

Monitoring and Managing Freshwater Ecosystems in the Face of Urbanization

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Abstract: Freshwater ecosystems are one of the most critically endangered ecological systems in the world due to increasing urbanization. Impervious surfaces, stormwater runoff, pollutants from industries, microplastics, and salinization are some factors introduced through urbanization and responsible for deteriorating the physicochemical stability and biodiversity of rivers, lakes, and wetlands. While addressing such an environmental issue becomes increasingly urgent, comprehensive frameworks linking real-time ecological monitoring and management are relatively nascent. This research aims to contribute to filling the gap regarding the management and monitoring of freshwater ecosystems by studying the Singanallur Lake system in Coimbatore, India a mid-sized Indian city undergoing rapid urbanization. Water quality parameters like dissolved oxygen (DO), biochemical oxygen demand (BOD), total dissolved solids (TDS), pH, turbidity, nitrate, and phosphate were evaluated across three sampling sites between June 2022 to May 2023. Bioindicators used for monitoring the lake's health include benthic macroinvertebrates and fish community indices. The results show spatial and temporal degradation gradients in physicochemical parameters where DO show a 38% reduction during monsoon flush events, while BOD exceeded permissible levels (>10 mg/L) at urban downstream sites. The Biotic Index demonstrated poor to fair water quality at 67% of sampled stations. Urbanization was found to account for 74% of the variation in the water quality index. These results show that there is an urgent need to develop integrated systems of monitoring that would include physical and biological aspects of water quality assessments. Several approaches to sustainable urban freshwater management are suggested.

Keywords: Freshwater Ecosystem; Urbanization; Water Quality Monitoring; Bioindicators; Adaptive Management; Riparian Buffer; Aquatic Biodiversity.

(Submitted: June 26, 2025; Revised: July 28, 2025; Accepted: August 18, 2025; Published: September 30, 2025)

I. Introduction

Freshwater ecosystems comprising rivers, streams, lakes, wetlands, and groundwater systems deliver valuable ecological functions that include water purification, flood control, biodiversity, and nutrient cycling. These vital functions are being severely challenged by the rising wave of urbanization that affects the hydrology of the area, pollution loads, and degradation of habitats (Hughes et al., 2014; Park & Hwang, 2016). Over 50% of the world's population lives in urban areas, and it is expected that more than 70% of people will be living in urban areas by 2050. It means more impervious surfaces and higher amounts of runoff, and thus pollution of nearby waterbodies (Poff, 2009; Matthews, 2016). All these challenges combine to degrade the physiochemical composition and biological communities of urban freshwaters, and it has been called the "freshwater biodiversity crisis" (Reid et al., 2019). Urban Stream Syndrome, freshwater salinization, harmful algal blooms, and microplastics accumulation have become prevalent in today's aquatic environment (Kaushal et al., 2021; Trottet et al., 2022).

Although these issues are increasingly recognized, major knowledge gaps still exist in how these data are translated into actionable management strategies (Hering et al., 2010; Craig et al., 2017). Conventional monitoring programs have predominantly employed physicochemical metrics but neglected the ecologically integrated data available through biological metrics like macroinvertebrate assemblages and fish community indices (Park & Hwang, 2016; Freeman et al., 2019). In addition, management actions in fast-growing cities of the developing world, where the stresses imposed by freshwaters coincide with institutional weaknesses, remain mostly reactive as opposed to proactive. The use of green infrastructures such as wetlands, permeable pavement, and riparian buffers has shown great potential in tackling urban freshwater's problems, although their implementation has been inconsistent (Wang et al., 2024; Nainwal,

2021). Hence, an urgent need exists for integrated monitoring-management frameworks that are context-appropriate and scientifically sound.

This current study will fill this gap by studying the Singanallur Lake ecosystem of Coimbatore, Tamil Nadu, India, which is a medium-sized but highly urbanized city suffering from serious stress for fresh water supply. The significance of this paper is that this paper will (i) investigate urban influence-induced changes in water quality using multi-parameter approach; (ii) apply biological indicator indices in order to assess ecological condition; and (iii) provide context-specific suggestions for lake management based on findings.

The organization of this paper will be as follows: After introduction, the literature will be reviewed in section 2, followed by methods in section 3, findings in section 4, discussion and management implication in section 5, and conclusion in section 6.

II. Literature Survey

Urbanization poses multi-faceted stresses on the freshwater systems via alteration of hydrology, physical and chemical pollution, as well as biological impacts. Hughes et al. (Hughes et al., 2014) noted the increasing stresses on urban waters caused by changes in impervious surfaces, nutrient enrichment, and thermal pollution, which require mitigatory actions geared towards future urbanization trends. Nilsson et al. (Nilsson et al., 2003) pointed out the ecological forecasting issues associated with the process of stream urbanization, indicating that scientists from fields of hydrology, ecology, and geomorphology will need to cooperate in order to foresee future negative impacts on streams. It can be considered that these pioneering works have demonstrated that the phenomenon of urbanization-caused freshwater systems degradation is not just a problem of local importance, but an ecological catastrophe of a global character.

There have been marked improvements in the approach to ecological monitoring of freshwater ecosystems since the last two decades, shifting from purely physicochemical approaches to combined biological monitoring. Park and Hwang (2016) put forward a general theory on the need for ecological monitoring in freshwater ecosystems, highlighting the importance of biological indicators like diatoms and macroinvertebrate indices for assessing ecosystem condition (Nainwal, 2021). Hering et al., (2010) took this understanding into account while investigating the effects of climate change on freshwater ecosystems, and found that multispecies ecological monitoring schemes had higher chances of detecting emerging threats compared to single-species schemes. Feio et al., (2024) added yet another dimension to this line of thought by introducing a system to combine remotely sensed data along with on-ground biological surveys in order to monitor urban aquatic ecosystems - a very important addition to monitoring methodologies indeed.

Consequences that come with inadequate monitoring and management of the freshwater biodiversity are dire, as evident by studies. For instance, Reid et al., (2019) have documented several emerging threats to the freshwater biodiversity, naming pollution, modification of habitat, modification of the flow of water, biological invasion, and overexploitation as the major threats. Another serious issue with global implications in freshwater biodiversity is the 'freshwater salinization syndrome' described by Kaushal et al., (2021) which is attributed to road salt applications, irrigated runoff, and wastewater discharge causing serious implications for the aquatic life and urban infrastructures. Freeman et al., (2019) showed that estuarine and freshwater systems in urbanized watersheds experience high nutrient loading, sedimentation, and hypoxic episodes that contribute to the suppression of biodiversity in such systems. Other emerging threats include chemical and plastic contamination of urban water as pointed out by Bashir et al., (2020) and Ihenetu et al., (2024). Thus, contemporary management of freshwater in urban areas needs a biodiversity-focused strategy rather than pollution-focused.

Management approaches used in relation to urban freshwater ecosystems have been diverse over the years, including but not limited to green infrastructure and adaptive management approaches. Hale et al. (2015) proposed the use of an 'ecological traps' approach to urban freshwater ecosystem management, where well-meaning interventions end up attracting organisms into degraded areas in urban watersheds.

Evidence-based management guidelines for urban ponds were presented by Oertli & Parris (2019), whereas Craig et al. (2017) appealed for the creation of a unified approach to freshwater threat interactions. The importance of urban green infrastructure as a link between biodiversity conservation and sustainable urban development in terms of adaptive management was proposed by Wang et al., (2024). Matthews (2016) highlighted the role of community resilience in freshwater management, whereas Poff (2009) discussed flow variability as an integral part of freshwater ecosystem functioning. Bănăduc et al., (2022) presented a detailed review of freshwater stressors and different approaches to protection, including regulatory measures and nature-based solutions. Therefore, it can be inferred that both structure and regulation have to be incorporated into freshwater management.

III. Materials and Methods

Study Area

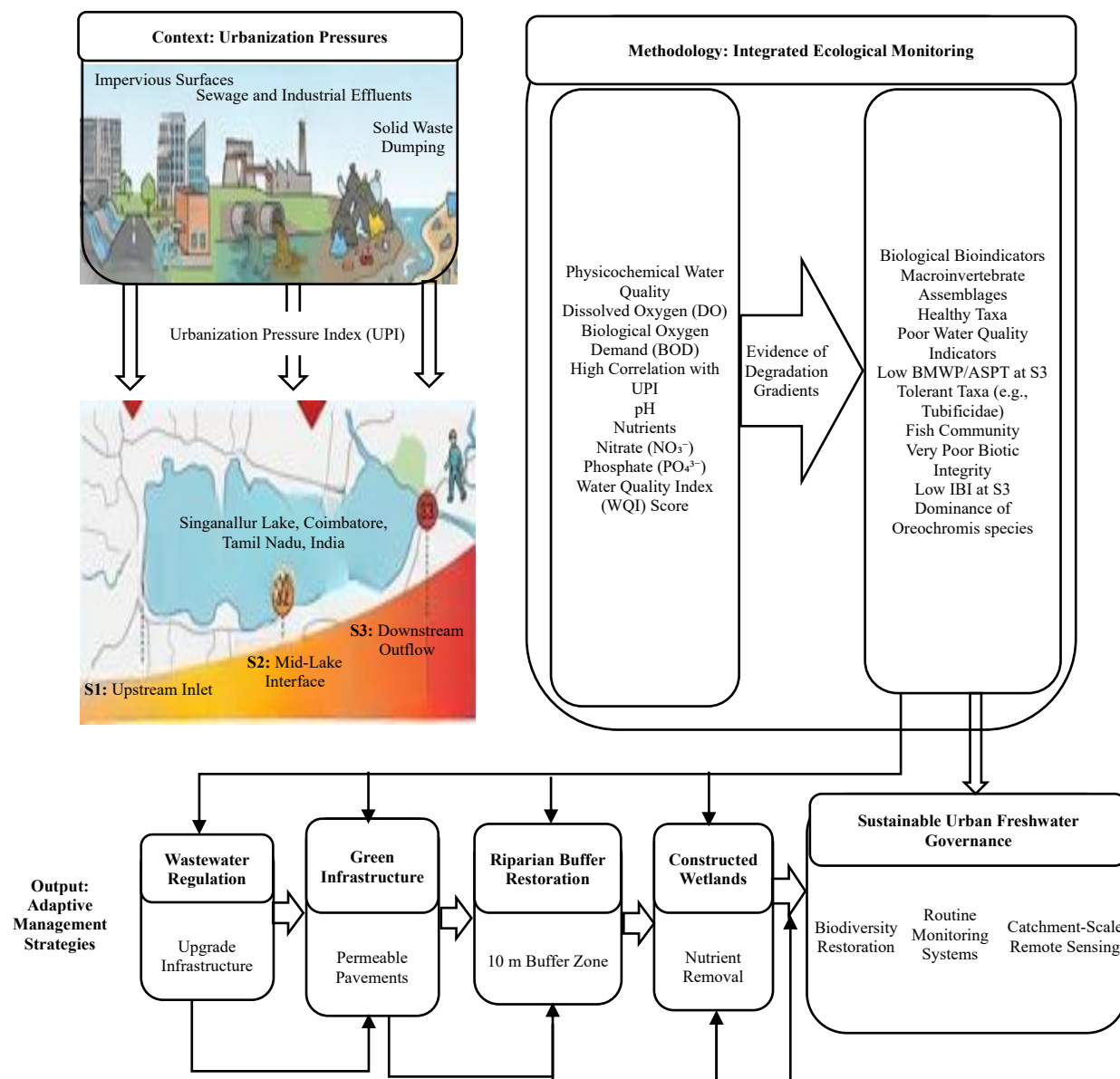


Figure 1: Conceptual Framework for Integrated Urban Freshwater Management

The experiment took place in the Singanallur Lake system (10°58'N, 77°02'E) in Coimbatore, Tamil Nadu, India. Coimbatore is an industrially and urbanly developing city having more than 2.1 million people (as per 2021 census) located within the rain shadow region of the Western Ghats. The Singanallur Lake occupies about 236 hectares area and is the important urban water body receiving effluents directly from the heavily polluted Noyyal river because of industries like textiles and dyeing, domestic wastewater and agricultural drainage into the lake. The lake plays a key role in groundwater recharge besides supplying water to residents, industries and agriculture in and around the city. But it has seen significant degradation owing to encroachments, wastewater discharges, solid waste disposal and the establishment of macrophytes within the lake premises. In all, three stations were established along the gradient of urbanization intensity; station S1 (semi-rural upstream inlet zone of low urban impact); station S2 (urban interface mid-lake zone of moderate urban influence) and station S3 (downstream outflow channel of high urban influence).

Figure 1 below is a comprehensive representation of the study framework. It highlights the causal relationship between Urbanization Pressures (impervious surface cover, sewage, and solid wastes) and the subsequent degradation of the Singanallur Lake ecosystem. Figure 1 shows the concept of an Integrated Ecological Monitoring strategy that combines physico-chemical (DO, BOD, TDS, nutrients) and biological (Macroinvertebrate communities and fish community indices) assessments in the identification of feasible Adaptive Management Approaches towards effective environmental governance.

Sample Collection and Physicochemical Analysis

Water and biological samples were collected every month from June 2022 to May 2023, for a period of one year (a total of 12 sampling campaigns) in all the three stations, providing an entire year's coverage, which includes pre-monsoon (March-May), southwest monsoon (June-September), northeast monsoon (October-November), and post-monsoon/winter (December-February). Water samples were collected in polyethylene bottles of 2 L volume at 0.5 m depth and transported to the laboratory on ice. The following physical and chemical parameters were analyzed following standard procedures (APHA 2017): DO by Winkler titration; pH by pH meter (Eutech CyberScan pH 510); TDS by gravimetric technique; BOD₅ by incubating water samples for five days at 20°C; turbidity by nephelometer (HACH 2100Q); nitrate nitrogen (NO₃-N) by ultraviolet spectrophotometer; and phosphate (PO₄-P) by ascorbic acid method. All measurements were done in triplicate. In terms of the biological parameters, the benthic macroinvertebrate organisms were sampled through a Surber sampler (size: 0.09 m²; mesh size: 250 µm) and preserved in 5% formalin in order to identify the samples up to the family level using keys in the laboratory. The fish assemblages were sampled through cast nets and electrofishing tools on pre-set transects. The Urbanization Pressure Index (UPI) for each sampling station was estimated from the proportional land uses (impervious surfaces, vegetation, and distance from sewage outfalls) based on 10 m Sentinel-2 satellite imagery.

Statistical and Ecological Analysis

Normality testing of data was carried out using Shapiro-Wilk test. One-way ANOVA with Tukey's multiple comparison test was used to check for any significant difference in the physicochemical parameters across the stations and seasons ($p < 0.05$). PCA was done on the standardized data set obtained on water quality to detect major pollutant gradients and inter-correlation of water quality parameters. Pearson correlation test was used to correlate UPI values with water quality parameters. Biological community composition was determined by BMWP (Biological Monitoring Working Party) score and ASPT (Average Score Per Taxon) for macroinvertebrates, and the IBI index adapted for South Asian rivers for fish assemblages. Water quality index (WQI) was calculated using the weighted arithmetic method for all physicochemical parameters with respect to WHO and BIS guidelines. Redundancy analysis (RDA) was done to establish the relationship of the biological community composition with environmental variables. All statistical analyses were performed in R v 4.3.0 utilizing the vegan, ggplot2, and FactoMineR packages. Temporal analysis for 12 months was performed using the Mann-Kendall non-parametric test.

IV. Results

Physicochemical Water Quality Parameters

Substantial spatial as well as seasonal variability was found for all physicochemical variables tested. A decline of 45% in the DO levels was found from upstream (S1) to downstream (S3) sampling locations. Furthermore, periodic variations showed a decline of 38% in DO during the monsoon-flush periods, with minimum DO record during the post-monsoon seasons when organic load is highest (ANOVA: $F = 34.7$, $p < 0.001$). Values of BOD₅ were above WHO guideline standards (5 mg/L) at S3 location in 9 out of 12 sample months, with maximum value recorded during monsoon flush period of August 2022, 13.2 mg/L. There existed a high correlation between TDS and UPI ($r = 0.87$, $p < 0.001$) due to contributions by both industrial and domestic discharge. The turbidity level at S3 was 4.7 times higher than that at S1 during the monsoon season. The pH level remained nearly neutral at all stations (6.8-8.2). However, the slight increase in pH at S3 during the dry season indicated the contribution of carbonates to the water body due to discharge of effluents. The levels of nitrate and phosphate at S3 were above eutrophication limits ($\text{NO}_3\text{-N} > 5 \text{ mg/L}$; $\text{PO}_4\text{-P} > 0.3 \text{ mg/L}$) for 75% of sampling instances (Table 1).

Table 1: Seasonal and Spatial Mean Values ($\pm$ SD) of Key Physicochemical Parameters Across Sampling Stations

Parameter	S1 (Upstream) Mean $\pm$ SD	S2 (Mid-lake) Mean $\pm$ SD	S3 (Downstream) Mean $\pm$ SD	WHO Limit	p-value
DO (mg/L)	7.4 $\pm$ 0.6	5.8 $\pm$ 0.7	4.1 $\pm$ 0.8	>6.0	<0.001
BOD ₅ (mg/L)	2.1 $\pm$ 0.4	5.6 $\pm$ 1.2	10.8 $\pm$ 2.3	<5.0	<0.001
TDS (mg/L)	180 $\pm$ 22	420 $\pm$ 56	780 $\pm$ 98	<500	<0.001
Turbidity (NTU)	4.2 $\pm$ 1.1	18.6 $\pm$ 4.3	42.1 $\pm$ 9.8	<5.0 (drinking)	<0.001
pH	7.2 $\pm$ 0.3	7.6 $\pm$ 0.4	8.1 $\pm$ 0.5	6.5–8.5	0.012
NO ₃ -N (mg/L)	0.8 $\pm$ 0.2	3.1 $\pm$ 0.7	6.4 $\pm$ 1.4	<10	<0.001
PO ₄ -P (mg/L)	0.05 $\pm$ 0.01	0.18 $\pm$ 0.04	0.52 $\pm$ 0.12	<0.3	<0.001
WQI Score	72.4 $\pm$ 5.1	51.2 $\pm$ 6.8	31.6 $\pm$ 7.4	—	<0.001

Note: WQI scores: >90 = Excellent; 70–90 = Good; 50–70 = Medium; 25–50 = Bad; <25 = Very Bad. All values are annual means across 12 months.

Biological Indicators and Biotic Indices

Assemblages of benthic macroinvertebrates exhibited a definite gradient of impairment from S1 to S3 stations. There were altogether 48 families of macroinvertebrates identified in all stations, with diversity decreasing drastically from 36 families in station S1 to 14 families in S3 station. Assemblages in S3 station included pollution-tolerant families (Tubificidae, Chironomidae), which comprised 78% of the total abundance, while sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) families were almost non-existent at S3 station (EPT richness = 1). The BMWP score indicated poor water quality in station S3 (BMWP = 28; ASPT = 2.8), fair water quality in station S2 (BMWP = 54; ASPT = 4.9), and good water quality in station S1 (BMWP = 89; ASPT = 7.2). Fish IBI scores also indicated a gradient of degradation with a score of 48 for S1 station (fair), 34 for S2 station (poor), and 22 for S3 station (very poor). There were totally 21 fish species found, among which 12 occurred in S1 station, 7 in S3 station, and the dominant species were exotics and tolerant. Detailed biotic index results are summarized in figure 2.

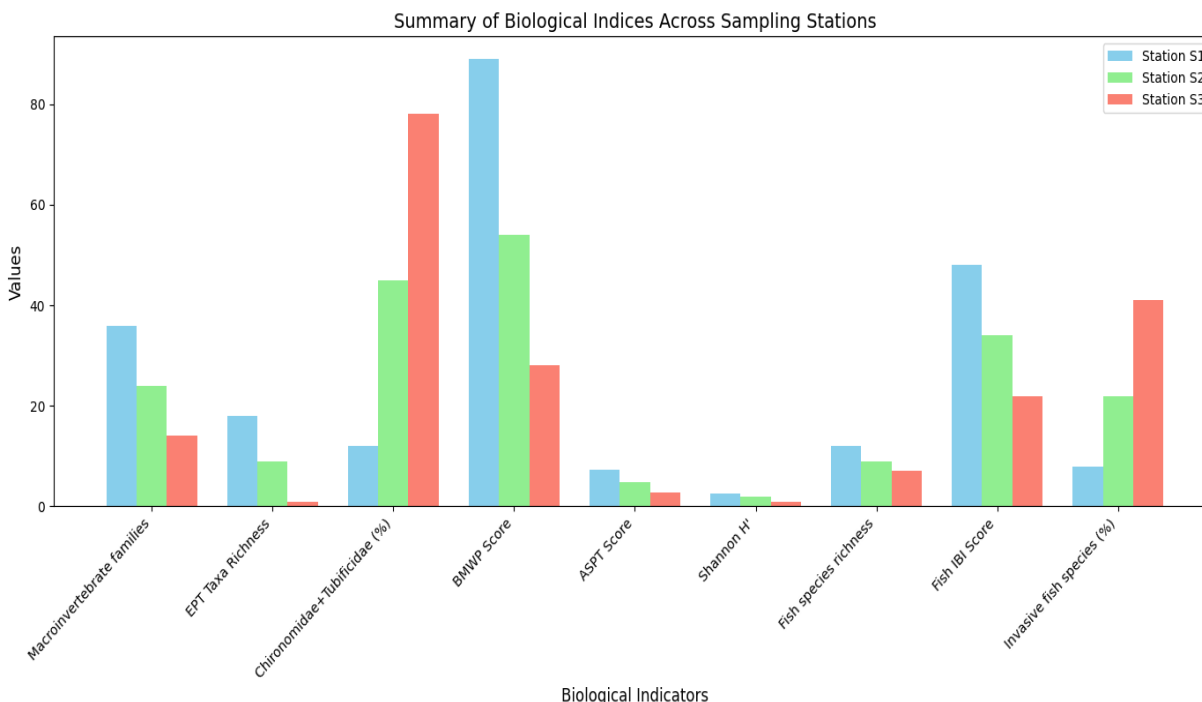


Figure 2: Summary of Biological Indices Across Sampling Stations

Urbanization Pressure and Multivariate Analysis

PCA for the nine physio-chemical parameters accounted for 71.4% of total variation through PC1 and PC2. PC1, which accounted for 46.8% of variance, had BOD₅, TDS, phosphates, and turbidity, depicting a gradient of organic pollution and nutrient enrichment linked to urbanization. On the other hand, PC2 (accounting for 24.6% of variance) was characterized by DO and pH, depicting oxygen depletion and carbonate buffering dynamics. A Pearson correlation test showed significant positive correlations between UPI and BOD₅ ($r = 0.91$), TDS ($r = 0.87$), phosphates ($r = 0.84$), and turbidity ($r = 0.82$), while a significant negative correlation was found between UPI and DO ($r = -0.89$) and WQI ($r = -0.93$). Multiple regression analyses also indicated that UPI accounted for 74% of the variance in composite WQI scores ($R^2 = 0.74$, $F = 31.2$, $p < 0.001$). RDA results revealed that the environmental factors BOD₅, DO, and TDS were key explanatory variables affecting community structure (Cumulative $R^2 = 0.68$). The seasonal Mann-Kendall trend test detected significant negative trends for both DO ($Z = -2.34$, $p < 0.05$) and WQI ($Z = -2.71$, $p < 0.05$) at S3 during the 12-month observation period. The PCA loadings and correlation matrix for selected variables in table 2.

Table 2: PCA Factor Loadings and Pearson Correlations of Water Quality Parameters With Urbanization Pressure Index (UPI)

Parameter	PC1 Loading	PC2 Loading	Correlation with UPI (r)	Significance (p)
DO (mg/L)	-0.81	0.42	-0.89	<0.001
BOD ₅ (mg/L)	0.88	-0.11	0.91	<0.001
TDS (mg/L)	0.84	0.18	0.87	<0.001
Turbidity (NTU)	0.79	0.22	0.82	<0.001
pH	0.31	0.76	0.44	0.008
NO ₃ -N (mg/L)	0.72	-0.31	0.76	<0.001
PO ₄ -P (mg/L)	0.83	0.09	0.84	<0.001
WQI Score	-0.91	0.14	-0.93	<0.001
Variance Explained (%)	46.8	24.6	—	—

V. Discussion

The findings of the current research indicate that urbanization is the main factor responsible for the impairment of freshwater ecosystems in the case of the Singanallur Lake system. The significant negative correlation of urbanization with water quality, as well as the high explanatory power of urbanization in relation to variance in composite water quality score, suggests the role of urbanization as a predictor of water ecosystem degradation. Levels of dissolved oxygen dropped sharply within the lake waters, while biological oxygen demand levels rose dramatically, indicating that urbanization caused the development of hypoxic conditions unfavorable for the diverse biological community inhabiting these waters. This is associated with major modifications in benthic macroinvertebrate communities characterized by dominance of pollutant-tolerant species and lack of sensitive taxa as a result of constant organic matter accumulation and oxygen depletion. Fish communities also exhibit signs of disturbance with a low biotic integrity index and dominance of invasive species, as well as decreased diversity.

Nutrient enrichment, especially in terms of excessive phosphates, favors algal blooms, while increased salinity and dissolved solids show how different chemicals work together to stress urban lakes. Analysis of the temporal data suggests a steady decrease in the condition of the water body, meaning that the situation is worsening over time. Thus, there should be an integrative approach, where the focus will be put on pollution sources, its transportation, and biodiversity. This way, combining regulations of the discharge of wastewater, restoration of riparian buffers, and constructing wetlands along with the use of cutting-edge monitoring technologies can help improve ecosystem resilience. Lastly, this paper proves how important it is to utilize multisource environmental information to create a complete picture of urban freshwater condition.

VI. Conclusion

The current research has thoroughly assessed the physio-biological conditions of the Singanallur Lake ecosystem in Coimbatore, India during an entire year hydrological cycle, generating a multidimensional basis for studying the impact of urban freshwater degradation on ecology. Some of the main results include an evident urbanization gradient, where there was a reduction in the concentration of dissolved oxygen by 45% from upstream to downstream stations. Additionally, the levels of BOD₅ were found to exceed the WHO guidelines for more than 75% sampling incidences at the most influenced downstream station (S3). Furthermore, the levels of TDS and nutrient enrichment were also found to cross critical limits at the most affected site. Biotic indices also indicated severe environmental deterioration at the downstream sites, where the ASPT ratings were 'poor', while EPT richness was close to zero and IBI of fish was rated as 'very poor.' The urbanization pressure index alone accounted for 74% of the variance of composite WQI through multivariate analysis.

There are clear implications of the results of this study for management. It is necessary to prioritize the pollution of water, nutrient enrichment, TDS levels, and biological impacts recorded at station S3. These would involve immediate steps such as enhancing the wastewater collection and treatment infrastructure before reaching the lake, creating a minimum of 10-meter riparian buffers, and constructing wetlands that intercept nutrient-enriched stormwater runoff. In the medium term, there is a need to undertake restoration of biodiversity through restoring native macrophytes and the removal of invasive plant species. There is also the need for governance changes in which the proposed combined physicochemical and biological indicators can be used for regular monitoring.

There is a need for further research into the effects of microplastics on freshwater ecosystems and an assessment of the effectiveness of particular green infrastructure interventions using before-and-after-control impact study designs. There should also be research into remote sensing techniques that can be used for continuous, inexpensive monitoring of water quality in urban catchments. Smart sensor networks and artificial intelligence for predicting ecological disturbances through early warning is an area of promising future work and one that aligns with the global trends in the management of freshwater ecosystems.

Declarations

Conflict of Interest: The authors declare no conflict of interest.

Funding: This research received no specific funding from public, commercial, or not-for-profit funding agencies.

Dataset Description: The physicochemical and biological monitoring dataset generated in this study is available from the corresponding author upon reasonable request and will be archived in a public repository upon acceptance.

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