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Physicochemical and Bacteriological Assessment of Water Quality in the Hooghly River, Eastern India

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Abstract

Rivers play a critical role in sustaining human civilization by supporting domestic, agricultural, and industrial water needs. They also function as pathways for conveying treated and untreated wastes toward downstream environments. The Hooghly, a major distributary of the Ganges, flows through densely populated and industrialized regions of eastern India and is subject to complex interactions among tidal forcing, urban effluents, and sediment dynamics. This study presents a post-monsoon (September 2021) assessment of water quality at seven strategically selected sites, focusing on key physicochemical and bacteriological parameters: total solids (TS), pH, alkalinity, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total coliforms. DO ranged from 6.0-7.0 mg/L, COD from 3.0-28.1 mg/L, and total coliforms peaked at 74.63 × 105 MPN/L at Garden Reach, indicating localized organic loading and significant fecal contamination. Spatial trends showed heterogeneous conditions influenced by population density, sewage discharge, and tidal hydrodynamics, rather than a uniform upstream-to-downstream gradient. As this represents a single-season snapshot (n = 7 sites), interpretations are conservative and avoid broad generalization. The findings highlight the need for enhanced wastewater management, targeted monitoring of pollution hotspots, and improved treatment strategies to support safe water abstraction and ecological resilience.

Keywords

Alkalinity, Biochemical oxygen demand, Chemical oxygen demand, Dissolved oxygen, Dissolved solids, Hooghly estuary

Article History

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1. Introduction

Rivers are dynamic conveyors of water, sediment, nutrients, and anthropogenic materials. India's river systems underpin agriculture, industry, domestic water supply, transport, fisheries, and urban ecosystems; their quality therefore has direct socio-economic and ecological implications [1,2]. The Ganges river system, with its many distributaries and tidal reaches, is particularly complex. The Ganges (Bhagirathi-Hooghly system in its lower course) experiences large seasonal variations in discharge and sediment transport and is strongly influenced by human activities along its banks [3,4].

The Hooghly, a principal distributary of the Ganges in West Bengal, flows through a densely populated, industrialized corridor before reaching the Bay of Bengal [5]. Urban centers such as Serampore, Dakshineshwar, Howrah, and Kolkata have grown along its banks and contribute to both point- and non-point pollution loads. The southern deltaic portion experiences tidal influence and episodic saltwater intrusion from the sea. These factors affect chemistry, sediment transport, and ecological communities [6]. The Hooghly's lower reaches present a mosaic of water-quality regimes shaped by anthropogenic discharges, land use, hydrodynamics, and tidal forcing.

Past studies document elevated organic loads, heavy metals, and bacteriological contamination at many sites in the Hooghly and lower Ganges [7-9]. These studies used field sampling, statistical tools, Geographic Information System (GIS), and predictive models to describe spatial and temporal patterns and to propose management measures [10-12]. Recent research has focused on estuarine processes, salinity intrusion, micropollutants, and the use of remote sensing with in-situ monitoring [13-15]. Monitoring campaigns in 2022-2024 show the Hooghly estuary still faces episodic pollution and chronic contamination that impact ecosystem health and human use [16].

The current study builds upon this body of work by presenting a tightly focused, post-monsoon (September 2021) sampling campaign at seven locations in the southern Hooghly (Table 1, Figure 1). The aim is to quantify key physicochemical and bacteriological parameters, analyze spatial trends against possible drivers such as distance from the Farakka diversion canal, and interpret the results in light of recent findings and management needs. The emphasis is on robust laboratory methods (American Society for Testing and Materials/Indian Standard (ASTM/IS) standard procedures), multiple replicate tests, and interpretation that links measured patterns to likely sources and processes, including tidal mixing, self-purification, and upstream inflows.

Table 1. Sampling locations[1] (Goswami et al. [6]).

Locality	Distance from Farakka (km)
Palta	267
Serampore	272
Dakshineshwar	284
Shibpur	296
Garden Reach	300
Uluberia	324
Diamond Harbour	369

Note: [1]The water samples were collected during September 2021 which was a post-monsoon period in the year.

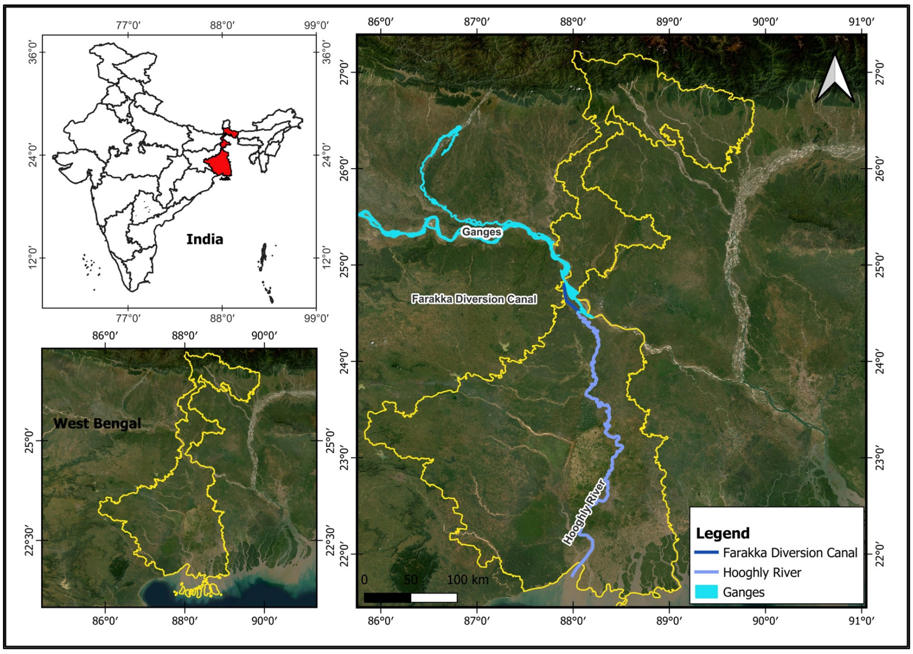

Figure 1. Schematic diagrams of the rivers Ganges and Hooghly (Modified after Goswami et al. [6]).

To situate this study within a broader research agenda, it is important to emphasize three interlinked themes that recur through literature and inform our methodological choices. First, the interplay between hydrodynamics (flow, tides, mixing) and pollutant transport means that a single snapshot can reveal complex signatures of past and ongoing processes; thus, interpretation must combine local observations with process understanding [10]. Second, urbanization and industrialization around river corridors create heterogeneous sources and sinks of pollutants, so land-use and point-source mapping are essential to understanding spatial patterns [9,11]. Third, emerging contaminants (micropollutants, polycyclic aromatic hydrocarbons (PAHs)) and sediment-bound legacy pollutants complicate simple water-quality assessments, requiring targeted chemical analyses alongside standard monitoring parameters [13,14].

This study contributes two specific types of advances: (a) it adds an updated, post-monsoon dataset for seven strategically selected locations that bridge upstream urban-industrial zones and the tidal-influenced downstream corridor; and (b) it provides an integrated interpretation that explicitly links measured concentrations to plausible processes, including tidal resuspension, urban sewage inputs, industrial effluents and geomorphologic controls such as channel narrowing, dredging and bank erosion. These findings can assist water-resource managers in designing targeted monitoring strategies and prioritizing remediation in the lower Hooghly basin.

Recent water quality studies have assessed Himalayan basins [17] and transboundary estuaries [18]. These studies documented varying degrees of physicochemical and microbiological pollution. However, systematic evaluation of chemical oxygen demand and biochemical oxygen demand ratios (COD:BOD ratios) and the explicit identification of bacteriological hotspots remain limited [3,5-7]. This study addresses this gap by assessing pollution patterns with an emphasis on organic load resilience and spatial variability in microbial contamination, particularly at highly impacted locations such as Shibpur and Garden Reach. The assessment is guided by testable expectations: (a) water quality may follow a longitudinal gradient reflecting distance from upstream freshwater influence, and (b) alternatively, spatial patterns may correlate more strongly with localized anthropogenic pressures such as population density and wastewater discharge intensity.

The principal objectives of the present study are threefold. First, it seeks to quantify the post-monsoon values of key water-quality parameters, including total solids, pH, alkalinity, dissolved oxygen (DO), BOD, COD, and total coliform—at seven strategically selected locations along the Hooghly River near Kolkata (as shown in Table 1 and Figure 2). Second, it aims to analyze the spatial variability of these parameters in relation to the distance from the Farakka diversion canal, as well as the influence of local population density and prevailing land-use patterns. Finally, the study endeavors to compare the obtained results with findings from previous investigations and recent literature, emphasizing emerging environmental concerns such as salinity intrusion, the presence of micropollutants, and episodic turbidity events, while formulating suitable monitoring strategies and management recommendations to enhance water-quality governance in the region.

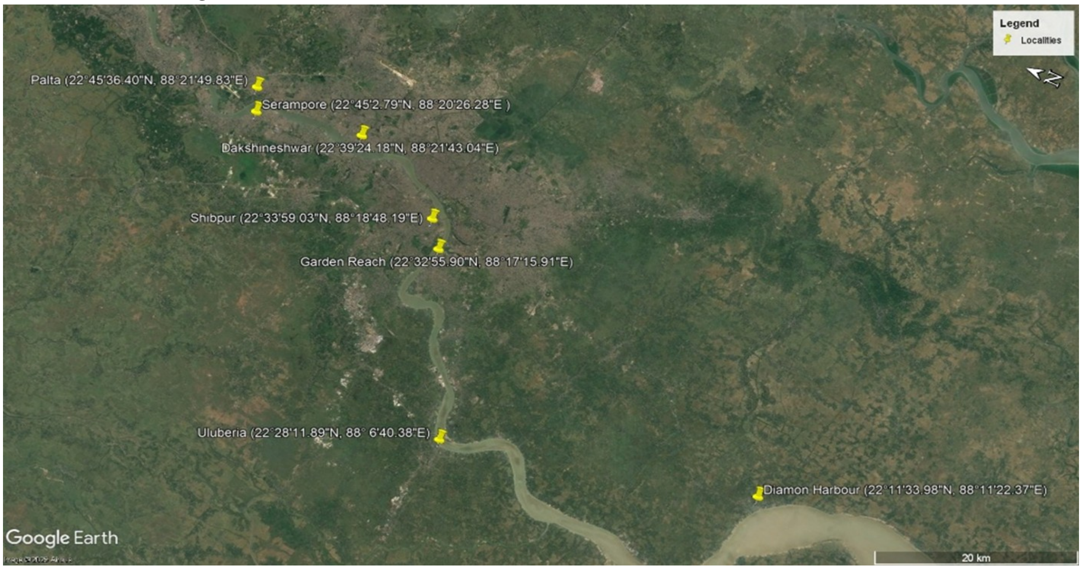

Figure 2. The study area (Modified after Goswami et al. [6]).

2. Study Area and Sampling Locations

The study area is shown in Figures 1 and 2. Sampling points (Table 1) were selected to represent the river continuum from the upstream locality near Palta down to Diamond Harbour, incorporating urban/industrial zones (Serampore, Shibpur), significant river confluences, and tidal-affected downstream points. The study purposely included areas of different population densities to gauge anthropogenic influence (Table 2, Figure 3).

Site rationale: Palta was chosen for its proximity to major water-supply intakes and its representation of upstream urban influence; Serampore and Shibpur represent densely built corridors with mixed industrial and residential loads;

Dakshineshwar and Garden Reach capture tidal modulation and municipal discharge influence; Uluberia and Diamond Harbour provide contrast as downstream, tidal-dominated points approaching the estuarine mouth. This gradient allows analysis of both longitudinal and local drivers of water quality.

Table 2. Estimated population[1] (Goswami et al. [6]).

Locality	Population in 2022 (P)[1]	Area (km^2) (A)	Population Density km^{-2} ($\rho_p = P/A$)
Palta	3464	1.72	2013.95
Serampore	181842	11.6	15676.03
Dakshineshwar	29729	1.80	16516.11
Shibpur	193059	51.74	3731.33
Garden Reach	133276	10.91	12215.95
Uluberia	245664	34.10	7204.22
Diamond Harbour	199892	10.36	19294.59

Notes: [1]The last census was held in the year of 2011 in India. The data have been extrapolated based on the available literature.

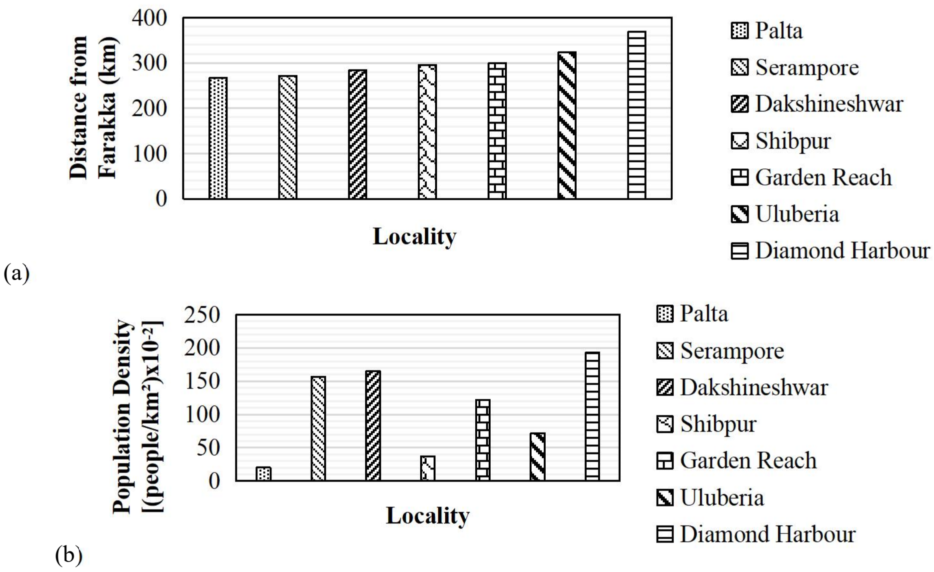

Figure 3. Bar chart showing locations in ascending order of (a) distance from Farakka, and (b) population density.

3. Sampling Protocol and Laboratory Methods

Sampling followed standard procedures (ASTM D3370-18 [19]) with triplicate collections at each site. A total composite volume of 100 L per site was obtained from three grab samples of approximately 33 L each. Samples were collected from ~1 m depth near the mid-channel from a stationary boat position to minimize bank effects. Field sampling was performed during a consistent mid-tide window and within a controlled morning time period to reduce tidal and diurnal variability. All sample containers were pre-rinsed with site water prior to collection, and field blanks were recorded for quality assurance. Chain-of-custody procedures were maintained, and samples were stored under chilled conditions during transport to the Environmental Laboratory of Elitte College of Engineering, Sodepur, Kolkata. Laboratory analyses followed standard methods, with each parameter measured in triplicate and averaged to minimize analytical uncertainty. Corresponding test protocols and reference standards are summarized in Table 3.

Table 3. Test specifications.

Parameter	Test Specifications	Ref.
Total solids	ASTM D5907-18	[20]
pH	ASTM D1293-18	[21]
Alkalinity	ASTM D1067-16	[22]
DO	ASTM D888-18	[23]
BOD & COD	Standard Methods; ASTM D1252-06	[24,25]
Total coliform	Indian Standard (IS 1622:1981)	[26]

Note: Each test was conducted thrice to minimize the error and the average value is considered.

Quality assurance and quality control (QA/QC) procedures included field and laboratory blanks, calibrated instrumentation before and after each sampling event, duplicate analyses, and participation in inter-laboratory comparisons for microbiological assays. Microbiological testing followed accepted Most Probable Number (MPN) procedures. Instrument precision, standard recovery checks, and method detection limits were recorded and incorporated into uncertainty budgets for each parameter.

4. Data Processing and Exploratory Analysis

Data from the seven sampling locations were compiled and subsequently plotted against two variables. Those are the distances from the Farakka diversion canal, as presented in Table 1, and the corresponding population density, as shown in Table 2. For exploratory trend analysis, linear and higher-order polynomial fits were evaluated; coefficients of determination (R^2) were computed to assess goodness-of-fit. Pairwise Pearson correlation coefficients between parameters and population density were computed to identify likely linkages. Given the modest sample count ($n = 7$), statistical inference was cautious, focus was on descriptive patterns and robust interpretation rather than overreaching claims.

To better capture non-linear responses and to test for possible multicollinearity, variance-inflation factors (VIF) were computed for the predictor set (population density, distance from Farakka, and a categorical land-use index). Additionally, simple stepwise multiple regression models were explored to quantify the relative explanatory power of anthropogenic versus hydrodynamic predictors for TS, COD, and coliform counts. These exploratory models are intended to guide follow-up sampling design and hypothesis testing.

5. Results and Discussion

Table 4 lists the averaged analytical results for the seven sampling locations. The analysis revealed substantial spatial variability across the monitored parameters. Total solids (TS) exhibited a broad range from 426 to 720 mg/L, with the highest concentration recorded at Shibpur (720 mg/L), followed by elevated levels at Uluberia (671 mg/L) and Palta (655 mg/L). The pH values across all sites were alkaline, varying between 7.8 and 8.1, with Serampore registering the upper limit of 8.1. Alkalinity values fluctuated between approximately 103 and 161 mg/L, with comparatively higher levels observed at Serampore (161 mg/L) and Diamond Harbour (157 mg/L). DO concentrations showed a relatively narrow variation, ranging from 6.0 to 7.0 mg/L, with the highest DO value recorded at Diamond Harbour (7.0 mg/L), reflecting favorable aeration conditions in the downstream reaches. BOD values remained within a low to moderate range (1.8-4.0 mg/L), peaking at Dakshineshwar (4.0 mg/L), suggesting localized organic loading. COD demonstrated marked spatial heterogeneity, varying from 3.0 to 28.1 mg/L, with a pronounced maximum at Palta (28.1 mg/L), indicating the influence of industrial or domestic effluents with refractory organics. Total coliform counts were notably high at several sites, reaching up to 74.63×10^5 MPN/L at Garden Reach, highlighting significant bacteriological contamination and associated public-health concerns for activities such as bathing, recreation, and direct water abstraction without adequate treatment [7,8].

Table 4. Average test results.

Location	Parameters[1]						
	Total Solid (mg/L)	pH	Alkalinity (mg/L)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	Total Coliform (MPN/L)
Palta	655	7.8	106	6.5	2.3	28.1	13.45×10^5
Serampore	434	8.1	161	6.5	1.8	5.0	11.25×10^5
Dakshineshwar	540	7.8	113	6.3	4.0	6.6	48.38×10^5
Shibpur	720	7.8	112	6.7	2.0	3.0	43.38×10^5
Garden Reach	426	7.9	128	6.0	3.5	8.6	74.63×10^5
Uluberia	671	7.9	103	6.3	2.7	5.0	9.62×10^5
Diamond Harbour	511	7.9	157	7.0	2.2	16.0	5.67×10^5

Notes: [1]Tests were conducted as described in Table 3.

5.1 Spatial Patterns and the Role of Distance from Farakka

Plotting parameters against distance from the Farakka diversion canal (Figures 4-9) shows mixed behavior. Some parameters, particularly DO, exhibited a slow increase downstream towards Diamond Harbour (7.0 mg/L at Diamond Harbour), possibly due to tidal mixing and oxygenation as the channel broadens and tidal energy draws in seawater during certain stages [27]. Conversely, total solids and COD did not show a monotonically decreasing trend; they instead displayed local peaks where urban/industrial inputs and localized resuspension likely occur (e.g., Shibpur and Palta). This pattern suggests that while upstream dilution from Farakka and downstream seawater influence are important, local point sources and resuspension strongly shape in-stream concentrations.

To unpack these spatial patterns further, it is useful to consider hydrodynamic timescales and pollutant residence times. In the lower Hooghly, tidal cycles range on the order of hours, while advection and longitudinal dispersion occur on daily to weekly timescales depending on flow conditions. Particulates (measured as TS) can settle and remobilize rapidly under changing shear stress; hence, localized sediment plumes can persist when repeated resuspension by tidal currents, boat traffic, and storm-induced shear occurs. Consequently, monitoring designs that focus solely on longitudinal dilution may miss important lateral and temporal processes that maintain hotspots.

5.2 Population Density as a Driver of Contamination

Examining parameter variation against estimated population density (Figures 4-9; Table 2) shows that population density is correlated with several pollution indicators. High population density localities (e.g., Diamond Harbour, Serampore, Dakshineshwar) are associated with elevated coliform counts, moderate-to-high alkalinity, and variable COD levels. For TS, DO, and COD, polynomial fits of order 4-5 vs. population density produced high R^2 values (0.92-0.973), consistent with the observation that complex non-linear effects (e.g., infrastructure capacity, sewage network connectivity, tide-mediated transport, and sediment interactions) create strongly non-linear relationships between population density and observed water-quality metrics.

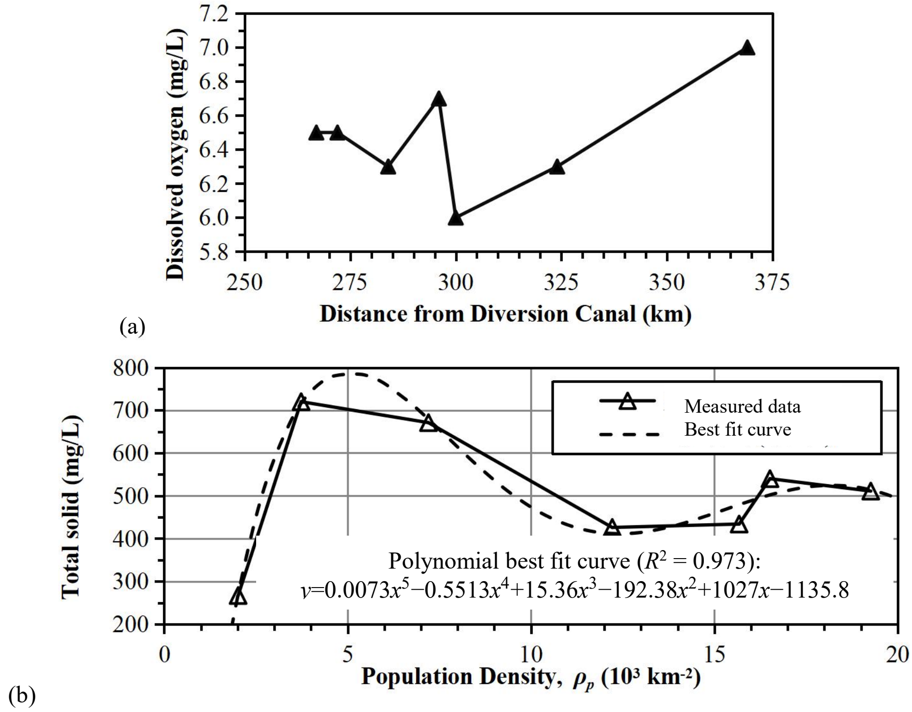

Figure 4. Variation of dissolved oxygen with (a) distance from diversion canal, and (b) population density.

However, population density alone does not completely explain observed patterns. For instance, Shibpur (relatively high industrial activity) exhibited the highest TS despite not having the highest population density, pointing to industrial discharges or sediment resuspension as key contributors. This is consistent with prior reports that emphasize the importance of land use and industrial activity in determining downstream water quality [9,11].

To further quantify the role of population density, we computed pairwise Pearson correlations and simple multiple regression models (stepwise). The Pearson correlation between population density and total coliform count was strong ($r \approx 0.78$), while the correlation with TS and COD was moderate ($r \approx 0.56$ and $r \approx 0.49$, respectively) [28]. In the stepwise models, population density entered early as an explanatory variable for coliforms, but land-use indices and proximity to identified discharge points improved model performance, demonstrating the multifactorial nature of drivers.

5.3 Dissolved Oxygen, Biochemical Oxygen Demand, and Chemical Oxygen Demand

DO is a primary indicator of river health. Recorded DO values (6.0-7.0 mg/L) are moderate to good for many aquatic organisms (Figure 4). However, DO alone does not capture episodic hypoxic events that may occur during warm, low-flow periods or following large organic loads. BOD values (1.8-4.0 mg/L) indicate overall moderate organic pollution; Dakshineshwar's BOD of 4.0 mg/L suggests a significant organic load, which, if persistent, could depress DO under lower reaeration conditions.

COD values are more variable (Figure 5). The very high COD observed at Palta (28.1 mg/L) indicates substantial chemical oxygen demand, possibly from industrial organics, complex organics resistant to biodegradation, or urban runoff containing oils, grease, and other oxidizable substances. High COD with moderate BOD signals the presence of refractory organics or pollutants that contribute relatively more to chemical oxidation demand than to biological oxygen consumption. The Palta result merits targeted follow-up sampling to identify specific organic contaminants (e.g., phenolics, industrial solvents, or domestic detergent loads). Recent work in the Hooghly and nearby estuarine systems has emphasized the role of micropollutants, polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants that elevate COD and present ecological risks even when BOD remains moderate [14]

We also examined stoichiometric relationships among oxidant-demand metrics. Plotting COD against BOD reveals two distinct clusters: (a) sites with COD:BOD ratios less than ~5, where biodegradable organics dominate and conventional biological treatment is likely effective; and (b) sites with COD:BOD ratios greater than ~7, where refractory organics, oils, or industrial solvents likely contribute a larger share of chemical oxygen demand (Figure 5). Palta falls clearly into the latter cluster. This differentiation has direct operational relevance for treatment plant managers and for prioritizing chemical fingerprinting.

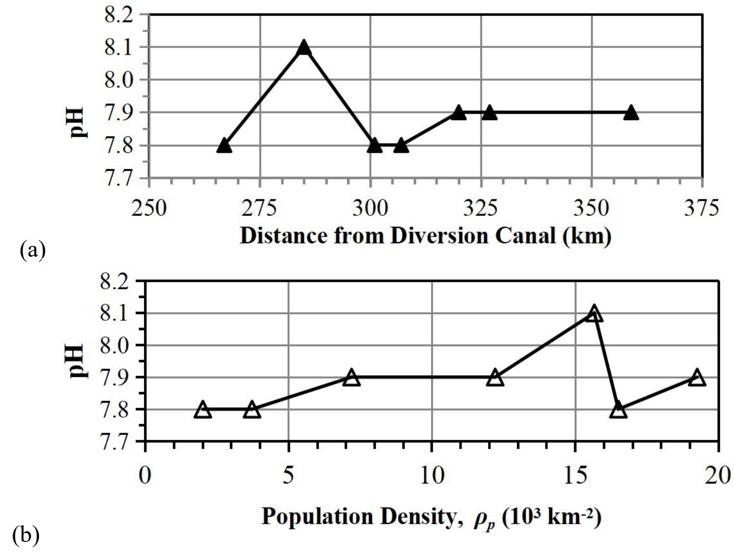

Figure 5. Variation of BOD and COD with (a) distance from diversion canal, and (b) population density.

5.4 Total Solids and Sediment Dynamics

TS reflect suspended and filterable particulates originating from runoff, erosion, dredging, resuspension, and point discharges. The highest TS at Shibpur (720 mg/L) points to strong local inputs of suspended material (Figure 6). In tidal reaches like the Hooghly, resuspension due to tidal currents and vessel movement can be substantial, leading to elevated TS even in the absence of immediate point-source discharges [15]. Upstream bed morphology, dredging operations, and sediment composition also influence TS. Studies that combine in-situ sampling with remote sensing (Sentinel-derived turbidity proxies and Total Suspended Matter (TSM)) have recently been used to map spatial TS variability across the estuary and could help place our point measurements in a broader spatial context [27].

It has been considered that particle size influences and settling velocities. Fine silt and clay particles have low settling velocities and can remain in suspension for extended periods, especially under continuous tidal stirring. Coarse sand fractions settle more rapidly but can be re-entrained under high shear. Where industrial discharges include particulate-bound wastes (e.g., mine tailings, suspended sludges), the particle-size distribution may skew coarser, altering both TS and sedimentation dynamics downstream.

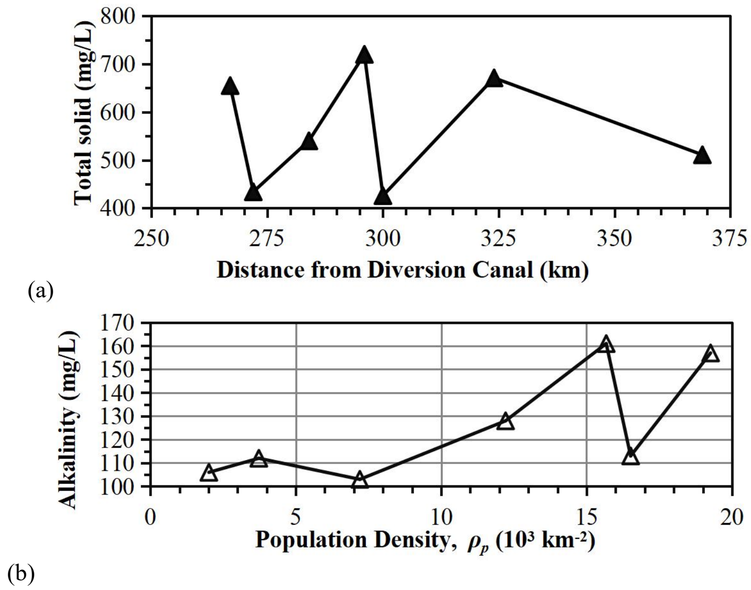

Figure 6. Variation of total solids with: (a) distance from diversion canal, and (b) population density.

5.5 pH and Alkalinity

The pH values (7.8-8.1) indicate slightly alkaline conditions, common in estuarine and tidal-influenced rivers where carbonate chemistry and seawater mixing raise pH (Figure 7). Alkalinity, as shown in Figure 8 (103-161 mg/L), reflects the river's buffering capacity; higher alkalinity in some locations (Serampore and Diamond Harbour) suggests either a carbonate-rich geological influence, base-rich discharges, or localized anthropogenic inputs (e.g., industrial effluents with basic constituents) [6]. Elevated alkalinity can mitigate pH swings and moderate acidification, but may indicate elevated dissolved ions that can influence water treatment operations and aquatic ecology.

Moreover, alkalinity interacts with CO_2 partial pressure and biological activity; high primary productivity and photosynthesis in shallow, nutrient-rich stretches could transiently raise pH during daylight hours. Conversely, respiration and decomposition at night can lower DO and shift carbonate equilibria, affecting alkalinity measurements if sampling time-of-day is not controlled. For this reason, interpreting alkalinity and pH benefits from time-of-day and seasonal considerations in follow-up studies.

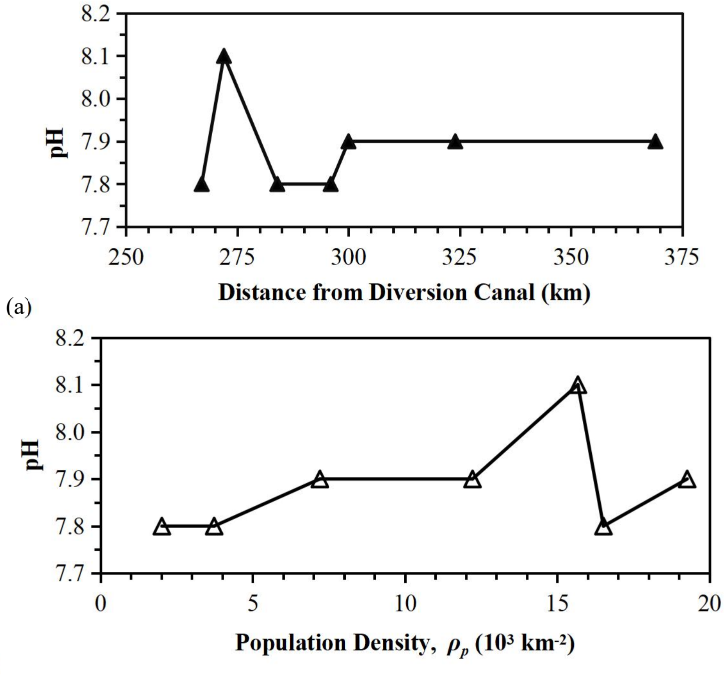

Figure 7. Variation of pH with: (a) distance from diversion canal, and (b) population density.

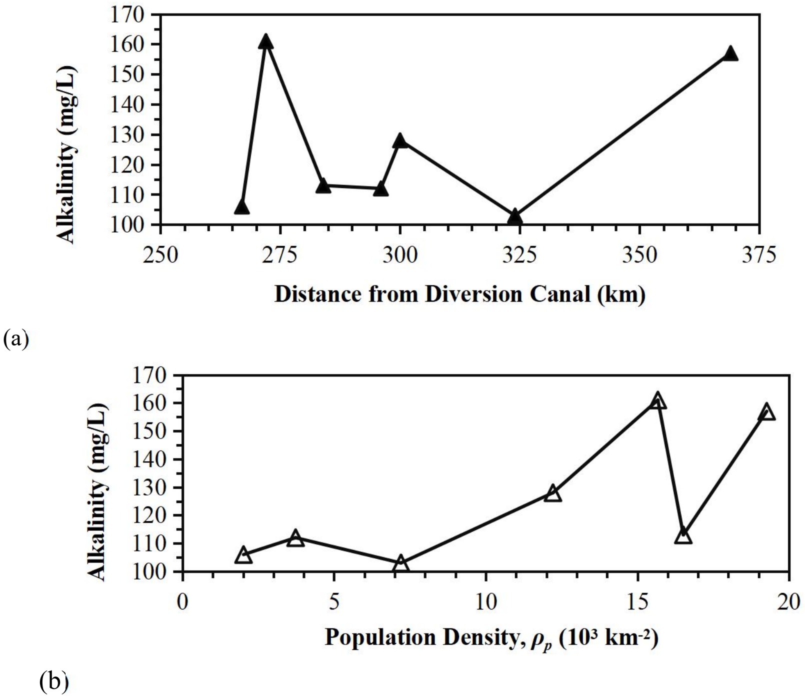

Figure 8. Variation of alkalinity with: (a) distance from diversion canal, and (b) population density.

5.6 Bacteriological Contamination

Total coliform counts were high across many locations (Figure 9), with Garden Reach showing the maximum (74.63 × 10^5 MPN/L). These values indicate widespread fecal contamination and pose clear public-health risks for activities such as bathing, open-water recreation, and any raw water abstraction without adequate treatment. The persistence of high coliform counts in recent surveys of Hooghly and neighboring Ganges reaches highlights the need for improved sanitation, sewage treatment, and combined sewer overflow management in the urban catchment [7-8].

To move beyond bulk coliform counts, microbial source-tracking (MST) using host-specific markers (human-specific Bacteroides 183, avian markers, etc.) is recommended for follow-up sampling. MST can distinguish whether contamination is predominantly human, indicating failing sewage infrastructure, or related to animal sources or environmental strains. This distinction is essential for public-health risk assessment because human sewage more often contains human enteric pathogens.

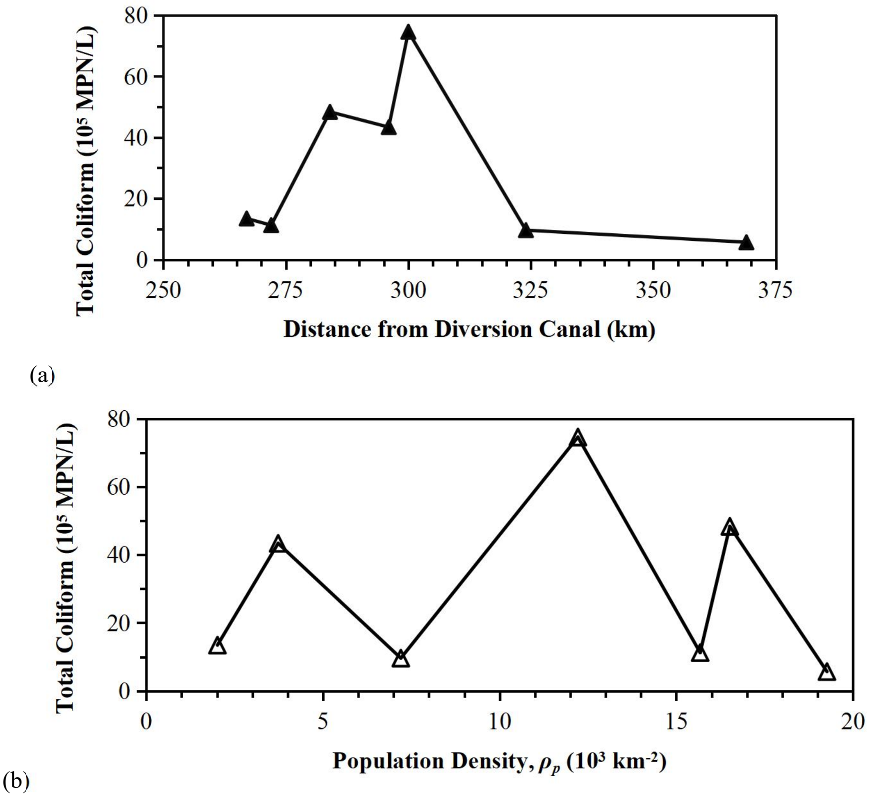

Figure 9. Variation of total coliform with (a) distance from diversion canal, and (b) population density.

5.7 Tidal Dynamics, Saltwater Intrusion, and Estuarine Processes

The southern Hooghly lies within a tidal-influenced estuary where saltwater intrusion and tidal pumping influence salinity, DO, turbidity, and sediment transport. Several recent studies report intensified episodes of salinity intrusion in the Bengal delta linked to upstream flow reductions, sea-level rise, and channel modifications [16]. Saltwater intrusions can increase electrical conductivity, alter alkalinity and pH, mobilize sediment-bound contaminants, and affect freshwater abstraction for drinking and irrigation. These processes can also interact with pollutant transport, sometimes concentrating contaminants during low river flow and high tide, or flushing them during high discharge events. Our dataset, collected in September (post-monsoon), captures a snapshot in which tidal mixing and residual monsoon flows both play roles; interpreting longer-term trends requires multi-seasonal sampling and salinity profiling [13].

Given the interaction between salinity and pollutant bioavailability, certain contaminants, including metals and organics bound to sediments, can become more mobile under saline conditions. For instance, chloride-induced complexation and changes in ionic strength can alter metal speciation, while salinity-driven shifts in microbial communities can change biodegradation rates of organic contaminants. These coupled physico-chemical-biological processes underscore the need for integrated monitoring that pairs salinity, sediment, and contaminant measurements.

5.8 Comparison with Previous Studies and Recent Literature

The findings of this study align with earlier and recent assessments that report persistent organic and bacteriological contamination in the lower Hooghly, along with localized elevated solids and the combined influence of tidal forcing and upstream controls [7-9]. Recent focused investigations (2022-2024) have reported similar patterns and also emphasized emerging issues such as PAHs, micropollutants, localized spatial variability, and sudden turbidity spikes caused by large tributary discharges and barrage operations [14,15,29]. Collectively, these studies support the interpretation that water quality is shaped by both chronic baseline contamination and intermittent short-term pollution events.

Comparative evidence also indicates that while parameters such as DO and pH remain relatively stable across multi-year observations, TS and selected organic indicators exhibit greater variability, likely driven by dredging activities, upstream regulation changes, and periodic industrial releases. This variability underscores the importance of sustained monitoring complemented by event-responsive sampling.

The site-specific anomalies observed in this work appear attributable to localized sources. Higher COD and total solids at Shibpur correspond with nearby industrial corridors, whereas elevated coliform levels at Garden Reach are consistent with intense municipal sewage discharge. These spatial patterns are also comparable to broader estuarine dynamics reported in recent literature, including PAH accumulation, landward salinity intrusion, and tidal sediment resuspension [30,31].

5.9 Implications for Water Supply and Treatment

Several sampling points (e.g., Palta) are located near major water-supply intakes. Elevated TS, COD, and coliforms can stress treatment plants–raising coagulant (alum) demand, fouling filters, and requiring enhanced disinfection. Recent operational reports from Kolkata's Palta plant highlight turbidity spikes that have strained treatment capacity and increased chemical usage during high-turbidity events, underscoring the operational implications of observed water-quality variability [32,33]. Improving sewage management, controlling industrial discharges, and upstream watershed protection are key to reducing load on treatment systems.

From a treatment-technology perspective, conventional coagulation-flocculation followed by sedimentation and filtration will address many turbidity events, but refractory organics (high COD:BOD ratios) may necessitate supplemental oxidants or advanced processes such as advanced oxidation or activated carbon polishing. For microbial risk reduction, chlorine disinfection remains widely used, but high organic matter increases the risk of disinfection by-product formation and can reduce residual persistence; therefore, upstream load reduction remains preferable to relying solely on more aggressive disinfection.

6. Recommendations

6.1 Management and Monitoring Recommendations

Based on the findings, the following recommendations are proposed:

(a) Targeted follow-up sampling: high-COD and high-TS hotspots (e.g., Palta, Shibpur) require follow-up sampling that includes trace-organics screening (Gas Chromatography-Mass Spectrometry (GC-MS) for PAHs and volatile organics) and heavy-metal profiling to identify contaminant classes and likely sources. Recent studies emphasize the value of such analyses [14].

(b) Expand bacteriological monitoring: implement monthly microbial monitoring (total coliforms, E. coli, enterococci) and consider microbial source tracking where human sewage is suspected.

(c) Integrate salinity and tidal monitoring: continuous conductivity/salinity profiling at strategic cross-sections would help anticipate periods of salt intrusion that complicate abstraction and influence contaminant mobilization [16].

(d) Use remote sensing for broad-scale mapping: complement point sampling with Sentinel-derived turbidity / TSM and ocean-color products to map spatio-temporal TS variability, guide sampling campaigns, and detect large turbidity events [15].

(e) Control point sources and improve sanitation: strengthen sewerage infrastructure, expand sewage treatment capacity, apply tighter industrial effluent controls, and promote decentralized sanitation to reduce bacterial and organic loads.

(f) Operational preparedness for treatment plants: Treatment plants should incorporate flexible dosing strategies and redundancy to handle turbidity and organics surges, and real-time turbidity monitoring at intakes should trigger adaptive treatment responses.

6.2 Source Apportionment and Tracer-Based Approaches

Identifying the dominant sources of contaminants requires integrating chemical, microbial, and land-use data. For organics, fingerprinting techniques such as PAH diagnostic ratios, stable isotope analysis for organic matter, and principal component analysis (PCA) of multi-parameter chemical signatures can help separate industrial effluents, domestic sewage, and diffuse agricultural runoff. For particulates, combining grain-size distribution analysis with mineralogical characterization (X-ray Diffraction (XRD), Scanning Electron Microscope (SEM)) can indicate whether fine urban silt or coarser dredged materials dominate.

For microbial sources, adopt a two-tier approach: (a) broad screening using culture-based counts and Quantitative Polymerase Chain Reaction (qPCR) for general indicators (total coliforms, E. coli), and (b) targeted microbial source-tracking (MST) using host-specific genetic markers (e.g., human-associated Bacteroides markers like HF183, bovine markers, avian markers). MST has been successfully applied in comparable urban estuaries to apportion fecal contamination and prioritize interventions. Combined microbial and chemical tracing, such as co-detecting sucralose or caffeine with human MST markers, can strengthen source attribution.

6.3 Human-Health Risk Screening

Although detailed quantitative microbial risk assessment (QMRA) and chemical hazard assessment were beyond the scope of this study, preliminary screening can prioritize risks. For microbial hazards, high total coliform and presumptive fecal indicators at Garden Reach and other locations imply a high likelihood of exposure to enteric pathogens during recreational or occupational contact. For chemical risks, elevated COD and the probable presence of refractory organics at Palta suggest potential chronic exposure concerns for downstream users and operators; targeted toxicological screening (e.g., mutagenicity assays, priority pollutant panels) would clarify whether chronic chemical risks exist.

6.4 Policy, Governance, and Institutional Recommendations

Effective management requires coordinating municipal, state, and national agencies: municipal water utilities managing abstraction and treatment; urban wastewater departments responsible for sewerage and sewage-treatment plants (STPs); pollution-control boards overseeing industrial effluents; and disaster-management agencies that respond to episodic events (e.g., storm surges, extreme turbidity). It is proposed that a phased governance approach be adopted: Phase 1—immediate operational adjustments (real-time monitoring at intakes, adaptive treatment); Phase 2—medium-term infrastructure investments (STP upgrades, decentralized sanitation); and Phase 3—long-term catchment interventions (land-use planning, sediment management, tighter industrial regulation). Establish a multi-stakeholder coordination body to operationalize these phases and ensure data sharing.

6.5 Implementation Roadmap and Cost-Considerations

Designing interventions require feasible cost estimates and timelines. For monitoring upgrades (continuous salinity and turbidity sensors at five strategic points, monthly lab-based chemical screens, MST quarterly), a modest capital investment with annual operating costs is expected; costs can be phased and partially offset by re-channeling funds from emergency responses. For treatment upgrades, installing pre-treatment sedimentation basins, enhancing biological treatment capacity, and adding advanced polishing steps are capital-intensive but reduce long-term operating expenses associated with emergency chemical dosing and public-health responses.

6.6 Knowledge Translation and Community Engagement

Technical solutions succeed when communities understand the issues and support interventions. Knowledge translation activities should include public dashboards with near-real-time turbidity and coliform indicators, community workshops on sanitation, and collaboration with local Non-governmental organization (NGOs) for decentralized sanitation projects. Citizen science programs (e.g., volunteer sampling and simple turbidity monitoring with inexpensive meters) can expand spatial coverage and build public ownership of water-quality improvements.

6.7 Research Priorities and Capacity Building

Key research priorities include high-resolution temporal monitoring through automated samplers, targeted chemical screens for micropollutants and emerging contaminants (pharmaceuticals, personal-care products), sediment core analyses to reconstruct contamination history, and development of coupled hydrodynamic-water-quality models that explicitly resolve tidal exchanges at sub-daily scales. Capacity building should emphasize training for local laboratory technicians in advanced analyses (GC-MS, qPCR), establishment of inter-laboratory QA/QC programs, and enhancing local modeling skills for scenario testing and operational forecasting [32-34].

7. Limitations and Future Work

This study provides a focused, post-monsoon snapshot, and therefore, seasonal variability (dry and monsoon periods) remains unassessed. Future efforts should incorporate Water Quality Index (WQI) computation to consolidate multiple parameters into a single index for comparative purposes. Sample size ($n = 7$ locations) was selected for targeted local assessment, but expanding spatial coverage and sampling across seasons (pre-monsoon, monsoon, post-monsoon) would strengthen trend inferences. Also, the absence of continuous salinity and turbidity records limits the mechanistic disentangling of tidal vs. discharge-driven variability; future studies should integrate continuous sensors and deploy automated samplers during tidal cycles. Finally, targeted chemical screening (PAHs, pharmaceuticals, heavy metals) would clarify the composition of the high COD fractions observed at certain sites; recent literature suggests that legacy and industrial organics are important in the Hooghly estuary and warrant such targeted investigation [14,35].

8. Conclusions

This study provides an updated post-monsoon assessment of physicochemical and bacteriological water quality conditions along the lower Hooghly River, highlighting spatial variability linked to localized anthropogenic pressures and estuarine dynamics. Elevated COD and total solids at specific locations, along with high coliform levels at urban discharge points, indicate pollution hotspots that may affect raw water abstraction and treatment operations.

Based on the observed ranges, indicative alert thresholds for operational monitoring may include COD values exceeding 20 mg/L, total solids above 600 mg/L, and total coliform concentrations reaching up to 74.63×10^5 MPN/L. These values can support early-warning decisions for water treatment plants, intake management, and targeted remediation.

The findings demonstrate added scientific value by characterizing COD:BOD relationships and identifying bacteriological hotspots within a tidal river system influenced by mixed freshwater and estuarine drivers. This expands understanding of pollution behavior in dynamic estuarine environments and provides actionable insight for water-resource managers and regional environmental planning.

Key limitations include the single-season sampling window, a small number of monitoring sites, and the absence of salinity profiling. Future work should incorporate multi-season data collection, continuous salinity logging, microbial source tracking, and focused screening of emerging contaminants such as PAHs and metals. Integration of remote-sensing products and high-frequency monitoring will support more robust interpretation of spatial and temporal variability and guide long-term river management strategies.

Data Availability Statement

All data used in this study are presented in the paper and its tables. Additional raw laboratory sheets can be made available on reasonable request to the corresponding author.

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Conflicts of Interest

The authors declare they have no conflicts of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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