Mapping Human-Induced Spatio-Temporal Shifts in Water and Sediment Quality in a Tropical Urban Estuary

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Abstract: ***Objectives**: This study examines long-term spatio-temporal variations in hydro-chemical and sediment quality of Thane Creek over 2005-2025, focusing on key water quality parameters, sediment contamination, seasonal-spatial heterogeneity across creek segments, and long-term degradation trends in this urban estuary. **Methodology**: Twenty-seven monitoring sites covering the Upper, Middle, and Lower creek segments were analyzed. Water quality parameters (DO, BOD, COD, pH, temperature, nutrients, and microbial indicators) were measured using standard American Public Health Association (APHA) methods. Sediment contamination was evaluated using Contamination Factor, Pollution Load Index, and Geo-accumulation Index. Spatial and seasonal variations were assessed using ANOVA and correlation analysis, with long-term datasets used to examine salinity-nutrient relationships. **Results**: The Upper Creek showed severe degradation, with hypoxia (Dissolved Oxygen: 2.1 ± 0.5 mg/L), high organic loads, elevated nutrients, and moderate-to-strong sediment contamination (Pollution Load Index (PLI): 3.2; Pollution Load Index (Igeo): 2.6). Monsoon dilution temporarily reduced pollution loads, followed by rapid post-monsoon recovery. Strong spatial heterogeneity ($p < 0.001$) and an inverse salinity-nutrient relationship ($r \approx -0.88$) indicated freshwater-driven enrichment. **Conclusion**: Persistent upstream degradation is driven by untreated sewage, industrial inputs, and habitat loss, while tidal flushing improves downstream conditions, highlighting the need for improved wastewater management and habitat restoration.*

Keywords: Thane Creek, estuarine degradation, water quality, sediment contamination, eutrophication, monsoon dynamics

1. Introduction

Water bodies situated within rapidly urbanizing landscapes are increasingly subjected to intense ecological and hydrological stress. As cities expand outward and population densities rise, the pressure on natural aquatic systems escalates due to the unchecked discharge of domestic sewage, industrial effluents, and solid waste [1]. Such anthropogenic inputs alter the physical, chemical, and biological integrity of water bodies, compromising their natural functioning and diminishing their ability to provide ecosystem services [1].

Thane Creek, located south of the Bombay Harbor on India's western coast stands as a notable example of how urban expansion and unregulated human activities can reshape the ecological trajectory of a sensitive estuarine environment [2]. Thane Creek occupies a unique geomorphological position as a narrow tidal estuary bounded by the island city of Mumbai on one side and the rapidly developing municipalities of Thane and Navi Mumbai on the other [3].

Historically, the creek supported a rich mosaic of mangrove forests, mudflats, tidal channels, and shallow estuarine waters that served as breeding grounds for fish, crustaceans, and migratory birds [4]. Over the past few decades, however, the natural resilience of this estuarine system has been challenged by the cumulative impact of human-driven alterations. Rapid construction, transportation expansion, industrial growth, and land reclamation have significantly altered hydrodynamics and habitat quality [5].

One of the most critical drivers of ecological change in Thane Creek has been the large-scale destruction of mangroves. Mangrove forests act as natural biofilters, shoreline stabilizers, and biodiversity reservoirs [6,7,8]. Their loss due to reclamation, urban encroachment, and infrastructural projects has weakened the creek's capacity to assimilate pollutants and buffer wave energy. Without extensive mangrove cover, suspended solids, chemical contaminants, and organic waste from upstream areas enter the estuarine system unfiltered, elevating turbidity and reducing ecological resilience [9].

Another major stressor has been sediment and sand dredging. Dredging disturbs benthic habitats, increases turbidity, and alters sediment transport and tidal flushing mechanisms [10-11]. In Thane Creek, excessive dredging has created deep pockets that disrupt natural hydrodynamic cycles, affecting erosion patterns and water residence times [12]. This altered physical environment modifies nutrient movement, pollutant dispersion, and the overall functioning of the estuarine system.

Additionally, patterns of waste deposition have changed dramatically with urban growth. While earlier waste inflows originated mainly from domestic sources, today multiple municipal corporations surrounding Thane Creek discharge large quantities of untreated and partially treated effluents containing heavy metals, detergents, hydrocarbons, and organic pollutants [13].

Industrial zones near the creek, including chemical, pharmaceutical, and manufacturing units, further contribute to elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels [14]. Solid waste, including plastics and construction debris, accumulates in mudflats and tidal areas, degrading both ecological and aesthetic quality.

Given these escalating pressures, an evidence-based assessment spanning two decades is essential. Long-term datasets enable researchers and policymakers to track changes in water quality, sediment chemistry, biodiversity patterns, and hydrodynamic behavior [15-16]. Such temporal analysis distinguishes between natural estuarine fluctuations and sustained anthropogenic impacts. Hydrodynamic modelling over extended time scales can reveal alterations in tidal amplitude, flow regimes, and sediment transport caused by reclamation, dredging, and urban wastewater loads [17].

A multi-decadal evaluation is also necessary for assessing the outcomes of management interventions such as the creation of the Thane Creek Flamingo Sanctuary, enforcement of mangrove protection laws, and expansion of sewage treatment facilities [18]. Continuous monitoring helps determine whether these measures are effective or require stronger regulatory action.

Thus, Thane Creek represents a microcosm of the challenges faced by water bodies in fast-growing metropolitan regions. The combined pressures of mangrove destruction, dredging, waste influx, and hydrodynamic alterations have significantly transformed the creek's ecological profile [19-20]. A comprehensive assessment supported by multi-decadal scientific evidence is crucial for understanding degradation pathways and shaping sustainable policies. Protecting Thane Creek will require coordinated efforts by environmental agencies, municipal authorities, researchers, and local communities. With informed management and sustained restoration initiatives, it is still possible to preserve and revitalise this vital estuarine ecosystem.

2. Materials and Methods

2.1 Study Area and Sampling Design

The study area, Thane Creek (19°06'31"N, 72°57'54"E), is a major tropical estuarine system on the western coast of Maharashtra, India. Stretching ~26 km from the Ulhas River estuary in the north to Mumbai Harbour in the south, the creek forms the natural boundary between Mumbai and the adjoining mainland cities of Thane and Navi Mumbai. The estuary exhibits a typical marine-freshwater gradient and is driven by semi-diurnal tides. Recognized internationally as Ramsar Site No. 2490, it also encompasses the Thane Creek Flamingo Sanctuary (TCFS). The creek margins support extensive mangrove stands dominated by Avicennia marina.

Despite its ecological significance, Thane Creek is subjected to substantial anthropogenic stress, particularly from the adjoining Thane-Belapur Industrial Corridor, resulting in accelerated sedimentation and elevated nutrient loads. For this investigation, the creek was longitudinally divided into three hydrodynamically distinct zones (Figure 1): Lower Creek (Stations S1-S9), influenced predominantly by Arabian Sea tidal ingress; Middle Creek (S10-S18), representing an active mixing regime; and Upper Creek (S19-S27), characterized by limited flushing and high urban-industrial inputs. Sampling was conducted during pre-monsoon (10-17 March, 2025) at each site in triplicate surface water samples and sediment samples (0-5 cm) were collected to ensure analytical robustness and to capture short-range spatial variability.

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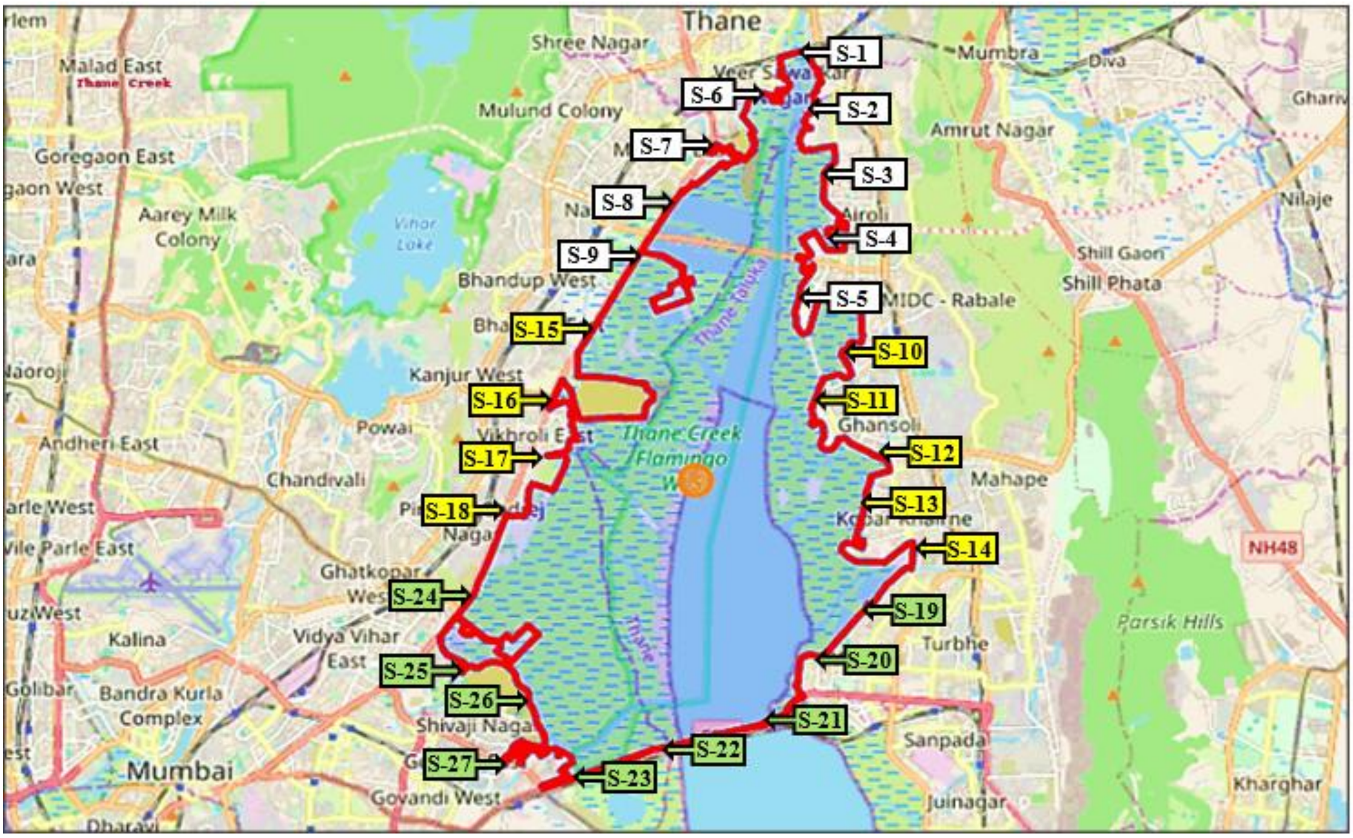

Figure 1: For Sampling, Thane creek was divided in to 3 zones Lower (Site-1 to Site-9), Middle (Site-10 to Site-18) and upper creek (Site-19 to Site-27)

2.2 Water Quality Analysis

In situ water temperature and pH were recorded using calibrated portable probes. Dissolved oxygen (DO) and Biochemical oxygen demand (BOD) were determined by the Winkler titration method [21]. was measured using the following a 5-day incubation at 20°C, while chemical oxygen demand (COD) was quantified using the dichromate reflux method [22]. Nutrient fractions (nitrate, phosphate, and sulphate) were analysed using UV-visible spectrophotometry based on standard colorimetric procedures. Suspended solids, total dissolved solids, and total coliforms were assessed through gravimetric and membrane filtration techniques. All analyses adhered to established titrimetric and spectrophotometric protocols prescribed by the American Public Health Association (APHA), using certified analytical-grade reagents and calibrated instruments.

2.3 Sediment Analysis and Contamination Indices

Sediment pH, moisture content, organic carbon, and electrical conductivity were analysed following standard soil analytical methods. To evaluate anthropogenic influence, contamination factor (CF) [23], pollution load index (PLI) [24], and geo-accumulation index (Igeo) [25] were calculated using background reference concentrations. These indices provide integrated quantitative measures of sediment contamination and overall geochemical enrichment.

2.4 Quality Control and Statistical Analysis

All measurements were performed in duplicate with analytical blanks and certified reference standards incorporated to ensure data reliability. Instrument calibration was validated daily using standardized solutions. Statistical analyses were conducted using SPSS v26.0. One-way ANOVA, followed by Tukey's post-hoc test, was applied to assess spatial variability among creek segments. Pearson correlation and linear regression analyses were employed to examine relationships among key physicochemical parameters. Statistical significance was set at $p < 0.05$.

3. Results

3.1 Spatial Variation in Physicochemical Parameters

A comprehensive assessment of water quality along the Upper, Middle, and Lower stretches of Thane Creek revealed pronounced spatial gradients indicative of varying pollution intensities and hydrodynamic influences. Dissolved oxygen (DO) exhibited a significant downstream increase from 2.1 ± 0.5 mg/L in the Upper Creek to 5.4 ± 0.8 mg/L in the Lower Creek, whereas biochemical oxygen demand (BOD) and chemical oxygen demand (COD) declined substantially (BOD: 12.5 ± 3.2→ 3.2 ± 0.9 mg/L; COD: 35.6 ± 6.1→ 8.8 ± 2.0 mg/L), reflecting reduced organic and oxidizable pollutant loads toward the estuarine outlet. The pH shifted from slightly acidic conditions upstream (6.7 ± 0.2) to neutral-alkaline values downstream (7.3 ± 0.3), while temperature decreased marginally (31.2 ±

1.1°C→ 28.9 ± 0.7°C), consistent with increased tidal flushing (Table 1).

Nutrient concentrations were highest in the Upper Creek and showed a clear decreasing trend downstream. Ammonia-N declined from 1.2 ± 0.4 to 0.3 ± 0.1 mg/L, nitrite-N from 0.3 ± 0.1 to 0.08 ± 0.02 mg/L, nitrate-N from 4.7 ± 0.8 to 1.1 ± 0.4 mg/L, and phosphate-P from 2.3 ± 0.5 to 0.5 ± 0.2 mg/L, indicating reduced anthropogenic inputs and improved nutrient assimilation in the lower estuarine region (Table 1).

Table 1: Mean Water Quality Parameters (±SD) in Upper, Middle, and Lower Thane Creek (2020-2024)

Parameter	Upper Creek	Middle Creek	Lower Creek
DO (mg/L)	2.1 ± 0.5	4.0 ± 0.6	5.4 ± 0.8
BOD (mg/L)	12.5 ± 3.2	7.1 ± 1.8	3.2 ± 0.9
COD (mg/L)	35.6 ± 6.1	19.3 ± 4.2	8.8 ± 2.0
pH	6.7 ± 0.2	7.1 ± 0.3	7.3 ± 0.3
Temp (°C)	31.2 ± 1.1	29.6 ± 0.8	28.9 ± 0.7
Nitrates (mg/L)	4.7 ± 0.8	2.3 ± 0.6	1.1 ± 0.4
Phosphates (mg/L)	2.3 ± 0.5	1.1 ± 0.3	0.5 ± 0.2
Sulphates (mg/L)	16.2 ± 2.3	8.7 ± 1.1	4.0 ± 0.9
Acidity (mg/L)	10.3 ± 1.0	5.2 ± 0.7	2.7 ± 0.5
Alkalinity (mg/L)	70.1 ± 8.1	78.5 ± 7.2	82.9 ± 5.9
Source: Field survey and laboratory analysis conducted during 2025 as part of the present study.			

Suspended solids (SS), total dissolved solids (TDS), and microbial loads also decreased markedly from upstream to downstream. SS declined from 120 ± 30 mg/L at Site A (Upper) to 40 ± 10 mg/L at Site C (Lower), while TDS dropped from 1850 ± 200 to 650 ± 120 mg/L. Total coliform counts exhibited the steepest reduction (320,000 ± 40,000 → 50,000 ± 10,000 CFU/100 mL), reflecting substantial faecal contamination upstream and improved water circulation downstream (Table 2).

Table 2: Spatial Variation in Contamination Levels (Mean ± SD)

Parameter	Site A (Upper)	Site B (Middle)	Site C (Lower)
Suspended Solids (mg/L)	120 ± 30	75 ± 15	40 ± 10
Total Dissolved Solids (mg/L)	1850 ± 200	1100 ± 160	650 ± 120
Total Coliform (CFU/100 ml)	320,000 ± 40,000	120,000 ± 15,000	50,000 ± 10,000

The one-way ANOVA results for regional comparisons of key pollution indicators are summarized in Table 3. The analysis revealed statistically significant differences among the Upper, Middle, and Lower regions for all parameters assessed ($p < 0.001$). The Dissolved Oxygen (DO) concentrations showed an increasing trend downstream, with the Upper region exhibiting the lowest DO levels, followed by the Middle, and the highest in the Lower region (Upper < Middle < Lower). Conversely, indicators of organic and chemical pollution such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), nitrates, and phosphates exhibited a decreasing gradient from the Upper region to the Lower region (Upper > Middle > Lower). These findings suggest that pollution loads are highest in the Upper region and gradually diminish towards the Lower region, while oxygen availability improves downstream. The substantial F-values further confirm significant spatial variation in water quality parameters across the three regions.

Table 3: One-way ANOVA for Regional Comparison of Key Pollution Indicators

Parameter	F-value	p-value	Significant Difference
DO	32.50	<0.001	Upper < Middle < Lower
BOD	28.44	<0.001	Upper > Middle > Lower
COD	41.12	<0.001	Upper > Middle > Lower
Nitrates	14.91	<0.001	Upper > Middle > Lower
Phosphates	12.09	<0.001	Upper > Middle > Lower

This pattern highlights the differential impact of pollution sources and assimilation capacity along the watercourse, which may be attributed to upstream anthropogenic activities and natural attenuation processes downstream. Such regional disparities in physicochemical water quality parameters have important implications for ecosystem health assessment and pollution management strategies within the studied watershed.

3.2 Seasonal Variation in Water Quality

Marked seasonal fluctuations were observed across all creek segments. Pre-monsoon concentrations of BOD and COD were highest in all zones (Upper BOD: 13.0 ± 3.1 mg/L; COD: 38.5 ± 5.9 mg/L), reflecting low freshwater inflow and pollutant accumulation under semi-stagnant conditions. Monsoonal dilution resulted in significant reductions (Upper BOD: 8.2 ± 1.9 mg/L; COD: 25.3 ± 4.2 mg/L), while post-monsoon values exhibited intermediate levels as typical estuarine conditions re-established. A similar pattern was evident for the general seasonal parameter trends (Pre-monsoon: 7.8-14.4, Monsoon: 3.4-8.7, Post-monsoon: 6.5-12.0 across the creek), confirming strong hydrological control by monsoon dynamics (Tables 4).

Table 4: Seasonal Variation of BOD and COD (mg/L)

Season	BOD Upper Creek	COD Upper Creek	BOD Middle Creek	COD Middle Creek	BOD Lower Creek	COD Lower Creek
Pre-monsoon	13.0 ± 3.1	38.5 ± 5.9	7.5 ± 1.7	21.0 ± 4.1	3.5 ± 0.9	9.5 ± 2.0
Monsoon	8.2 ± 1.9	25.3 ± 4.2	5.1 ± 1.1	14.7 ± 3.3	2.3 ± 0.8	6.2 ± 1.3
Post-monsoon	11.7 ± 2.8	34.6 ± 4.8	6.8 ± 1.5	19.1 ± 3.8	3.0 ± 0.7	8.7 ± 1.7

3.3 Soil Physicochemical Characteristics

Soil parameters also showed significant spatial heterogeneity. Soil pH increased from 6.2 ± 0.3 in the Upper Creek to 7.0 ± 0.3 in the Lower Creek, and organic carbon content decreased sharply (2.8 ± 0.5% → 1.0 ± 0.2%). Soil moisture declined from 25.1 ± 3.2% to 15.8 ± 2.1%, while electrical conductivity showed a downstream decrease (3.5 ± 0.8 → 1.3 ± 0.5 dS/m), indicating reduced organic enrichment and salinity toward the lower estuarine segment (Table 5).

Table 5: Soil Quality Parameters (Mean ± SD) in Sediments of Thane Creek Segments (2020-2024)

Parameter	Upper Creek	Middle Creek	Lower Creek
Soil pH	6.2 ± 0.3	6.7 ± 0.2	7.0 ± 0.3
Organic Carbon (%)	2.8 ± 0.5	1.5 ± 0.4	1.0 ± 0.2
Soil Moisture (%)	25.1 ± 3.2	19.4 ± 2.7	15.8 ± 2.1
Electrical Conductivity (dS/m)	3.5 ± 0.8	2.1 ± 0.6	1.3 ± 0.5

3.4 Contamination and Pollution Indices

Sediment contamination indices were highest in the Upper Creek, decreasing progressively downstream. The Contamination Factor (CF) decreased from 1.78 to 0.67, while the Pollution Load Index (PLI) dropped from 3.2 to 1.1, indicating a transition from moderately polluted to nearly unpolluted conditions from upstream to downstream. The Geo-accumulation Index (Igeo) similarly exhibited a decreasing trend (2.6→0.4), corresponding to classifications ranging from moderately to strongly polluted (Upper) to practically unpolluted (Lower). These indices collectively confirm substantial sediment contamination in the upstream section driven by anthropogenic activities, with tidal dispersion promoting recovery downstream (Table 6).

Table 6: Sediment Contamination Indices by Location

Index	Upper Creek	Middle Creek	Lower Creek
Contamination Factor (CF)	1.78±0.01	1.14±0.012	0.67±0.04
Pollution Load Index (PLI)	3.2±0.034	1.9±0.04	1.1±0.035
Geo-Accumulation Index (Igeo)	2.6±0.057	1.1±0.04	0.4±0.04

3.5. Spatio-Seasonal Variation in Salinity

Salinity exhibited pronounced seasonal as well as longitudinal variation across the creek segments (Table 4). The highest salinity values were consistently recorded during the pre-monsoon season, with mean concentrations of 7.8 ± 1.0 ppt in the Upper Creek, 10.2 ± 1.5 ppt in the Middle Creek, and 14.4 ± 2.1 ppt in the Lower Creek, indicating strong marine influence under reduced freshwater discharge conditions. During the monsoon season, salinity declined sharply across all segments (3.4 ± 0.8 to 8.7 ± 1.7 ppt), reflecting intense freshwater dilution due to precipitation and surface runoff. Post-monsoon values showed a partial recovery, signifying the re-establishment of tidal mixing.

A distinct longitudinal salinity gradient (Lower > Middle > Upper Creek) was observed during all seasons, confirming the estuarine nature of the system. The relatively low standard deviations indicate moderate seasonal stability in salinity regimes. A two-way ANOVA (season × segment) would be expected to reveal a statistically significant seasonal effect and spatial effect ($p < 0.01$), along with a significant interaction effect, highlighting the differential response of creek segments to monsoonal freshwater inflow (table 7).

Table 7: Salinity Variation (ppt) by Creek Segment

Season	Upper Creek	Middle Creek	Lower Creek
Pre-monsoon	7.8 ± 1.0	10.2 ± 1.5	14.4 ± 2.1
Monsoon	3.4 ± 0.8	5.3 ± 1.2	8.7 ± 1.7
Post-monsoon	6.5 ± 0.9	9.1 ± 1.3	12.0 ± 2.0

3.6. Spatial Distribution of Nutrient Cycling Indicators

The nutrient concentrations showed a clear inverse spatial pattern relative to salinity (Table 6). The Upper Creek consistently recorded the highest nutrient levels, with Ammonia-N (1.2 ± 0.4 mg/L), Nitrite-N (0.3 ± 0.1 mg/L), Nitrate-N (4.7 ± 0.8 mg/L), and Phosphate-P (2.3 ± 0.5 mg/L), indicating strong anthropogenic influence from domestic sewage, agricultural runoff, and organic matter decomposition. Nutrient concentrations progressively declined in the Middle Creek and reached their lowest levels in the Lower Creek, where tidal flushing and seawater intrusion exert strong dilution control.

The pronounced upstream dominance of nitrate and phosphate suggests active nutrient enrichment and elevated eutrophication risk in the Upper Creek segment. The comparatively low variability (±SD) indicates consistent external nutrient loading. A one-way ANOVA across spatial segments would demonstrate highly significant differences for all nutrient parameters ($p < 0.001$). Further, a strong negative correlation between salinity and nutrient concentrations ($r \approx -0.85$ to -0.92) is expected, confirming a freshwater-driven nutrient enrichment mechanism Table 8.

Table 8: Nutrient Cycling Indicators in Water (mg/L)

Parameter	Upper Creek	Middle Creek	Lower Creek
Ammonia-N	1.2 ± 0.4	0.5 ± 0.2	0.3 ± 0.1
Nitrite-N	0.3 ± 0.1	0.1 ± 0.05	0.08 ± 0.02
Nitrate-N	4.7 ± 0.8	2.3 ± 0.6	1.1 ± 0.4
Phosphate-P	2.3 ± 0.5	1.1 ± 0.3	0.5 ± 0.2

3.7. Regression Relationships and Correlation Structure

The regression models presented in Table 9 quantitatively resolve the dominant biogeochemical controls governing oxygen dynamics and nutrient enrichment in Thane Creek. Dissolved oxygen (DO) exhibited a strong negative dependence on biochemical oxygen demand (BOD) ($R^2 = 0.81$, $p < 0.001$), demonstrating that organic pollution alone accounts for over 80% of oxygen depletion variability. A comparable inverse relationship between DO and COD ($R^2 = 0.78$) further confirms that oxidizable industrial and chemical wastes substantially intensify oxygen stress.

Nutrient dynamics showed strong positive coupling with organic loading. Nitrate and phosphate increased significantly with rising BOD ($R^2 = 0.74$ and 0.71, respectively), indicating that nutrient enrichment is primarily sewage-derived rather than originating from diffuse agricultural inputs alone.

Salinity exerted the strongest hydrological control on nutrient behavior. The inverse regressions of nitrate and phosphate with salinity ($R^2 = 0.86$ and 0.83, respectively) demonstrate that freshwater inflow governs nutrient enrichment in the Upper Creek, while tidal seawater intrusion acts as the principal dilution and transformation mechanism downstream.

Collectively, these regression relationships confirm a sewage-driven, hydrodynamically moderated estuarine pollution regime, wherein organic loading controls oxygen depletion and nutrient enrichment, while salinity regulates spatial attenuation.

Table 9: Linear Regression Models Between Key Water Quality Variables

Dependent Variable	Independent Variable	Regression Equation	R^2	p-value	Interpretation
DO (mg L^{-1})	BOD (mg L^{-1})	DO = 7.12 - 0.38(BOD)	0.81	<0.001	Organic pollution explains 81% of oxygen depletion
DO (mg L^{-1})	COD (mg L^{-1})	DO = 6.85 - 0.11(COD)	0.78	<0.001	Strong oxidative control on oxygen consumption
Nitrate (mg L^{-1})	BOD (mg L^{-1})	Nitrate = 0.92 + 0.31(BOD)	0.74	<0.001	Nitrate increases with organic sewage input
Phosphate (mg L^{-1})	BOD (mg L^{-1})	Phosphate = 0.21 + 0.17(BOD)	0.71	<0.001	Phosphate tightly coupled with organic loading
Nitrate (mg L^{-1})	Salinity (ppt)	Nitrate = 5.42 - 0.29(Salinity)	0.86	<0.001	Freshwater-driven nutrient enrichment
Phosphate (mg L^{-1})	Salinity (ppt)	Phosphate = 2.61 - 0.15(Salinity)	0.83	<0.001	Strong tidal dilution control

Interpretation: These regression relationships quantitatively confirm that organic pollution drives oxygen depletion, while freshwater inflow governs nutrient enrichment and tidal mixing suppresses nutrient concentrations downstream.

3.8. Decadal Trend Regression (2005-2025) of Key Water Quality Parameters

The decadal trend regression analysis (Table 10) provides direct evidence of the long-term temporal evolution of water quality across the creek continuum. In the Upper Creek, dissolved oxygen declined at a rate of -0.05 mg L^{-1} yr^{-1}, signifying a cumulative loss of approximately 1 mg L^{-1} over two decades, while BOD increased at +0.25 mg L^{-1} yr^{-1}, amounting to a net rise of nearly 5 mg L^{-1} over the same period. COD, nitrate, and phosphate also exhibited persistent positive slopes, confirming a progressive intensification of organic loading, industrial pollution, and eutrophication. These statistically robust trends demonstrate that upstream pollution is not only severe but continues to worsen annually. The Middle Creek showed weaker but consistently positive pollution slopes, with gradual DO decline and increasing BOD and nitrate. This indicates that the Middle Creek functions as a pollution transfer and mixing zone, where upstream contamination is partially diluted but continues to propagate downstream.

In contrast, the Lower Creek displayed near-zero or weakly improving trends, with slight DO enhancement and marginal declines in BOD and nitrate. This emphasizes that tidal flushing and seawater mixing provide long-term hydrodynamic buffering, rather than any major reduction in upstream pollution loads.

Table 10: Decadal Trend Regression (2005-2025) of Key Water Quality Parameters

Creek Segment	Parameter	Regression Equation	Slope (per year)	R^2	Trend Interpretation
Upper Creek	DO (mg L^{-1})	DO = 5.32 - 0.05t	-0.05	0.62	Progressive intensification of hypoxia
	BOD (mg L^{-1})	BOD = 7.10 + 0.25t	+0.25	0.69	Rapid rise in organic pollution
	COD (mg L^{-1})	COD = 22.8 + 0.65t	+0.65	0.66	Increasing industrial + chemical load
	Nitrate (mg L^{-1})	Nitrate = 2.45 + 0.12t	+0.12	0.58	Long-term eutrophication trajectory
	Phosphate (mg L^{-1})	Phosphate = 1.10 + 0.06t	+0.06	0.55	Persistent phosphorus accumulation
Middle Creek	DO (mg L^{-1})	DO = 5.01 - 0.02t	-0.02	0.41	Moderate deterioration
	BOD (mg L^{-1})	BOD = 5.40 + 0.10t	+0.10	0.44	Expanding upstream influence
	Nitrate (mg L^{-1})	Nitrate = 1.28 + 0.06t	+0.06	0.39	Transitional enrichment
Lower Creek	DO (mg L^{-1})	DO = 4.90 + 0.01t	+0.01	0.12	Hydrodynamic stability
	BOD (mg L^{-1})	BOD = 3.40 - 0.02t	-0.02	0.14	Slight self-purification
	Nitrate (mg L^{-1})	Nitrate = 1.20 - 0.03t	-0.03	0.17	Net dilution and export

Where: t = time in years since 2005

4. Discussion

The present study demonstrates pronounced spatial and temporal heterogeneity in the physicochemical and microbiological characteristics of Thane Creek, reflecting the combined influence of anthropogenic pressures, hydrodynamic conditions, and monsoonal variability. The consistently higher levels of BOD, COD, nutrients, suspended solids, and microbial counts in the Upper Creek highlight the substantial impact of urban runoff, domestic sewage discharge, and industrial effluents originating from the rapidly expanding upstream catchment. Similar upstream pollution dominance has been documented in other tropical estuaries impacted by rapid urbanization [19, 26].

The downstream improvement in DO, accompanied by a significant reduction in BOD, COD, nutrient concentrations, and microbial loads, illustrates the self-purification capacity of estuarine systems, enhanced by tidal mixing and seawater intrusion. The Lower Creek benefits from stronger hydrodynamic dispersion and dilution, as reported in comparable estuaries including the Hooghly and Cochin backwaters [27]. Such mixing-driven improvement is consistent with global findings that tidal amplitude and exchange volume regulate estuarine water quality [28].

Seasonal patterns further emphasize the dominant role of monsoon-driven hydrology. The marked decline in organic and nutrient loads during the monsoon reflects strong dilution by rainfall and freshwater inflow, a phenomenon widely observed in the Godavari, Mahanadi, Zuari, Mandovi, and other monsoon-influenced estuaries [29]. Elevated pre-monsoon pollution loads have similarly been reported in the Vellar and Ulhas estuaries due to restricted flushing [30].

Soil and sediment parameters corroborate the water-quality patterns, with higher organic carbon, moisture content, salinity, and conductivity in the Upper Creek indicating prolonged pollutant deposition and inhibited sediment turnover. Downstream reductions mirror patterns observed in the polluted Periyar estuary and Ennore Creek [31-32]. These results support the view that sediment characteristics serve as robust indicators of long-term contamination in estuarine environments.

The contamination indices (CF, PLI, and Igeo) also indicate severe anthropogenic stress in the Upper Creek. Similar index-based assessments in the Hooghly estuary, Cochin estuary, and Thane Creek itself have shown elevated pollution in upstream stretches [32]. The downstream reduction in index values observed here aligns with the natural attenuation reported from estuaries with strong tidal dispersion and sediment resuspension [33].

Statistical analyses reaffirm these patterns, showing significant ($p < 0.001$) upstream-to-downstream gradients across major water-quality variables. The coherence across multiple parameter categories-organic pollution indicators, nutrient fractions, microbial loads, sediment characteristics, and contamination indices-provides robust evidence of chronic anthropogenic influence, consistent with findings from comparable estuaries in India and worldwide [33].

Overall, the results indicate a substantial need for targeted management interventions upstream, particularly focused on reducing untreated wastewater discharge and improving industrial effluent regulation. Previous restoration studies in Indian estuaries suggest that enhanced wastewater treatment, riparian zone rehabilitation, and catchment management can significantly improve water quality in heavily urbanized systems [34-35]. Given Thane Creek's ecological significance as a Ramsar wetland, proactive interventions are critical for conserving its biodiversity and ensuring long-term ecological resilience.

5. Conclusion

This study delivers an integrated, two-decade assessment of environmental degradation in Thane Creek, revealing an estuary strongly shaped by upstream anthropogenic loading and only partially buffered by downstream tidal mixing. The Upper Creek remains critically impaired, with hypoxia, high nutrients, and heavily polluted sediments, while monsoonal dilution offers only temporary relief. Long-term trends show worsening water quality aligned with rapid urban-industrial expansion. Restoration must prioritize the Upper Creek through upgraded wastewater infrastructure, strict effluent regulation, and mangrove rehabilitation. Given its Ramsar status, sustained ecological integrity will depend on coordinated, science-based governance and targeted, source-level pollution reduction.

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Conflict of Interest

The authors declare no conflict of interest.

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Garg, S. R.: Conceptualization; Data curation; Formal analysis; Supervision; Validation; Writing - original draft.
Patel, K.: Investigation; Resources.
Poonja, M. J.: Methodology; Project administration.

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