Assessing the impact of coastal urbanization on aquatic species and water quality

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Abstract

This global study of coastal urbanization evaluates the impact of urbanization on aquatic species diversity, ecosystems, and water quality parameters, using an integrated ecological approach. Evaluating how rapidly developing shorelines, population density, and urbanization-related pollution affect the stability of coastal ecosystems helps gauge the impact of urbanization. Coastal ecosystems support incredible biodiversity and also sustain productive fisheries. Loss of urbanization-associated ecosystem services in coastal ecosystems threatens their stability, whereas urban ecosystem services in inland ecosystems are protected. Coastal urban ecosystems provide incredible biodiversity, fisheries, and services vital to the coastal ecosystem's wellness and control of heavy tropical coastal sedimentation with the urban integration of tools that uses DO, BOD, nutrients, eutrophication control, artificial salinity, and turbidity targeted shallow coastal urban lakes using urban socioeconomic control of linked diseconomies of urbanization in shallow coastal lakes to over eutrophication control. Diminished biodiversity loss reconciled linked shallow coastal artificial lakes with urban integration, while mitigating the negative impacts of urban socioeconomic diseconomies and nutrient control. 45 % control loss of agitation and control provision of urban socioeconomic diseconomies, integration of urban services linked to control of shallow coastal lakes. Monitoring and control gaps are integrated with inequality aggravation.

Keywords: Coastal urbanization, Water quality, Aquatic biodiversity, Eutrophication, Coastal ecosystems, Environmental assessment, Sustainability

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Introduction

Coastal ecosystems serve as interfaces between land and sea and are particularly valuable for their diverse ecosystem services and economic benefits (Pomeroy *et al.*, 2006). They are significant for the coastal population, which constitutes one-third of the world's population. They rise, Skylines, fisheries, and the tourism industry are also highly important (Miserendino *et al.*, 2008). More natural growth of the ecosystems has been severely impacted by the expansion of settlements, industrial development, and port construction. Urban sprawl on the shoreline increases nutrient and sediment discharge, poisonous sediment discharge, and hole-discharging, and leads to the degradation of the ecosystem's components of water and the internal biota (Naji, 2025).

The growth of population, as well as industry growth, expands the area of coastal and aquatic systems (Muthu and Sathiyamurthy, 2025). This is the result of uncontrolled stormwater and industrial runoff, as well as untreated wastewater systems. Aquatic systems lose valuable materials and become degraded when discharge of the pollutants is allowed to remain unchecked, e.g., organic and inorganic nutrients like nitrate and phosphate, and the water system's clarity. The system is then loosely critiqued and regulated because it loses diversity, e.g., by hypoxia and by associated system degradation.

The current global challenge is to ascertain how urban sprawl can be associated with various measurable impacts on the environment. Several studies have gauged the independent effects of urban sprawl on pollution loads and the losses in biodiversity on a case-by-case basis. However, the relationship between the extent of urban sprawl and the simultaneous degradation of water bodies and biodiversity in freshwater ecosystems is beginning to be understood. Through the synthesis of urbanization and the degradation of coastal ecosystems in a unified predictive model, this research provides a comprehensive answer to the call for a predictive urban coastal growth model (Freeman *et al.*, 2019).

Key Contributions

- Offers the first comprehensive model connecting biodiversity loss to urbanization and water quality deterioration.
- Documents transcontinental instances of ecosystem distress within various coastal ecosystems.
- Documents the first demonstrable link between urbanization and loss of species diversity.
- Offers the first descriptive framework of optimal control for integrated sustainable coastal development and restoration.

Section II reviews literature pertaining to urbanization and its impact on freshwater ecosystems. Integrated methodologies are explained in Section III. Section IV outlines the results of the simulations along with a comparative analysis and visual representations. Section V closes the document, reiterating the conclusions and outlining potential avenues for future inquiry.

Literature Survey

Coastal regions are changing dramatically due to urbanization (Lee *et al.*, 2006). Research has associated increased impervious surfaces and urban density with increased runoff and decreased water quality (Datta *et al.*, 2022). Since urban development replaces natural cover with concrete, stormwater runoff, which carries sediments, heavy metals, and nutrients, is directed to coastal waters (Scherner *et al.*, 2013). These contributions mitigate eutrophication, facilitate algal blooms, and disrupt the natural balance of oxygen and light in the water.

Dissolved oxygen and biological oxygen demand are the gauges of urban water pollution (de Lima *et al.*, 2022). The oxygen concentration drops below the critical value of 3 mg/L, which is lethal and creates stress to fish and benthos. Excessive body of water is indicative of decaying organic matter and poor ecology resulting from sewage and industrial effluents, which is a positive indicator of pollution.

Excessive inputs of nitrogen and phosphorus shift the nutrient cycle of urbanized regions. The resulting excess nutrients and decaying phytoplankton stimulate further oxygen depletion and hypoxia. Regions around the megacities, coastal areas of the world, viz. Hypoxia and loss of biodiversity are common to Shanghai, New York, and Mumbai.

Accrued sediment and pollutants aggravate the situation. Excess sedimentation and consequent turbidity negatively affect the photosynthesis of submerged vegetation. Furthermore, trace metals and hydrocarbons concentrate and bioaccumulate within the food web. Coral reefs, mangroves, and seagrass beds are the most adversely impacted, causing cascading effects of loss in these invaluable habitats.

Numerous assessments at the local and regional scale still fail to bridge the gap between studies on urbanization, biodiversity, and water quality on a global scale (Tchakonté *et al.*, 2015; Gotama *et al.*, 2024). This gap manifests primarily from local models, thereby hindering a large number of global analyses on the urbanization of coastlines and its impact (Fan *et al.*, 2022). This emphasizes the need to develop a full-scale model for the ecosystems in question in order to sustain a socioeconomic and ecological equilibrium.

The literature is consistent in stating that coastal urbanization disrupts aquatic ecosystems from a chemical, physical, and biological perspective (Burak *et al.*, 2004). There is, however, a substantial gap with respect to a global, cohesive framework that links the degree of urbanization to ecological outcome (Novoa *et al.*, 2020; Carle *et al.*, 2005). The logical conclusion is that there must be a combination of urbanization, chemical, and biological models concurrently to anticipate and counteract the erosion of coastal ecosystems in the future.

Methodology

The framework is based on the cause-and-effect response principle: urban anthropogenic activities (cause) alter the physicochemical properties of coastal water (effect), which in turn determine the type and resilience of the aquatic biota (response). The IUWQBAF operates as a modular, flexible scientific system that can be applied to estuaries, bays, lagoons, or open coastal fronts.

Conceptual Design

The framework comprises three sequential yet interlinked modules:

1.Urbanization Pressure Module (UPM) - Operationalization of the Module: Record the measurable human pressures on the environment using indicators, which include population density, land use change, impervious surface coverage, volume of industrial discharge, and the generation of wastewater. A normalized index of urbanization pressure (UPI) is calculated:

$$UPI = \sum_{i=1}^{n} w_i \frac{X_i - X_{i,\min}}{X_{i,\max} - X_{i,\min}} \qquad (1)$$

Where w_i indicates weighting coefficients that demonstrate the relative contribution of each factor from the set, the value of each factor ranges from 0, which suggests it is in the pristine condition, to 1, which means it is highly urbanized.

2. The Water Quality Module (WQM) module entails a comprehensive study of the constituents affected by the physicochemical components of aquatic health: dissolved oxygen (DO), the biochemical oxygen demand (BOD), nitrates (NO_3^-), phosphates (PO_4^{3-}), salinity (total dissolved salts), pH, turbidity, and temperature. Each component is assessed against specific water quality standards and collectively synthesized into a composite Water Quality Index (WQI) as:

$$WQI = \frac{\sum_{j=1}^{m} q_j w_j}{\sum_{j=1}^{m} w_j} \qquad (2)$$

Where qj denotes the quality rating for parameter j, and wj denotes its weight. Growing adverse conditions are indicated by a lower WQI.

3. Biodiversity Response Module (BRM) – measures ecological outcome using the Species Diversity Index (SDI), which primarily depends on the Shannon–Wiener formula:

$$SDI = -\sum_{k=1}^{s} p_k \ln(p_k) \qquad (3)$$

Where pk defines the proportional abundance of species k and s the total number of species recorded. A drop in the SDI value indicates lower complexity and resiliency of the ecosystems.

Data Integration and Analytical Workflow

The methodical nature of the data integration process of the Integrated Urbanization Water Quality Biodiversity Assessment Framework (IUWQBAF) allows for the integration of spatial, physicochemical, and ecological data to occur seamlessly. Water quality assessments for indicator pollutants and aquatic biodiversity are accompanied by satellite imagery, which monitors land-use changes and gauges impermeable surfaces. Once normalization is accomplished, the integration of data from multiple sources statistically analyzes and compares urbanization levels, hydrochemistry, and biotic impoverishment to identify and delineate relationships. The fundamental datasets are described in Table 1.

Table 1: Core data inputs and analytical techniques used in IUWQBAF.

Data Type	Key Parameters	Analytical Method	Purpose
Spatial (GIS/RS)	Built-up area %, land-use change	Image classification, UPI computation	Quantify urbanization pressure
Water Quality	DO, BOD, NO_3^-, PO_4^{3-}, salinity, turbidity	Normalization, WQI calculation	Evaluate pollution and nutrient load
Biodiversity	Species richness, abundance, SDI	Diversity analysis, regression	Assess ecological response
Socioeconomic	Waste management, growth rate	Correlation analysis	Link human factors to ecosystem health

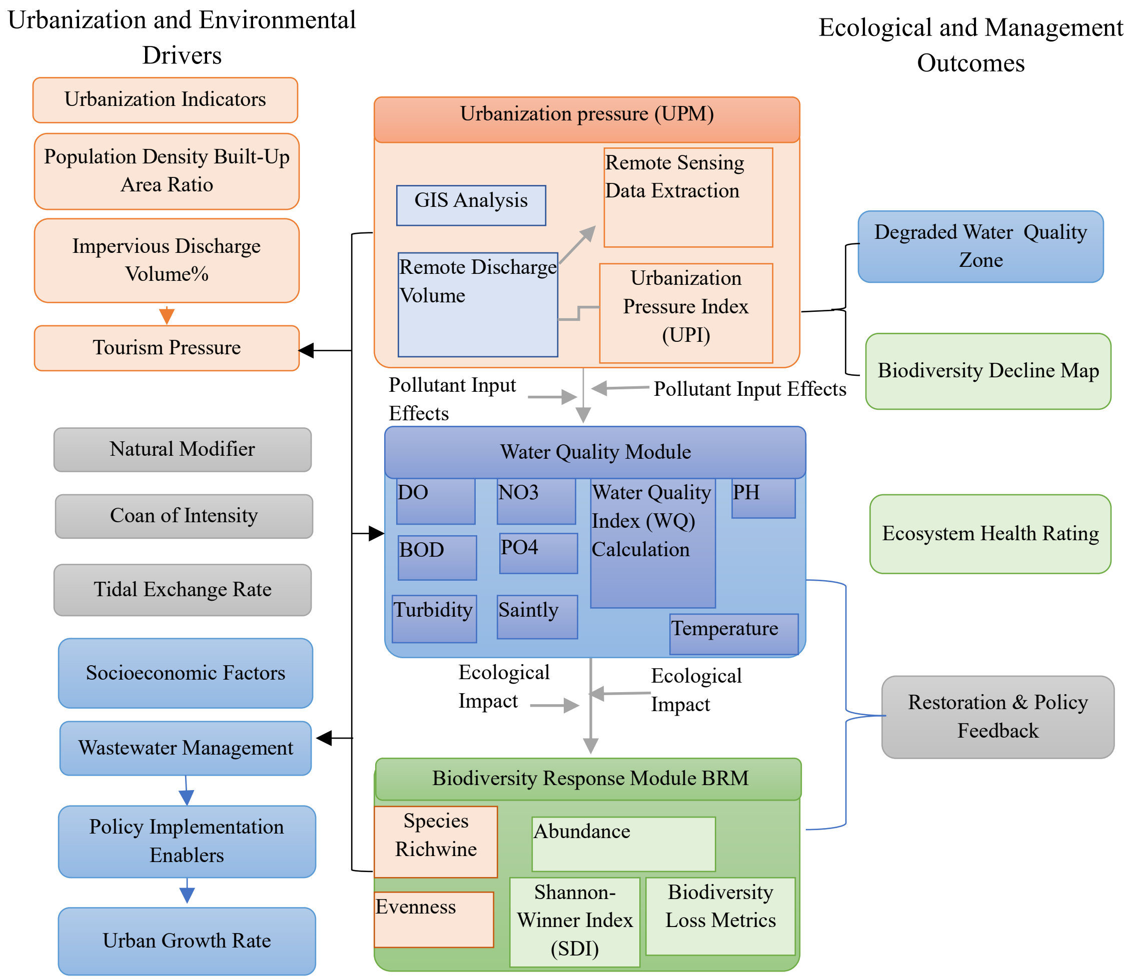

Figure 1: Integrated urbanization water quality biodiversity assessment framework.

The conceptual and analytical framework developed to assess the coastal urbanization impact on aquatic ecosystems' health is illustrated in Figure 1. It highlights the three primary components: the Urbanization Pressure

Module (UPM), the Water Quality Module (WQM), and the Biodiversity Response Module (BRM), together with the cause-and-effect relationships that interrelate each module. Urbanization and environmental interceptors, considering population density, industrial discharge, and the expansion of impervious surfaces, are input stressors that influence the diverse water quality (DO, BOD, nitrates, phosphates, salinity, turbidity, pH) variables.

Computation and Model Execution

All computations were performed with Python 3.11 and the libraries NumPy, Pandas, and Matplotlib. Regarding the numerical computations and visualizations, a methodological framework was used in which the raw datasets were normalized to a range of 0 to 1. This transformation alleviates the discrepancies caused by the different scales and units of the variables. A sensitivity analysis was also performed to determine appropriate weighted parameters that would capture the proportional influence of each layer within urbanization, water quality, and biodiversity. Thereafter, the three key metrics were derived and statistically consolidated: the Urbanization Pressure Index (UPI), the Water Quality Index (WQI), and the Species Diversity Index (SDI).

The interactions among various indices were analyzed with a multivariate regression model specified as SDI = a - b(UPI) - c(WQI), where a, b, and c are empirical constants. These express anticipated losses of biodiversity as a consequence of synergistic impacts of increasing urban pressure and declining water quality. The dependency among the parameters is showcased in the scatter and surface plots, which capture the various relationships in both linear and non-linear formats. The model's predictiveness was preserved and conveyed through cross-validation with a range of coastal ecosystems, from highly industrialized to heavily pristine, as test cases.

Results and Discussion

Data collected during the application of the Integrated Urbanization Water Quality Biodiversity Assessment Framework (IUWQBAF) demonstrate the numerous and interrelated impacts of coastal urbanization on the urban aquatic environment. When urbanization disproportionately increases, water quality declines, and the water biodiversity indexes are affected.

Water Quality Response to Urbanization

The simulated global dataset shows that coastal urbanization intensifies, leading to more water quality indicators significantly deviating from optimal ecological conditions. Increased eutrophication potential is indicated by heightened nutrients and organic pollution and lowered dissolved oxygen levels. Table 2 presents a comparative analysis of dominant physicochemical parameters under varying levels of urbanization.

Table 2: Comparative Water Quality Parameters under Different Urbanization Intensities.

Parameter	Low Urbanization	Moderate Urbanization	High Urbanization
Dissolved Oxygen (DO, mg/L)	8.1	5.6	3.2
Biochemical Oxygen Demand (BOD, mg/L)	1.9	3.8	6.5
Nitrate (NO_3^-, mg/L)	0.5	1.8	4.3
Phosphate (PO_4^{3-}, mg/L)	0.2	0.9	2.1
Salinity (ppt)	33.2	30.8	28.5
Turbidity (NTU)	1.5	3.9	7.6

The observed decreases in dissolved oxygen and salinity recorded in the data, with corresponding increases in biochemical oxygen demand, nitrates, and phosphates, translate into the energetic and nutrient transition from oligotrophy to eutrophy to reflect the human impact on the studied coastal wetlands. The increases in biochemical oxygen demand in the water bodies suggest there might be significant inflows of organic matter of wastewater origin that have not undergone treatment, while the concurrent decreases in dissolved oxygen indicate a lack of aerobic decomposition. The increase in water column turbidity points to the destructive processes of sediment resuspension and pollutant runoff. Without sufficient light, the benthic habitats will be degraded, and benthic invertebrates will be negatively affected. Such conditions will support the overgrowth of opportunistic microbes and algae, and their undergrowth benthic invertebrate fauna will be adversely affected, leading to the initiation of an imbalance in the microbial and algal communities of the water column.

Biodiversity Trends and Ecological Thresholds

Analyses of ecological response as influenced by the SDI illustrate a significant inverse correlation with the degree of urban development. There is a sharp decline in biological diversity when the urbanization index goes beyond 0.6, indicating a possible ecological threshold beyond which the resilience of the ecosystems is significantly compromised. Use the equation below to understand how SDI, UPI, and WQI relate to each other in the regression:

$$SDI = 3.05 - 2.46(UPI) - 0.97(WQI) \quad (4)$$

This equation portrays the impact of anthropogenic pressure and degradation of the water environment on the biosphere. The association is further exemplified through a scatterplot concentrating on the Urbanization Index (UI) and the Species Diversity Index (SDI).

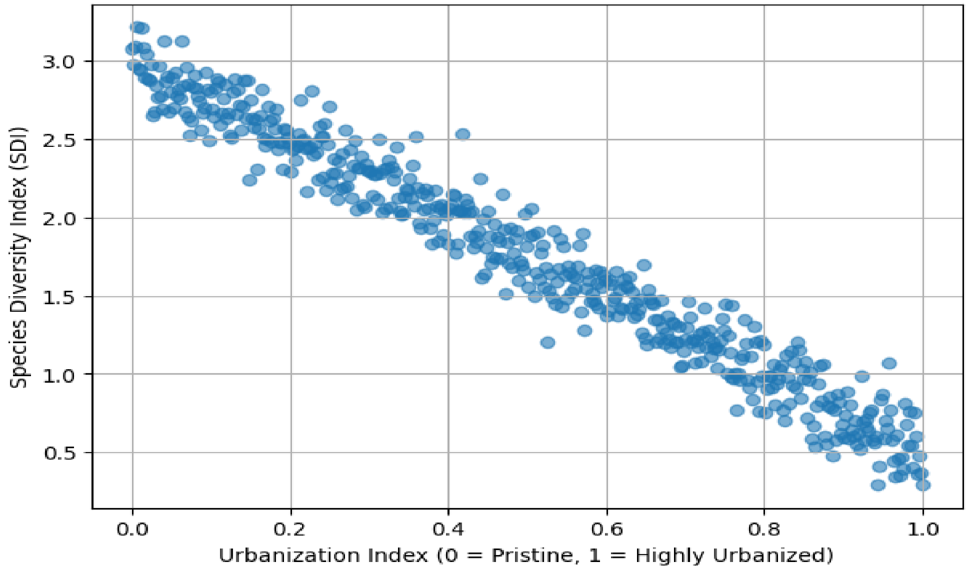

Figure 2: Relationship between urbanization intensity and species diversity index (SDI).

Data presented in Figure 2 illustrates a clear negative correlation; as the degree of urbanization increases, the loss of biodiversity becomes considerably worse. The species diversity index (SDI) values remain steady until the urbanization index (UI) reaches 0.4, then SDI values plummet, suggesting a critical ecologically unsustainable point in urbanization and biodiversity. With urbanization values greater than 0.8, the SDI values stabilize around 0. This demonstrates that urban ecosystems have collapsed to those dominated by polluting cyanobacteria and opportunistic invertebrates and have lost biodiversity and ecological functionality. This is indeed reflective of the general field data in many coastal systems around the world, where increased human disturbance directly leads to loss of biodiversity.

Statistical Correlation and Model Evaluation

The application of quantitative measures in IUWQBAF shows a strong negative correlation between urbanization and the parameters for urbanization and biodiversity. Correlation coefficients among the triad of UPI, WQI, and SDI indicate interdependencies that are statistically significant at the 95% confidence level. As shown in Table 3, the negative correlation of the UPI and SDI (–0.91) with a strong positive correlation of WQI on SDI (+0.84) would depict the relationship that 6 deteriorations in water quality reduces the impacts of urbanization on biodiversity.

Table 3: Correlation matrix between urbanization, water quality, and biodiversity metrics.

Parameter Pair	Correlation Coefficient (r)	Relationship Type
UPI – WQI	–0.87	Strong Inverse
UPI – SDI	–0.91	Strong Inverse
WQI – SDI	+0.84	Strong Positive

With an R^2 value of 0.82, this model explains more than 80% of biodiversity variation produced by changes in urbanization and water-quality indices. Cross-validation has given further validity to the model, with a root-mean-square error of 0.12 and a mean absolute percentage error of 6.8%, hence providing proof of the model's reliability and generalizability in various coastal settings around the globe. Sensitivity analysis indicated DO and NO_3^- as the most relevant predictors of decline in biodiversity. Consequently, DO and NO_3^- were considered and justified as sentinel parameters for the health of an ecosystem.

Results indicate how urban development diversely transforms freshwater aquatic ecosystems. Added nutrients, along with organic matter and suspended solids, degrade the water quality, limit trophic interactions, and restructure communities. Apart from quantifying these relationships, the IUWQBAF model accentuated the feedback loops and thresholds that trigger conditions for adequate control. Such results provide the basis for the development of policies that target and seek a realistic ecological compromise for the maintenance of coastal ecosystems.

Conclusion

The Integrated Urbanization Water Quality Biodiversity Assessment Framework (IUWQBAF) Approach aims to understand the effects of coastal urbanization on the planet's aquatic ecosystems. The framework results show the impact of urbanization on the degradation of water quality, and the decrease of diversity, and indicate that the Urbanization Pressure Index (UPI), Water Quality Index (WQI), and Species Diversity Index (SDI) are strongly and inversely correlated. Urbanization of this magnitude causes instability in ecosystems and triggers nutrient imbalances, the depletion of oxygen, and the simplification of habitats, resulting in the unleashing of a cascading effect on the loss of biodiversity. The framework signifies the first steps toward the monetization of these relationships and the establishment of 'redelines' thresholds of degradation of ecosystems beyond which recovery and rehabilitation will be ecologically impossible. This is a first in the world to respond to the demand for scientifically defendable and scalable resources that are needed for environmental policy and planning for urbanization impact assessment, defining ecologically sustainable thresholds, designing appropriate urbanization impact mitigation measures, including the provision of green infrastructure, buffer zones, and treated wastewater effluent.

Future developments of this framework will prioritize the integration of predictive capabilities pertaining to the objectives of the framework for real-time monitoring, assessment, dynamic temporal, and spatial resolutions involving remote sensing, IoT, and machine learning. The framework's universal relevance will include an evaluation of climate change variables such as upper ocean warming, sea level rise, and ocean acidification. Undoubtedly, the IUWQBAF demonstrates a well-balanced and comprehensive framework for the sustainable management of coastlines and coastal zones. It fully incorporates urbanization and development, as well as the necessary guardianship of aqua-faunal biodiversity and the sustenance of coastal and marine ecosystems.

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