Aquatic Ecosystems and Environmental Frontiers, Volume 4, Issue 4, December 2026 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V4I4/AF260410

Investigating the Role of Small Urban Wetlands in Supporting Regional Aquatic Biodiversity

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Abstract: Small urban wetlands are freshwater ecosystems of ecological importance that are helping aquatic species and the protection of aquatic biodiversity in a more urban environment. While they may cover small geographic areas, these ecosystems are vital for aquatic plants, macroinvertebrates, amphibians, fish, and other organisms that require fresh water. They are vulnerable to the threats of urban expansion, habitat fragmentation, water pollution, invasive species, and alteration of natural hydrological processes. In this study, the author creates a framework for an ecological assessment based on a simulation to explore the role that small urban wetlands play in the regional aquatic biodiversity. The proposed framework assesses how quality of wetland habitat and ecological connectivity, vegetation complexity, water quality, and surrounding urban land use intensity relate to aquatic species diversity. A hypothetical network of 30 small urban wetlands is assumed and classified as low, moderate, and high connectivity. Outputs are used to investigate non-linearities in the richness and Shannon diversity of species, as well as the biodiversity responses to different management options for wetlands. Simulated results suggest that there is a comparatively high number of aquatic species in wetlands that are more ecologically connected and have more habitat complexity. A 5-year time-course illustrates how biodiversity can increase from the combination of habitat restoration, native vegetation establishment, pollution abatement, and connectivity. The suggested framework emphasizes the need to treat small wetlands as an integral component of the regional biodiversity planning process, not as stand-alone, insignificant water features. The study gives a conceptual and quantitative basis for future field investigations and sustainable management of urban wetlands.

Keywords: Urban Wetlands; Aquatic Biodiversity; Ecological Connectivity; Species Richness; Habitat Complexity; Biodiversity Simulation.

(Submitted: August 27, 2026; Revised: September 28, 2026; Accepted: November 12, 2026; Published: December 30, 2026)

I. Introduction

Urban wetlands are freshwater ecosystems that are vital in preserving ecological processes in an urban setting. Small ponds, seasonal wetlands, man-made water bodies, marshes, retention wetlands, and shallow freshwater habitats in the urban and peri-urban landscape. While many wetlands may be small in size, they can be ecologically significant when they form part of a network of wetlands that offer breeding sites, feeding habitats, refuge sites, and dispersal opportunities for many aquatic organisms. They have ecological value beyond the boundaries of the wetlands, affecting other wetland vegetation, drainage systems, freshwater corridors, and other aquatic habitats.

The freshwater environments and landscape have been significantly impacted through urban development, surface runoff, and the manipulation of the natural water processes, including the land use in the urban setting. This impacts the availability of the aquatic organisms. Application of metacommunity theory will offer an important conceptual framework for understanding the role of local environmental conditions and landscape-level ecological processes in structuring wetland communities. This view highlights the importance of local habitat characteristics, as well as interactions between geographically distributed aquatic habitats on individual wetlands (Johnson et al., 2013).

There are also other small urban ponds and wetlands that serve as important ecological values in modified landscapes. They contribute to aquatic food web support, ecological process maintenance, breeding habitat provision, and support of species dependent on temporary or permanent freshwater. Ecological features, geographical distribution, and management status of urban ponds are related to their

biodiversity values. Thus, even small wetlands can have a regional conservation contribution if their ecological potential seems small (Hassall, 2014).

Freshwater ecosystems have been under growing pressure from the increasing expansion of urban settlements, including pollution, habitat fragmentation, removal of vegetation, and disturbance of hydrology. Such pressures can result in a reduction of habitat quality and barriers to the mobility of aquatic species. However, if adequate environmental conditions and management practices are implemented, small urban wetlands can provide valuable biodiversity resources. In urban settings, where natural freshwater habitats are getting more and more fragmented, their combined contribution is more significant (Hill et al., 2017).

Although urban aquatic habitat is becoming more well-known, small aquatic wetlands are often neglected in regional planning for conservation. Small water bodies are typically given a lesser amount of attention in conventional conservation strategies compared to large lakes, rivers, reservoirs, and protected natural wetlands. This poses a research challenge that requires assessment of the environmental contribution of small wetlands and the environmental factors that influence their potential for biodiversity.

To fill this research gap, the present study presents an ecological assessment framework using a wetland habitat simulation that explores relationships among wetland habitat attributes, water quality, ecological connectivity, and aquatic biodiversity. The main goal is to assess the role of small urban wetlands in the regional aquatic species diversity under various environmental and management conditions. The potential biodiversity effects of wetland restoration and habitat-network improvement are also explored.

The rest of the paper is structured as follows. In Section 2, small urban wetlands and the environmental factors affecting aquatic biodiversity are discussed. The proposed simulation methodology, variables, and mathematical framework are presented in Section 3. The results and the biodiversity response to the different ecological conditions discussed in Section 4. Section 5 contains the discussion on the implications for the urban wetland management, while Section 6 brings the study to a close.

II. Literature Review

Ecological Importance of Small Urban Wetlands

Small urban wetlands are valuable habitat areas in the modified landscape. They play ecological roles such as habitat for riverine and aquatic life, sediment trap, nutrient cycle, food chain and haven. Aquatic vegetation offers protection and/or food for invertebrates, amphibians and young fish and contributes to habitat diversity and water quality controls through submerged and emergent plants.

Intensive human development can be surrounded by substantial biodiversity, maintained by urban wetlands. Stormwater ponds and engineered wetlands can be designed to facilitate a variety of fresh water flora and fauna. They have biodiversity potential which is dependent on water availability, vegetation characteristics, habitat structure and environmental management. Studies contrasting stormwater ponds to unmanaged wetlands have proven that constructed urban water bodies are essential for water quality management but also have the potential to provide valuable habitat for biodiversity (Hassall & Anderson, 2015).

The value of small water bodies is not only for their species conservation but also for their contribution to ecosystem services. They provide water storage, nutrient cyclisation, flood control, carbon sequestration and amenity. Small waterbodies can have landscape-scale amenity value, if numerous, on the landscape scale, because they are important for the implementation of environmental policies and biodiversity conservation programmes (Biggs et al., 2017).

Habitat Complexity and Aquatic Species Diversity

Habitat complexity is the amount of structural diversity of the ecological features of a wetland. Aquatic organisms have various environmental niches due to differences in the water depth, substrate type, aquatic plant life, shore characteristics, and emergent plant cover. More structurally complex wetlands have more organisms that require different feeding, breeding, and shelter needs.

The narrowing of ecological niches is possible due to habitat simplification by the concrete lining, excessive vegetation removal, sediment disturbance, and making uniform shorelines. However, maintaining native aquatic vegetation and natural shoreline structures can promote greater habitat suitability and diversity of aquatic habitats.

Maintaining urban ponds needs to be done in a way that meets ecological goals and the environmental attributes of each wetland. Preventing over-vegetation removal and maintenance (including uniform habitat modification) can have a negative effect on freshwater biodiversity. Wetland management in the urban environment should therefore consider the needs of various groups of aquatic organisms, ecological assessment, and habitat heterogeneity and not be based on a generic approach to maintenance (Oertli & Parris, 2019).

Urban Wetland Management and Ecological Risks

Managing urban wetlands is a multifaceted problem and requires attention to several issues, such as water levels, vegetation control, population of invasive species, mosquito control, and pollution prevention. Actions taken by a management agency to promote one ecological function may have side effects on other aspects of biodiversity.

For instance, too much vegetation removal or poor water-level control can lead to a decrease in the availability of aquatic habitats. Conversely, management practices aimed specifically at the reduction of mosquitoes could also affect the community structure of the aquatic environment if the intervention is inappropriate, be it biological or chemical. Thus, conservation planning should take both biodiversity protection and public health goals into account to prevent unforeseen ecological impacts (Hanford et al., 2020).

Urban Drainage Systems and Aquatic Habitat Functions

Aquatic macroinvertebrates may be provided with alternative habitats in urban drainage systems, ponds, and artificial water channels. These habitats often are given less conservation priority, as they are more focused on water management. However, their biological communities can provide a contribution to the broader urban freshwater ecology.

Drainage-related water bodies are more or less able to support freshwater organisms depending on the availability of aquatic plants, the diversity of substrates, water permanence, and appropriate physicochemical conditions. The above properties suggest that the urban drainage infrastructure may support regional aquatic biodiversity if the ecological functions are considered in planning and managing the infrastructure (Vermonden et al., 2009).

There are also some unusual or unnoticed wetland habitats in urban landscapes that may arise as a result of changes in drainage, former fields, man-made low-lying areas, and other human activities. Limited recognition of such accidental wetlands in traditional conservation planning does not detract from their ecological roles. They can help fill gaps in regional environmental assessments by increasing knowledge of the overall freshwater habitat available in urban settings (Palta et al., 2017).

Regional Biodiversity Conservation and Research Priorities

Urban wetlands have environmental and cultural values beyond their biodiversity functions. They help to improve the environmental quality of cities, the attractiveness of the landscape, recreational activities,

education and public awareness of freshwater conservation. Incorporating ecological and social issues can improve the sustainability of urban wetland protection programmes in the long-term (Alikhani et al., 2021).

The urban landscapes in the tropics and in the monsoonal region are also faced with conservation challenges, as they are seasonal and have fluctuating hydroperiods, high temperatures and rapid urbanization, which affect aquatic habitat availability. Seasonality, connectivity, species distribution and the ecological nature of temporary and permanent water points are all important in wetland biodiversity assessment within these environments. To create successful conservation priorities in tropical urban areas, there is a need for a comprehensive understanding of these factors (Gebreselassie et al., 2022).

III. Materials and Methods

Simulation Research Design

A simulation-based ecological research design is used to assess the role of small urban wetlands in regional aquatic biodiversity. The proposed framework is a hypothetical urban wetland network of 30 individual wetland sites. The simulated network consists of wetlands of varying habitat features, vegetation conditions, water-quality profiles and landscape connectivity.

Ten wetlands are assigned to each of the three categories of ecological connectivity: low, medium, and high. Ten wetlands are allocated to low, medium, and high categories of ecological connectivity. The differences in the availability of nearby aquatic habitats, green corridors and suitable dispersal pathways are classified. An ecological condition prior to restoration and a condition after 5 years were simulated for the assessment.

This simulation is not intended to be a field observation from a real city or an inventory of measured species within a region. Rather, the values of these parameters are used to illustrate how environmental factors relate to patterns in biodiversity and that the proposed framework can be used to help future empirical investigations.

Selection of Environmental Variables

The proposed framework acknowledges five major environmental components: habitat complexity, water quality, ecological connectivity, native vegetation cover and surrounding urban area use pressure. Habitat complexity is the number of physical and biological features that are present in each wetland. A composite index is used for water quality, which includes dissolved oxygen, nutrient conditions, pH, conductivity, and pollutant pressure. Ecological connectivity is the functional link among individual wetlands to the surrounding aquatic or green environment.

Native vegetation is included because submerged, floating and emergent vegetation supplies critical habitat ecological resources for aquatic organisms. Urban land-use pressure is the impact of impervious surface, road infrastructure, intensive development and other related environmental disturbances. Species richness is used to measure aquatic biodiversity along with the Shannon diversity index. Species richness counts the number of aquatic species found in a ‘thought experiment' hypothetical wetland, whereas the Shannon index takes into account species abundance and community distribution.

Biodiversity Assessment Model

A linear relationship between species richness and environmental and landscape features is presented in equation 1:

$$S_i = \beta_0 + \beta_1 H_i + \beta_2 W_i + \beta_3 C_i + \beta_4 V_i - \beta_5 U_i + \epsilon_i \quad (1)$$

Where S_i represents the predicted species richness of wetland i, H_i represents habitat complexity, W_i represents water quality, C_i represents ecological connectivity, V_i represents native vegetation coverage, and U_i represents urban land-use pressure. The coefficients represent the relative contributions of the environmental variables, while ϵ_i represents random simulation variation.

The Shannon diversity index is calculated using equation 2:

$$H' = -\sum_{j=l}^{s} p_j \ln(p_j) \qquad (2)$$

Where p_j represents the relative abundance of species j, and s represents the total number of species within the wetland. The higher the number the more diverse and more evenly distributed are the species. The well-being of the major environmental dimensions is to be combined into a composite Wetland Ecological Quality Index (WEQI) using equation 3:

$$WEQI_i = 0.25H_i + 0.25W_i + 0.25C_i + 0.15V_i + 0.10(1 - U_i) \qquad (3)$$

All component variables are scaled from 0 to 1. The weighting structure gives more weight to the habitat quality, water quality, and ecological connectivity. The index produced is a relative one and not a validated universal wetland classification.

Simulation Procedure and Management Scenarios

The simulation is divided into a number of steps: The initialisation of environmental parameters, classification of the wetland, estimation of biodiversity, and comparison of different scenarios. The baseline scenario is a hypothetical scenario with current environmental conditions, with the restoration scenario including increased vegetation cover, decreased pollution, habitat diversification, and increased ecological connectivity.

This 5-year scenario is based on a gradual improvement, not an ecological restoration. The changes in the simulated regional biodiversity index constitute biological responses to biodiversity. In the model, it assumes that gains in biodiversity decrease as habitat approaches an ecological threshold to reflect that there could be a saturation point.

The proposed computational framework is briefly summarized in figure 1.

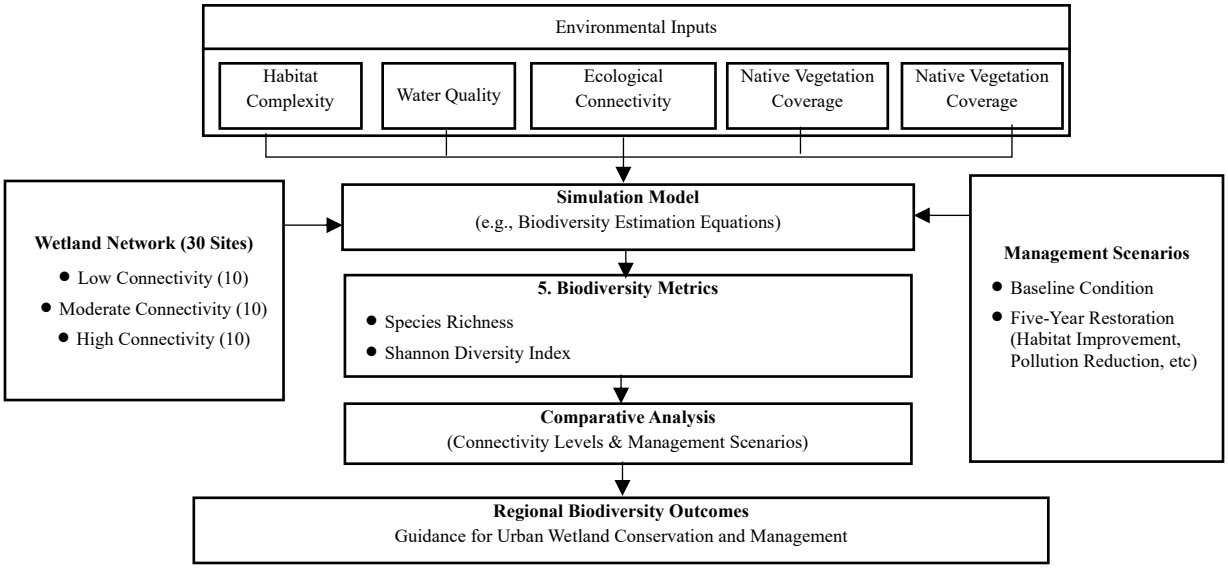


Figure 1: Framework for Assessing the Contribution of Small Urban Wetlands to Regional Aquatic Biodiversity

Model Evaluation

The simulation shows how biodiversity is affected in different management scenarios and connectivity categories. The average species richness is determined for each group, and the difference between community diversities is determined by using the Shannon index. The regional biodiversity response is expressed by a normalized index, from 0 to 1. The baseline and restoration trajectories are compared using the index, not to estimate an absolute number of regional species.

Sensitivity analysis is conceptually embedded to explore the effect of varying habitat complexity, water quality, and connectivity on the expected biodiversity results. The interpretation focuses on the direction of relationships and differences in scenarios, not on the statistical significance of an actual ecological sample.

IV. Results and Discussion

Comparative Biodiversity Performance Across Wetland Connectivity Categories

Table 1 shows that ecological connectivity has a significant role in small urban wetlands that can influence biodiversity potential. Average species richness and Shannon diversity are larger for the high connectivity group than for the low connectivity group. The differences are linked to the assumed dispersal route and surrounding vegetation and aquatic habitat.

Table 1: Biodiversity Characteristics Across Urban Wetland Connectivity Categories

Assessment parameter	Low connectivity	Moderate connectivity	High connectivity
Number of wetlands	10	10	10
Habitat quality index	0.42	0.63	0.81
Water quality index	0.48	0.65	0.82
Native vegetation coverage (%)	28	47	68
Connectivity index	0.25	0.55	0.85
Average species richness	8	12	16
Shannon diversity index	1.42	1.78	2.05
Wetland ecological quality index	0.35	0.58	0.80

The number of average species increases from 8 to 16 species between the low connectivity and high connectivity groups, respectively. This is a hypothetically 100% increase from this setting. Likewise, the Shannon diversity at the high-connectivity wetlands rises from 1.42 to 2.05, representing a more diverse and relatively well-balanced aquatic community at the high connectivity wetlands.

The findings highlight the importance of small wetlands in a connected habitat network, as a tool for promoting regional biodiversity. Green spaces and accessible aquatic habitats adjacent to wetlands can increase the potential for species movement, recolonization, and population persistence. The results also suggest that efforts to conserve urban wetlands for priority species should take into account the local environmental quality, based on habitat connectivity.

Influence of Habitat Quality and Native Vegetation

The simulation also suggests that the comparatively higher biodiversity values are related to the higher habitat quality and native vegetation cover for wetlands. Aside from providing important food sources for fish, native aquatic plants also serve as attachment sites and homes for various aquatic organisms, thus providing a complex habitat.

Insufficient vegetation in the wetlands could result in the reduction of niches available for the use of macroinvertebrates, amphibians, and other smaller aquatic creatures that use vegetation for shelter and reproduction. An increase in the percentage of vegetation cover from 28% in low-connectivity wetlands to 68% in high-connectivity wetlands is also correlated with an improvement in the habitat quality index and in biodiversity indicators.

Considering habitat complexity as part of the evaluation of conservation potential should be considered in addition to wetland surface area. A relatively small wetland with mosaic vegetation, natural borders, and conditions can be a more effective contribution to biodiversity than a large, but environmentally simplified, waterbody. Vegetation layer and natural shoreline characteristics can provide for habitat availability and promote ecological diversity.

Relationship Between Water Quality and Aquatic Biodiversity

Another key aspect of the simulated biodiversity response is water quality. The high-connectivity category has a water quality index of 0.82, while the low-connectivity category has a water quality index of 0.48. These values are environmental conditions and not actual observations of water quality.

Better water quality can enhance habitat suitability through adequate dissolved oxygen, decreased nutrient enrichment and prevention of excessive accumulation of harmful pollutants. On the other hand, aquatic organisms can be impacted and the community structure changed by untreated urban runoff, sewage discharge, sediment loading and chemical contamination.

Ecological responses can vary between phytoplankton, zooplankton, benthic organisms, amphibians, and fishes due to their different needs. Thus, the assessment of biodiversity in wetlands cannot be based on any single water-quality parameter. Physicochemical and biological parameters can be integrated into an assessment to give a fuller picture of ecological condition.

Simulated Five-Year Biodiversity Improvement Scenario

The restoration scenario is a five-year assessment of possible impacts of coordinated wetland management. The hypothetical intervention consists of native vegetation restoration, reduction in pollutant inputs, complexity of shorelines, invasive species control, and improved connectivity between appropriate wetland habitats.

Under the baseline condition the regional biodiversity index is 0.48. In the restoration scenario, the index slowly rises to 0.70 in year 5. The no-intervention scenario shows a gradual decrease to 0.43 as a result of ongoing habitat loss and urban environmental pressures.

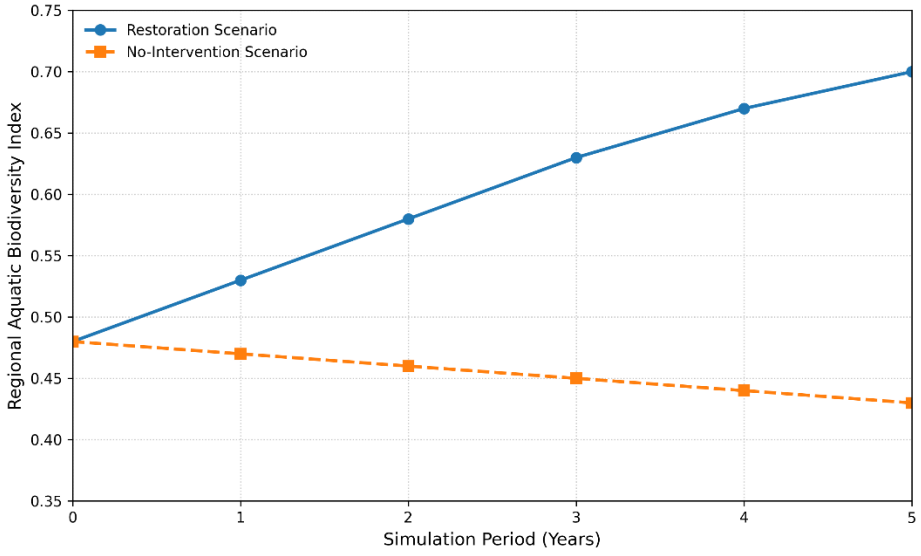


Figure 2: Regional Aquatic Biodiversity Response Under Restoration and No-Intervention Scenarios Over Five Years

The increase in the biodiversity index in figure 2 is from 0.48 to 0.70, which is about 45.8% of the initial value. By year 5 the difference between the restoration and no intervention cases is 0.27 index points. This

suggests that coordinated environmental interventions may be able to enhance the ecological function of small urban wetlands.

The progressive upward trend also reflects the assumption of the need for time to carry out ecological recovery. The time lag may be different for establishment of vegetation, water quality improvement, recolonization, and development of a stable aquatic community. The simulation thus does not make the assumptions of any immediate recovery of biodiversity after management operations.

Regional Implications of Small Wetland Conservation

The results from both simulations stress that small urban wetlands are assessed as a part of a regional ecological network. Different habitat conditions can create different communities of organisms on the landscape, and individual wetlands may have only a few species. Ecological variation can create species diversity in the regions via habitat complementarity.

The findings also indicate that conservation measures targeting only monetary increases in the size of existing wetlands may be missing other significant ecological enhancements. Habitat heterogeneity, pollution reduction, protection/restoration of native vegetation, and creation of appropriate linking of wetlands provide complementary biodiversity benefits.

The results should be considered in the context of the simulation design. These observed differences are based on a set of hypothetical parameters and are not used to infer causal relationships or statistically significant ecological effects. Actual responses to biodiversity would vary depending on regional climate, species pool, wetland hydrology, local land-use attributes, and specific dispersal needs of species.

V. Conservation and Management Implications

The simulation results indicate that these benefits can be achieved through an integrated urban wetland conservation strategy focused on habitat restoration, water quality enhancement, native vegetation management, and enhancement of ecological connectivity. Small wetlands are identified as important parts of regional freshwater biodiversity networks by urban planning authorities and are included in land-use and infrastructure development decisions that include protection of small wetlands. Water plants, various shore characteristics, and suitable water depth should be provided to improve the habitat for aquatic organisms. To reduce the ecological damage, it is necessary to have pollution controls, water quality checks, and restrictions on improper disposal of waste. Introducing non-native species also may be managed to limit changes to native aquatic communities. Additionally, wherever possible, phytoplankton, zooplankton, macroinvertebrates, aquatic plants, amphibians, and fish are monitored as part of the biodiversity monitoring program. Conservation interventions are proactive and strike a balance between biodiversity and public-health needs and do not result in practices that create unintended simplification of aquatic habitats. Although parameters are calibrated prior to operational conservation decisions based on actual field observations, the proposed simulation framework can give some guidance about prioritizing wetland restoration activities.

VI. Conclusion

The study has created a modelling framework to examine how small urban wetlands contribute to the regional aquatic biodiversity. The results show that ecological connectivity, habitat quality, native vegetation cover and water quality may all have a potential impact on the biodiversity potential of urban wetlands. Simulated species richness and Shannon diversity were higher in the high-connectivity group than the low-connectivity group. The five-year restoration time series also showed a positive trajectory in biodiversity, relative to the hypothetical no-intervention scenario. The outcomes highlight the need to consider small wetlands as a connected set of ecological resources, not simply as separate urban water resources. The proposed framework provides a basis for further work to combine field surveys of

biodiversity inventories, water quality data, spatial connectivity analyses and ecological modelling. There is a need for more empirical evidence to quantify the contribution of biodiversity in urban settings.

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