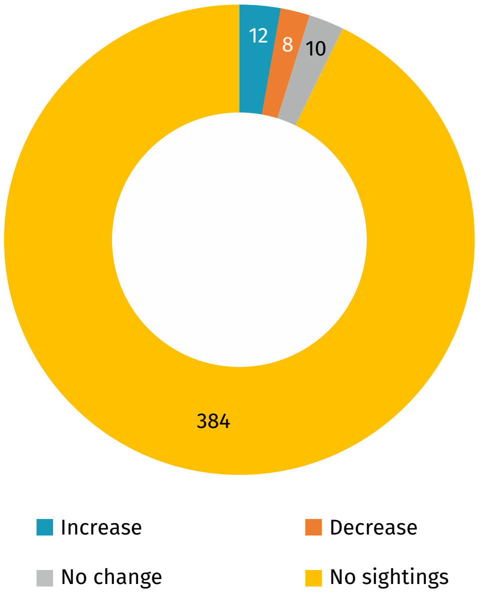
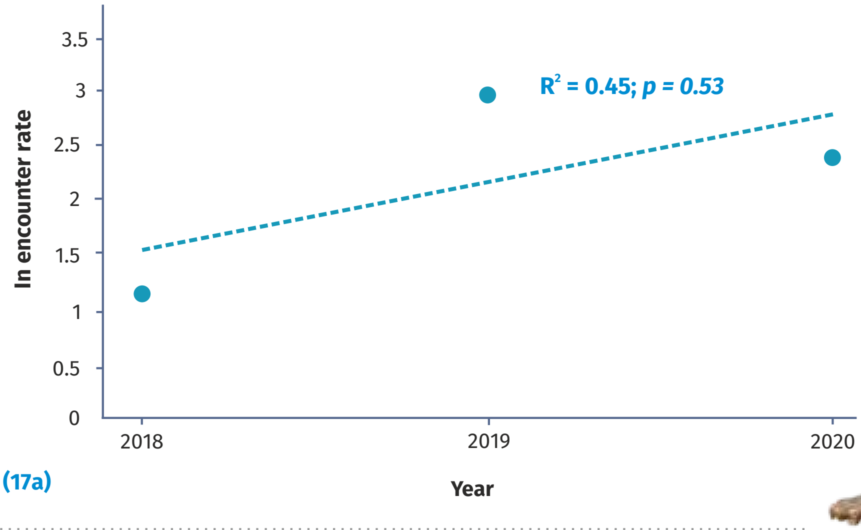


Figure 16a: Number of BEUs in the Ganga River, exhibiting changes in number of individuals of the gharial (*Gavialis gangeticus*), between 2018 and 2024.

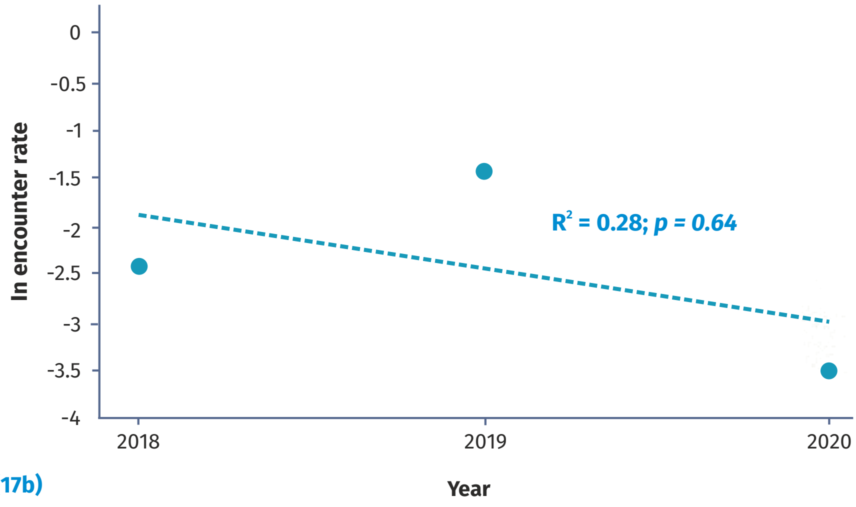
Figure 16b: Spatial depiction of trend in encounter rate of gharial

5.3. Turtle

The encounter rate (ER) of hardshell turtles along the Ganga River increased between 2018 and 2020 ($R^2 = 0.45$; $p = 0.53$; Figure 17a), while the softshell turtles showed a decline ($R^2 = 0.28$; $p = 0.64$; Figure 17b). However, both results are statistically insignificant. Turtles were found across most habitat zones, with the highest densities in the middle stretches, while the upper and extreme downstream stretches had few observations. The relative abundance of hardshell turtles rose from 97.10% in 2018 to 99.73% in 2020, while softshell turtles, which are found in smaller numbers, experienced a further decline in relative abundance from 2.86% in 2018 to 0.27% in 2020 (Table 1). The distribution of turtles is affected by factors such as the depth of water, the availability of basking sites, flow conditions, and human activities. Although encounter rates have increased, this trend does not show statistical significance and might be attributed to detection biases or seasonal influences. Our findings indicate that the relative abundance of softshell turtles has declined over time, and they are also among the most illegally traded freshwater turtles in India. From a conservation perspective, greater attention is needed to combat illegal trade and protect the natural habitats along the Ganga River. Long-term monitoring is crucial to confirm persistent changes in the population of freshwater turtles in the Ganga River.



(17a)



(17b)

Figure 17: Temporal trend in encounter rate (ER) of hardshell turtles (17a) and softshell turtles (17b) in the Ganga River between 2018 and 2020.

Table 1: Year-wise relative abundance (%) of hardshell and softshell turtle groups in the Ganga River.

Year	Hardshell (Geoemydidae)	Softshell (Trionychidae)
2018	97.10	2.86
2019	98.79	1.21
2020	99.73	0.27

5.4. Breeding Birds

Temporal trend in ERs for the four specialist waterbirds reveals variable patterns between 2018 and 2024. The Indian skimmer (*Rynchops albicollis*) showed a highly localised and sporadic distribution along the Ganga River during pre-monsoon surveys from 2018 to 2024. The mean encounter rate across the survey years saw an insignificant increase between 2018 and 2024 (p-value = 0.86; Figure 18). The low R^2 value also suggests that additional ecological variables may impact Indian skimmer distribution and abundance. The occupancy of the species along the Ganga River declined from 10.14% of the total stretch (n=42 BEUs) in 2018 to 3.14% (n=13 BEUs) in 2024, which reduced encounter rate in 36 BEUs and increased in 12 BEUs (Figure 19), indicating that the proportion of the river stretch supporting Indian skimmer nesting and sightings is decreasing. Mean colony size within occupied BEUs showed substantial temporal variation in colony aggregation. The average colony size of the species remained relatively constant in 2018 and 2019 (18.05 and 14.24 individuals, respectively), then increased exponentially to 30 individuals and 61.38 individuals in 2022 and 2024, respectively. This shows that the presence of Indian skimmers in specific areas decreased over time, while some river segments continued to host significant breeding colonies that contributed disproportionately to overall abundance patterns, highlighting the species' reliance on a few suitable nesting habitats throughout the river. The black-bellied tern (*Sterna acuticauda*) exhibited a slight, non-significant decline in encounter rate across the survey years (p = 0.71; Figure 20), with relatively small proportions of occupied BEUs showing increases (n = 31), decreases (n = 20), or no change (n = 24) in ER (Figure 21). The river lapwing (*Vanellus duvaucelii*) also displayed a negative, though insignificant, trend in ER (p = 0.21; Figure 22), with reduced ER in 114 BEUs, increased in 72 BEUs, and no change in 49 BEUs (Figure 23). The river tern (*Sterna aurantia*) exhibited slightly decreasing but not measurable change in encounter rates over the study period (p= 0.98; Figure 24). Among occupied BEUs, a relatively higher proportion showed a decrease (n = 30), followed by increases (n = 28) and no change (n = 12) occurred in a small number of BEUs (Figure 25).

These four waterbird species tend to breed in the riverine habitats of the Ganga and its tributaries; however, this trend might fluctuate annually owing to site-specific variations in availability of habitats, climatic conditions and anthropogenic factors. The endangered black-bellied tern and Indian skimmer are the most threatened inland waterbird species in India and elsewhere, which is also a habitat specialist species that mostly prefers river sand bars. Fewer than 1,500 black-bellied terns and 2,450–2,900 Indian skimmers are estimated to survive in India. Any alteration in the sand bars, especially due to cucurbit crops, could reduce the chances of their survival. Globally, there is a declining trend in their population with an unknown rate. Another threatened species, rive tern, is also a habitat specialist and usually prefers sandbar habitats in the riverine ecosystem. Overall, it has witnessed a declining population trend due to breeding failure and habitat alteration. While river lapwing occurs in sand bars as well as river banks and other types of habitats, their population sustenance also depends on the breeding productivity, recruitment rate, and local movement, which are often affected by human-induced factors.

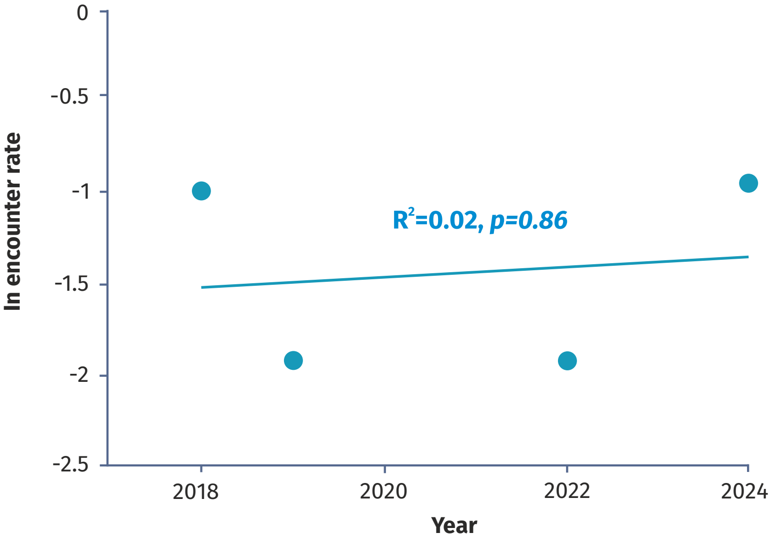


Figure 18: Temporal trend in encounter rate (ER) of the Indian skimmer (*Rynchops albicollis*) in the Ganga River between 2018 and 2024.

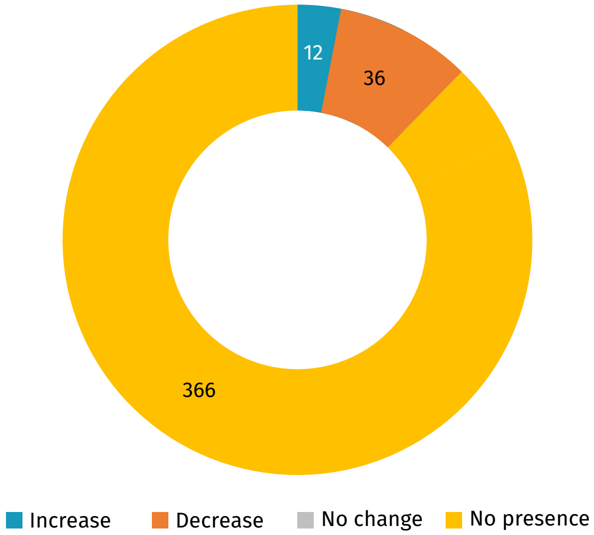


Figure 19: Number of BEUs in the Ganga River exhibiting changes in encounter rate of the Indian skimmer (*Rynchops albicollis*), between 2018 and 2024.

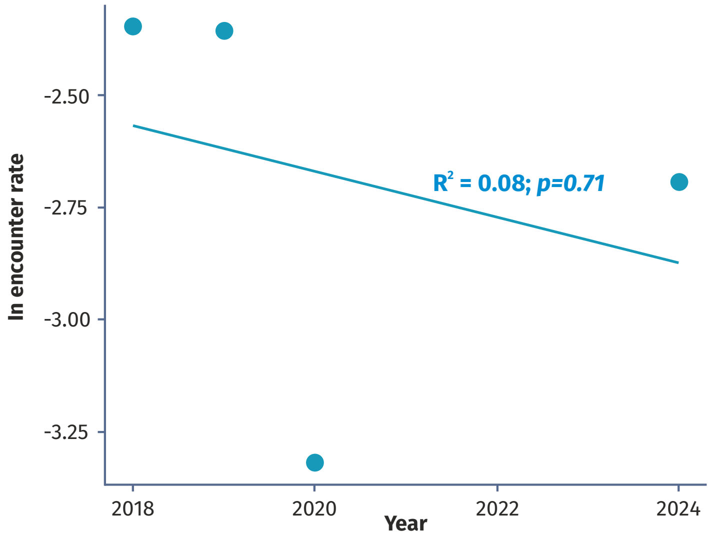


Figure 20:
Temporal trend in encounter rate (ER) of the black- bellied tern (*Sterna acuticauda*) in the Ganga River between 2018 and 2024.

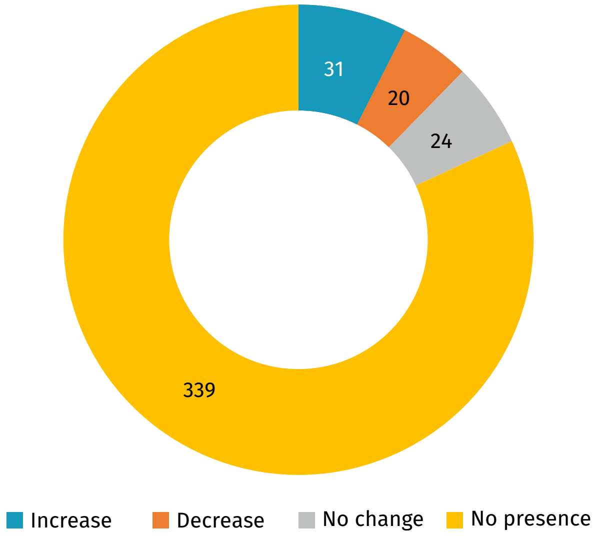


Figure 21: Number of BEUs in the Ganga River exhibiting changes in encounter rate of the black bellied tern (*Sterna acuticauda*), between 2018 and 2024.

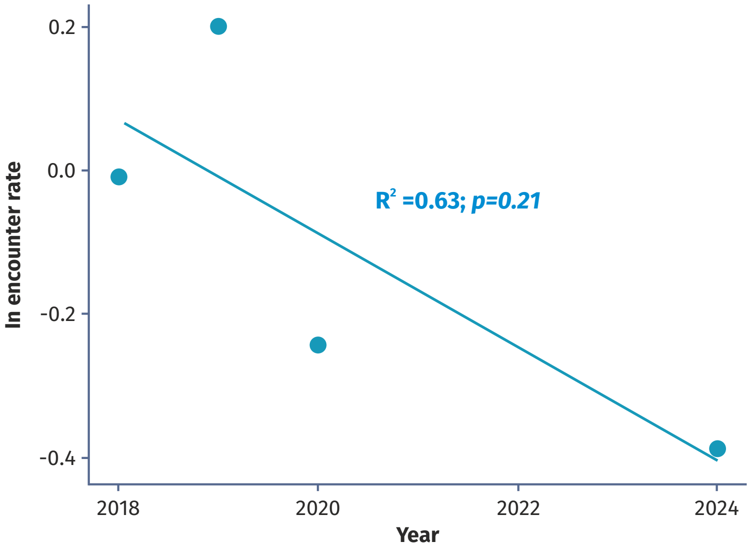


Figure 22: Temporal trend in encounter rate (ER) of river lapwing (*Vanellus duvaucelii*) in the Ganga River between 2018 and 2024.

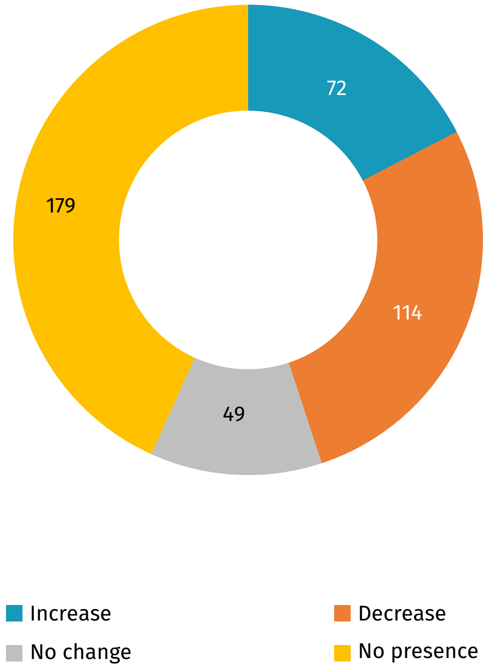


Figure 23: Number of BEUs in the Ganga River, exhibiting changes in encounter rate of the river lapwing (*Vanellus duvaucelii*), between 2018 and 2024.

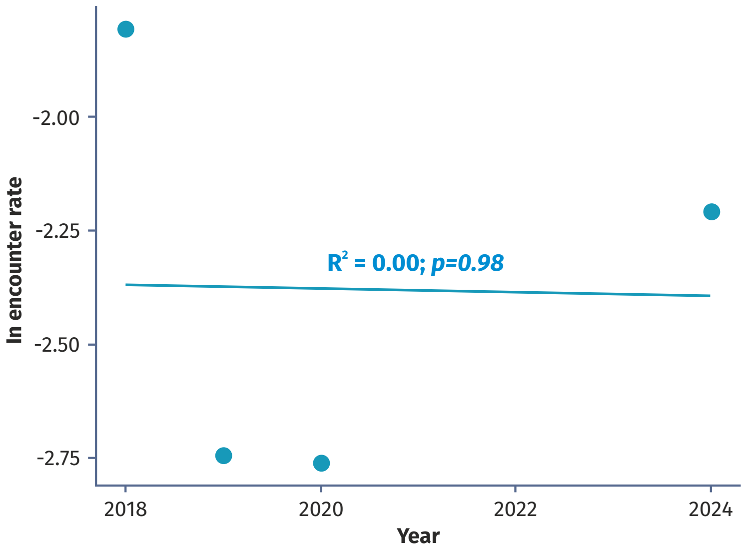


Figure 24: Temporal trend in encounter rate (ER) of the river tern (*Sterna aurantia*) in the Ganga River between 2018 and 2024.

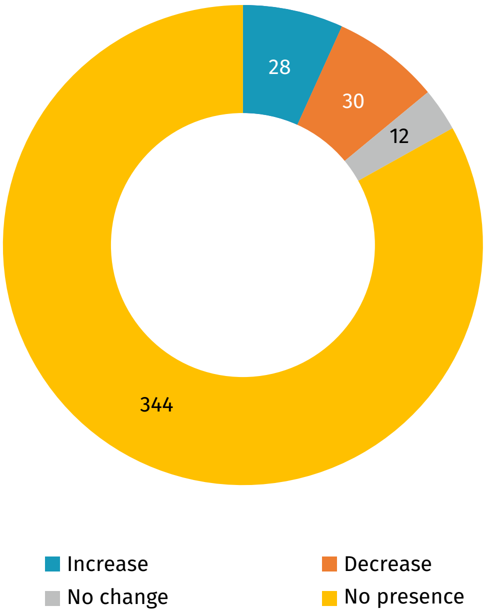


Figure 25: Number of BEUs in the Ganga River, exhibiting changes in encounter rate of the river tern (*Sterna aurantia*), between 2018 and 2024.

6. TRENDS IN SELECT STRESSORS

In human dominated landscapes, unsustainable use and extraction of river's resources lead to loss of river function and therefore, health. Human impacts are one of the major drivers of ecosystem function degradation and decline, and therefore, were assessed in the form of intensity of sand mining, fishing activity and ferry traffic.

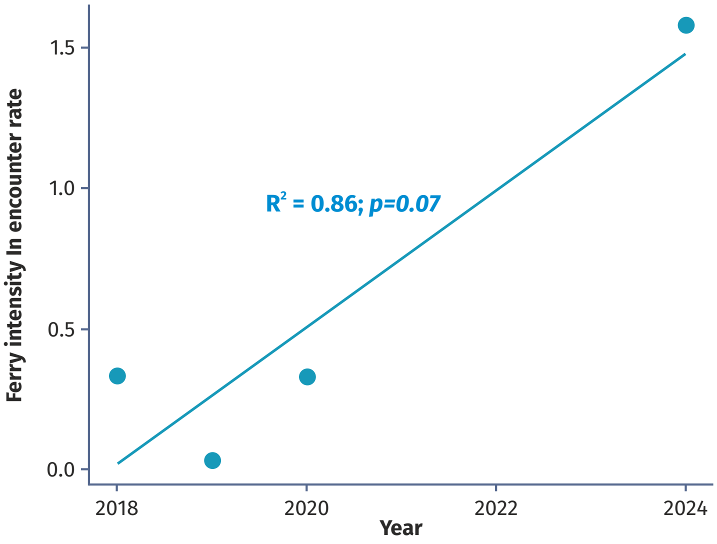


Figure 26: Temporal trend in ferry intensity (occurrence per km), in the Ganga River between 2018 and 2024.

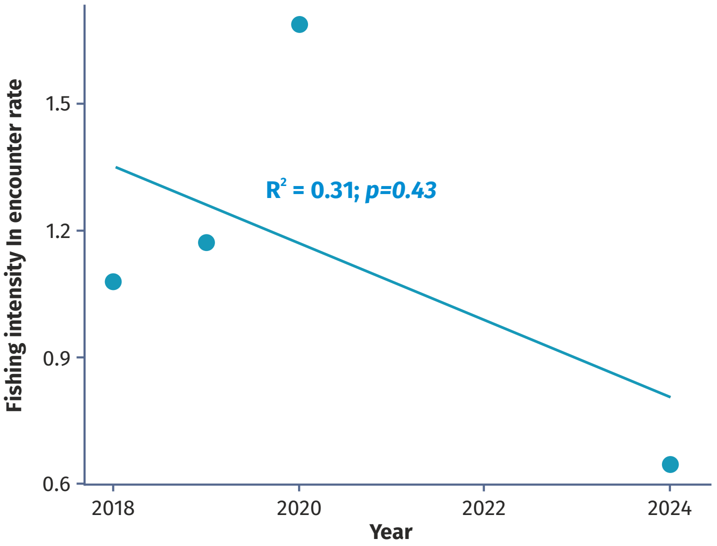


Figure 27: Temporal trend in fishing intensity (occurrence per km), in the Ganga River between 2018 and 2024.

The ferry and mining intensities increased between the survey years, rising from 1.39 to 4.85 per km and from 0.12 to 0.70 per km, respectively, while fishing intensity declined from 2.94 to 1.91 per km (Table 2). However, these observed changes in ferry (p = 0.07, Figure 26), fishing (p = 0.43, Figure 27), and mining (p = 0.46, Figure 28) intensities were not statistically significant. Finer-scale analysis of threat across the surveyed BEUs revealed contrasting patterns (Figure 29). Ferry intensity in the majority of the BEUs recorded an increase (n=326, 78.74%), with only a small proportion showing decreases or no change, and very few with no presence (n=27, 6.52%). Fishing activity showed a predominantly decreasing trend across BEUs (n=244, 58.94%), with a smaller number of BEUs experiencing increases and a small fraction showing no change (n=23, 5.56%). Declining fishing intensity may also reflect reduced fish availability. In contrast, mining activity was absent in over half of the surveyed BEUs and showed mixed pattern, with roughly equal proportions of BEUs showing increases, decreases, or no change.

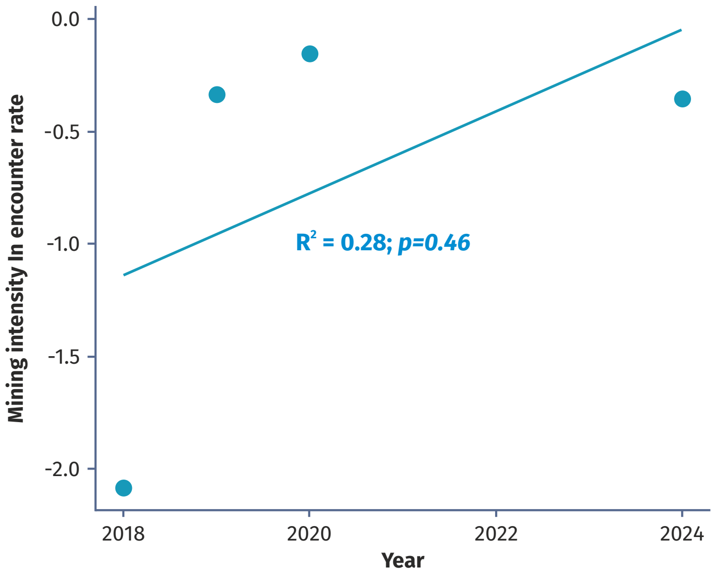


Figure 28: Temporal trend in sand mining intensity (occurrence per km), in the Ganga River between 2018 and 2024.

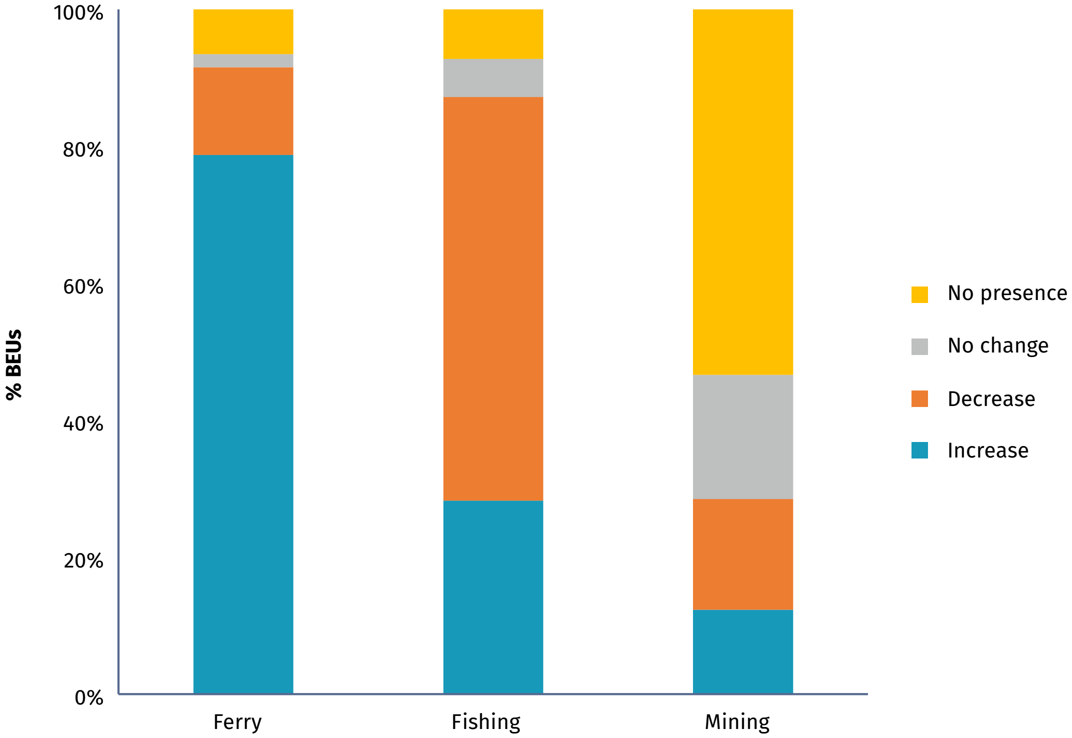


Figure 29: Percentage of BEUs in the Ganga River, exhibiting changes in threat intensity, between 2018 and 2024.

7. CONSERVATION IMPLICATIONS

The Ganga River represents India's most sacred and economically vital water resource, supporting millions of people across five states while sustaining diverse aquatic ecosystems of national and international significance. The river has faced decades of pollution pressure from multiple anthropogenic sources, including industrial effluents from tanneries and metal processing units, urban wastewater from inadequate sewage treatment infrastructure, agricultural runoff containing pesticides and fertilizers, and other diffuse pollution sources.

In response to these challenges, comprehensive pollution control initiatives have been implemented across the Ganga basin, under NMCG, through coordinated efforts of central and state agencies, local governments, and community stakeholders. These interventions include strengthened enforcement of effluent discharge standards with mandatory online monitoring systems for nitrate polluting industries, upgraded Common Effluent Treatment Plants serving industrial clusters, closure and relocation of non-compliant industrial units, promotion of sustainable agricultural practices including integrated pest management and Zero Budget Natural Farming, establishment of riparian buffer zones and constructed wetlands, and extensive community-based awareness and capacity building programs engaging farmers, industry associations, and local communities in pollution prevention efforts.

The findings of this study highlight the positive biodiversity and water quality outcomes (Table 2). However, the results should be interpreted with caution, as a decline in ER in some BEUs indicates spatially variable effectiveness, highlighting the need for site-specific conservation and management strategies. The variability found in the ER and other parameters is typical of large scale conservation programs. It underscores the importance of continued monitoring to identify both successful and failing interventions for informed adaptive management actions. Table 3 summarizes the key interventions that aided in the ecological recovery of the Ganga River and the future management priorities.

Table 2: Summary of the trend of ecological health indicators of the Ganga River.

Parameters		2017	2023	Status	p-value
Forest Cover (km^2)		26226	26480.99	Positive	0.401
Forest Type	Very Dense Forest (VDF) (km^2)	3982	4195.77	Positive	0.062
	Moderate Dense Forest (MDF) (km^2)	11387	11148.16	Negative	0.023*
	Open Forest (OF) (km^2)	10324	10613.63	Positive	0.24
	Scrub Forest (SF) (km^2)	533	523.43	Negative	0.527

Parameters		2018		2024		Status	p-value
		Mean	SEM	Mean	SEM		
River Depth (m)		4.53	0.177	5.13	0.134	Positive	0.06
Water Quality**	DO (mg/L)	7.51	0.25	9.07	0.28	Positive	0.41
	pH	8.30	0.04	8.32	0.07	Stable	0.64
	TDS (mg/L)	263.12	43.77	274.88	23.75	Positive	0.74
	Conductivity (µS/cm)	394.37	66.45	409.62	36.22	Positive	0.58
	Salinity (ppt)	0.14	0.01	0.21	0.02	Positive	0.33
	Nitrate (mg/L)	1.25	0.32	0.19	0.57	Positive	0.68
Contaminants**	Heavy Metals (µg/L)	31.92	4.63	26.62	3.89	Positive	0.36
	Organochlorine Pesticides (ng/L)	488.12	223.32	3.03	1.01	Positive	0.16
	Organophosphorus Pesticides (ng/L)	634.41	152.14	5.63	1.31	Positive	0.25
Indicator species/taxa	Gangetic dolphin (ER)	0.65	0.05	0.77	0.06	Positive	0.03*
	Gharial (ER)	0.013	0.01	0.021	0.01	Positive	0.18
	Hardshell turtle (ER)	3.22	0.65	11.14^	1.96^	Positive	0.51
	Softshell turtle (ER)	0.09	0.03	0.03^	0.01^	Negative	0.65
	Indian skimmer (ER)	0.37	0.10	0.39	0.15	Positive	0.86
	Black bellied tern (ER)	0.10	0.04	0.07	0.01	Negative	0.71
	River lapwing (ER)	0.99	0.12	0.68	0.10	Negative	0.21
	River tern (ER)	0.16	0.05	0.11	0.03	Negative	0.98
Anthropogenic Stressors***	Ferry (per km)	1.39	0.19	4.85	0.28	Negative	0.07
	Fishing (per km)	2.94	0.22	1.91	0.51	Positive	0.43
	Mining (per km)	0.12	0.02	0.7	0.25	Negative	0.46

* significant <0.05 confidence level; ** trends based on threshold values; ***trends based on impact; ^ values for the year 2020

A mixed trend in habitat quality parameters suggests continuous scientific monitoring of the parameters to pinpoint the management interventions needed and suggest the necessary course correction. Table 3 provides the detailed parameter-specific management interventions and monitoring imperatives for improved outcomes of the *Namami Gange* Programme.

Table 3: Key interventions that aided in improvement and future management priorities for key parameters of river ecosystem

Parameters		**Trend**	**Key Interventions**
Forest Cover (km^2)		Increasing	Implementation of CAMPA, plantation under various schemes including Namami Gange, improved patrolling, and social forestry schemes.
Forest Type	Very Dense Forest (VDF) (km^2)	Increasing	Improved patrolling, conservation of natural habitats under different umbrella projects like Project Tiger, Project Elephant etc.
	Moderate Dense Forest (MDF) (km^2)	Decreasing	Declining trend is attributed to increasing demand for forest resources.
	Open Forest (OF) (km^2)	Increasing	Encouragement of social forestry and conversion of MDF into OF could be a major factor of increase.
	Scrub Forest (SF) (km^2)	Decreasing	Conversion of SF into other land uses for development. SF are often misconstrued as degraded patches.
River Depth (m)		Increasing	e-flow notification
Water Quality	DO (mg/L)	Positive	Reduced organic loading through improved STP and industrial treatment; enhanced BOD removal; reduced surfactant contamination
	pH	Stable	Maintained carbonate buffering; localized industrial/agricultural influences
	TDS (mg/L)	Positive	EMERGING CONCERN: Ionic enrichment from urban wastewater and agricultural return flows; conventional treatment inadequate for dissolved inorganic; possible climatic amplification
	Conductivity (µS/cm)	Positive	EMERGING CONCERN: Diffuse ionic loading from urban/agricultural sources; inadequate inorganic removal in conventional systems
	Salinity (ppt)	Positive	Progressive ionic accumulation; evaporative concentration during low flows; increased high-ionic baseflow contribution
	Nitrate (mg/L)	Positive	Reduced nitrogen loading from improved wastewater treatment and agricultural management; enhanced STP operations and precision fertilizer application. However, episodic spikes (2022 anomaly) indicate persistent vulnerability to monsoon-driven agricultural runoff and point source discharges.

Management Priorities	Monitoring Imperatives
Prioritize ecological integrity, minimize disturbance, and enhance resilience.	Afforestation to be continuously monitored to assess survival rate, preference of native species, and ensure the integrity of natural ecosystems by avoiding imprudent/unscientific plantations. Regular monitoring for fire and invasive species.
Conservation and protection of VDFs and prevent land use conversion. Promote native species regeneration.	Monitoring of VDFs for encroachment, fire, land use changes.
Focus on a combined strategy of restoration, regulation, and river-sensitive landscape management. Afforestation should focus on native species.	The survival rate of the afforestation to be monitored and will also identify causes of plantation failure that would be essential to find scientific solutions to improve the survival rate.
Active intervention through canopy augmentation, stabilization and reduction of chronic disturbances.	Engage local communities and other stakeholders in afforestation, protection and monitoring, particularly with regard to invasive and forest fire incidences.
Identifying if the SF is a naturally occurring ecosystems in the riverscape or is a result of anthropogenic disturbance. Site-specific actions for restoration and revival of the natural conditions.	Long-term monitoring of scrub patches along the river banks. Invasive species control and minimizing fire incidences, through community and stakeholder engagement and awareness.
Enhance and ensure water use efficiency.	A hydrology monitoring mechanism needs to be in place to carry out stage and discharge readings at regular intervals.
Baseline surveillance; maintain STP operational sustained reliability.	Extended monitoring confirms improvements are and not temporary fluctuations from operational changes.
Targeted investigation of non-compliant sites.	Routine and periodic monitoring. Continued surveillance identifies emerging localized alkalization before widespread impacts occur.
Early warning surveillance for threshold approaches; investigate Kanpur-Varanasi sources; evaluate advanced tertiary treatment.	Long-term trend monitoring is critical to distinguish anthropogenic from climatic drivers, detect threshold approaches early, and enable preventive rather than interventions.
Intensive monitoring in urban-industrial corridors; source apportionment studies; enhanced treatment.	Sustained monitoring is essential to track cumulative enrichment from diffuse sources and validate the effectiveness of watershed-scale interventions.
Track trajectory for compliance; the highest relative rate of increase.	Continuous surveillance is required, given the rapid rate of change, to ensure the threshold is not approached and enable timely source reduction strategies.
Intensify surveillance during monsoon periods. Validate treatment system performance. Promote precision agriculture and constructed wetlands for nutrient interception.	Sustained monitoring is essential to track eutrophication risk. Moderate variability requires continuous monitoring to detect reversals and confirm intervention effectiveness.

Parameters		Trend	Key Interventions
Contaminants	Heavy Metals (μg/L)	Positive	Strengthened enforcement with mandatory online monitoring; upgraded CETPs; closure of non-compliant facilities; strategic drain interception
	Organochlorine Pesticides (ng/L)	Positive	Surveillance for illegal reintroduction; maintain ban enforcement; natural attenuation proceeding
	Organophosphorus Pesticides (ng/L)	Positive	Agricultural transformation via IPM and ZBNF adoption; farmer capacity building; riparian buffers and constructed wetlands; rapid biodegradation
Indicator species	Gangetic dolphin (ER)	Positive	A larger percentage of river stretches with suitable depth
	Gharial (ER)	Positive	A larger percentage of river stretches with suitable depth
	Hard shell turtles (ER)	Positive	Rearing followed by release, along with rescue, rehabilitation efforts have emerged as a critical conservation strategy to address threats such as entanglement, poaching, injury and mortality.
	Hard shell turtles (ER)	Negative	
	Indian skimmer (ER)	Positive	The observed increase in colony aggregation along with declining site occupancy suggests progressive contraction and fragmentation of suitable nesting habitats, likely driven by river regulation, sand mining, floodplain encroachment, and anthropogenic disturbance.
	Black bellied tern (ER)	Negative	Although the decreasing trend in the encounter rate is statistically insignificant, anthropogenic stressors, particularly agriculture and mining on the river islands could have contributed to the trend.
	River lapwing (ER)	Negative	Although the decreasing trend in the encounter rate is statistically insignificant, anthropogenic stressors, particularly agriculture and mining on the river islands could have contributed to the trend.
	River tern (ER)	Negative	Although the decreasing trend in the encounter rate is statistically insignificant, anthropogenic stressors, particularly agriculture and mining on the river islands, could have contributed to the trend.

Management Priorities	Monitoring Imperatives
Continuous surveillance is essential; intensify CETP monitoring and enforcement; investigate moderate -risk sites. HIGH REVERSAL RISK if controls lapse-no concentration rebound. natural degradation.	Long-term monitoring is non-negotiable to detect source control failures immediately, validate treatment system performance, and prevent rapid.
Natural depletion of banned legacy POPs through environmental degradation, volatilization, photo degradation, and sediment burial following regulatory bans	Long-term monitoring is essential to confirm environmental complete depletion to background levels and detect unauthorized reintroduction.
Validate sustained practice adoption; maintain extension services and buffer infrastructure.	Continuous monitoring is required to detect reversal and confirm that interventions produce.
Improve seasonal depth regime	Seasonal monitoring to know the preferred habitat, population trend, and responses to stressors.
Seasonal depth regime should align with the natural life cycle of the species.	Seasonal monitoring to know the preferred habitats, population trend, and responses to stressors. Seasonal monitoring also needs to be aligned with the life cycle events and seasonal changes in habitat conditions.
Strengthen rescue and rehabilitation network; improve head start and reintroduction program; reduce accidental mortality; strengthen anti-poaching and trade surveillance; protect and restore critical habitats	Integrated riverine habitat protection into river basin management plan. Enforce reduction of fisheries-related mortality, scientifically managed reintroduction programs, and strengthened anti-poaching measures. Long-term monitoring of post-release survival, nesting success, population demography, genetic integrity, and mortality hotspots is essential to evaluate conservation effectiveness and ensure recovery of hard-shell and soft-shell turtle populations.
Identify, protect and secure key nesting habitats; maintain e-flows and sediment dynamics; retain river's dynamism and channel heterogeneity with exposed sandbars, shallow braided channels; avoid abrupt discharge releases during nesting season.	Focus on securing dynamic sandbar habitats through integrated riverine habitat protection, long term population monitoring, inclusive of annual synchronised surveys; track habitat availability; anthropogenic and e-flow monitoring is essential to guide adaptive conservation interventions.
Being a rare species, 24/7 monitoring of nesting and protection from external threats is required. Restrict anthropogenic stressors (cucurbit farming, livestock grazing, mining).	Periodic long-term monitoring of breeding productivity and sites ensuring inviolate spaces of breeding and foraging. required.
Monitoring nesting river islands and mitigating threats, e.g., managing free-ranging dogs, restricting the movement of livestock, sensitizing farmers, and discouraging cucurbits farming and mining in and around key nesting sites.	At present, species might not be severely in danger, but stressors, e.g., continuous monitoring will ensure the long-term survival of the species.
Monitoring nesting river islands and mitigating threats, e.g., managing free-ranging dogs, restricting the movement of livestock, sensitizing farmers, and discouraging cucurbits farming and mining in and around key nesting sites.	Continuous long-term monitoring will ensure the long-term survival of the species. This will assist in planning for the mitigation of potential stressors and in conserving existing habitats.

Parameters		Trend	Key Interventions
Anthropogenic stressors	Ferry (per km)	Increasing	Since the increasing trend is not conclusive, it is imperative to carry out long-term monitoring.
	Fishing (per km)	Decreasing	Since the decreasing trend is not conclusive, it is imperative to carry out long-term monitoring.
	Mining (per km)	Increasing	Since the increasing trend is not conclusive, it is imperative to carry out long-term monitoring.

Management Priorities	Monitoring Imperatives
Stricter compliance with speed limits and promotion of green vessels.	Monitoring of the ferry/vessel movement measures throughout the River.
Strictly enforce the existing state level fishing regulations.	Periodic and seasonal monitoring of the fish base; compliance measures throughout the River.
Identification of the nesting and other habitat uses. Restrict mining activities in areas known to have nesting sites of gharial, mugger, turtle, and bird species.	Continuous and seasonal monitoring to identify the use of sand bars and river islands by the species.

Increasing forest cover may be attributed to the proper implementation of various plantation and protection schemes in the riverscape. The decreasing trend in the MDF and scrub forest may be due to conversion to other land use classes. These forests require regular monitoring, focusing on forest fire, invasive species, and plantation survival rate. Involvement of local communities and other stakeholders could also help in the improvement of forest cover. The afforestation programme initiated to restore the river's riparian cover has covered less than 3% of its stated target area. Increasing depth and stable pH has improve the riverscape quality and availability of habitat, enabling range expansion or rehabilitation of the historic home ranges of the indicator species. However, recovery of the apex species requires sustained flow regimes. In retrospect, the e-flow monitoring thus needs to look beyond hydrological parameters viz., stage, discharge, in-flow/out-flow and include the ecological indicators to validate the effectiveness of the flow regime. The e-flow data also need to be integrated with the real time water quality parameters to assess the e-flow dilution. Increasing ferry traffic heightens collision risks for the Gangetic dolphins, and other aquatic species. Though the encounter rate of turtles has increased, it is noteworthy to highlight that the softshell turtles, which are found in smaller numbers, experienced a decline in relative abundance. The softshell turtles are amongst the most illegally traded freshwater turtles in India, thus we need stricter regulations and their compliance to combat illegal trade, establish functional rescue centres for turtles, and protect the natural habitats along the Ganga River. Increased colony size along with the reduced occupancy, in case of Indian skimmer, points out to decline in availability of the suitable habitats for nesting. This trend for Indian skimmer and declining or inconclusive encounter rate of other waterbirds indicates loss of habitat either due to inundation, sand mining or encroachment for agriculture or due to disturbances by the free ranging livestock and dogs.

The reduction in high-risk contamination sites suggests that infrastructure investments (sewage treatment plants, drain interception) have addressed acute pollution sources. Still, challenges associated with diffuse pollution and operational inefficiencies remain (Table 3). As the result suggests, though the fishing pressure has declined, the disturbances from ferries and mining continue to remain challenging for sensitive aquatic species. Site-specific conservation and management interventions must be integrated with stricter regulation of ferries and mining activities. Unlike organochlorine pesticides, which are entirely banned, many organophosphorus compounds, such as Chlorpyrifos, Malathion, and Parathion, remain in current agricultural use but degrade more rapidly in the environment due to shorter

chemical half-lives ranging from days to weeks rather than years. The observed decline reflects the combined effects of multiple synergistic interventions undertaken by the NMCG. These interventions include pollution abatement measures through tapping wastewater inflow, promoting Zero Budget Natural Farming, for *Nirmal Ganga*, and e-flow notification for *Aviral Ganga*.

Regulatory measures, including enforcement of pesticide application regulations, restricted-use classifications, and community awareness campaigns educating farmers on judicious use and alternatives, have shown ground-level impacts. Agricultural practice transformation undertaken by NMCG, has accelerated the adoption of integrated pest management, precision agriculture, enabling targeted application, expansion of Zero Budget Natural Farming, eliminating synthetic inputs, organic farming certification, creating market incentives, and crop rotation with biological pest control, reducing chemical reliance. But these efforts need to be upscaled to a larger spatial unit and landscape for measurable positive causal changes in the contaminants in water and sediment.

Infrastructure investments enhanced landscape-scale filtration through riparian buffer zones, constructed treatment wetlands in high-burden catchments, and vegetated filter strips intercepting surface runoff. Natural processes contribute significantly through rapid microbial biodegradation, hydrolysis under alkaline pH conditions characterizing the Ganga River, and photolytic degradation in sunlit surface waters. Ecological risk with OCPs exhibited a substantial decline, with high-risk site prevalence decreasing by 34% from 2018 to 2024. The reduction in high ecological risk sites represents significant progress toward ecosystem restoration, though continued monitoring remains necessary to verify complete depletion and detect any illegal reintroduction of banned substances. Ecological risk attributed to OPPs markedly diminished by -89% from 2018 to 2024. These pesticide trend reflects the combined effectiveness of regulatory enforcement, community-based interventions, awareness, and capacity building of farmers on eco-friendly/sustainable agricultural techniques, targeted infrastructure investments such as constructed wetlands, buffer zone establishment, and Zero Budget Natural Farming.

The convergence with CPCB's water quality assessment reaffirms a consistent pattern of progressive ionic enrichment and localized pollutant persistence across the basin. While infrastructural interventions have yielded measurable improvements, sustained ionic buildup and residual contamination indicate that diffuse pollution sources and operational efficiency of treatment systems warrant continued strengthening.

The study suggests that immediate priorities must shift from capacity expansion to operational reliability, ensuring all STPs are functional, compliant, and digitally monitored in real time. Equally critical is the complete interception and treatment of high-burden drains in ecologically sensitive stretches. Strengthening these operational and governance mechanisms is essential to consolidate existing gains, address persistent pollution sources, and achieve sustained river health and ecological restoration across the Ganga Basin. The assessment findings point to a clear inflection point in the *Namami Gange* programme. The programme's emphasis on infrastructure development and institutional frameworks has produced measurable outcomes. The next phase should pivot from capacity expansion toward ensuring operational reliability and strengthening ecological management. This study also highlights the governance and institutional gaps. The monitoring framework is functioning, the legal instruments are in place, but there is a governance challenge. The capacity and political will to enforce regulations, coordinate across departmental silos, and hold public and private actors accountable for ecological harm is needed for the next phase of the programme to ensure sustained ecological resilience of the River.

The most urgent priorities are:

- Forest and Riparian Management: There is a need to shift from area-based afforestation targets to quality-focused restoration. There is a need to establish and restore continuous riparian corridors, by planting native species.
- Site-specific conservation planning: The variability in outcomes across BEUs confirms that blanket interventions are insufficient. Conservation and management strategies must be tailored to local conditions, threat profiles, and species needs, and thus there is a need to shift from uniform interventions to BEU level planning.
- Continued long-term monitoring: To track the range expansion of indicator species such as Gangetic dolphins and to understand why encounter rates are declining in certain river stretches even though the population is showing an increasing trend. To assess the impact of conservation measures such as plantation activities and water quality improvement on species encounter rate and distribution across the riverscape, there is a need to institutionalize long term ecological monitoring framework.

- Sustainable fishery practices: The local communities are dependent on fishery activities. While this is recognised, the mortality caused by fishing nets is one of the main factors affecting the population growth of large macrofauna. Capacity development of the implementing agencies such as Forests and Fisher departments need to be augmented and made sensitive to these underlying issues.
- Stricter regulation of ferries and sand mining: Both activities are intensifying at rates that threaten sensitive aquatic species. Regulation must be consistent, enforced, and data-driven.
- Expanded habitat protection for sand bar-nesting birds: Unlike aquatic megafauna, the island nesting bird species are more sensitive to physical habitat disturbance, highlighting gaps in riverbed and floodplain management.
- Operational compliance of STPs: All treatment plants must be fully functional, compliant with discharge norms, and digitally monitored in real time. Non- functional or under-performing STPs represent the single largest risk to water quality gains.
- Drain interception in sensitive stretches: High- burden drains entering the river in ecologically sensitive areas must be fully intercepted and treated. Partial interception is insufficient.
- Scaling up pesticide regulation: Regulatory enforcement and community awareness on pesticide use have demonstrated ground-level impact. These must now be expanded from targeted areas to the wider river basin to achieve measurable reductions in agricultural contamination.
- Engaging local communities in river conservation: Involving local communities in the Ganga conservation by adopting mass conservation education and awareness programmes and sustainable livelihood development likely to enhance the conservation outcomes in a faster way.

Finally, it is suggested that the ecological monitoring framework must continue and be strengthened. The variability documented in this assessment - across both improvements and deterioration - underscores the value of longitudinal, reach-scale monitoring in guiding adaptive management. The Ganga's recovery is real, but continuous effort needs to be put in place to make the recovery sustainable.

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