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# Synergistic Interaction of Hydrological Regulation and Habitat Networks in the Revitalization of Urban Blue–Green Spaces: A Case Study of Catharijnesingel Canal Park

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**Abstract** Under the dual background of global urbanization and climate change, challenges such as urban waterlogging, degradation of water environment, and fragmentation of biological habitats are intensifying. Advancing the transformation of blue-green infrastructure from a single function to multiple coordinated functions has emerged as a critical path for enhancing urban ecological resilience. The Catharijnesingel Canal Park in Utrecht, the Netherlands, serves as a case study to investigate the synergistic interaction of hydrological regulation and habitat network construction through the transformation of historical canals from grey to blue-green infrastructure. Initially, the implementation path of this "blue-green renaissance" is analyzed, followed by a detailed examination of the spatial realization patterns and mechanisms underlying hydrology and habitat synergy, focusing on river form remodeling, vegetation community alignment, and precise habitat design. The results indicate that the collaborative model of "hydrology and habitat" coupling not only enhances rain-flood resilience, biodiversity, and the quality of public spaces in urban areas but also serves as a reference model for high-density urban regeneration by integrating space, ecology, and efficiency. This model offers both a theoretical foundation and practical guidance for Chinese cities aiming to achieve functional integration and synergistic interaction in ecological restoration and the development of blue-green spaces.

**Keywords** Blue-green infrastructure, Hydrological regulation, Habitat network, Synergistic interaction, Urban renewal
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Amidst the rapid global urbanization, ecological challenges within urban environments have become increasingly pronounced. Issues such as frequent waterlogging, water pollution, and habitat fragmentation not only threaten the health of ecological systems but also directly impact residents' quality of life and the sustainable development of society. On a global scale, extreme climatic events are occurring with greater frequency. The Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) highlights the vulnerability of traditional grey infrastructure in this context[1]. Furthermore, exemplary international practices, including Boston's "Emerald Necklace" and Singapore's "ABC Water Plan"[2], demonstrate the systematic integration of blue, green, and grey infrastructures to achieve functional coupling and spatial superposition. This integration results in a synergistic effect exceeding the sum of individual components (1+1+1>3), thereby substantially enhancing urban resilience[3].

Many urban renewal projects continue to treat "hydrological management" and "ecological restoration" as separate projects, lacking systematic coordination. This separation results in inadequate integration of multiple ecosystem services within blue-green spaces, thereby limiting the potential to maximize ecological benefits. The term blue-green space is the combined concept of blue space and green space. Unlike the traditional notion of waterfront landscapes, the definition of blue-green space emphasizes complex, integrated systems[4]. From a theoretical perspective, although a systematic framework exemplified by "blue-green infrastructure" (BGI) has been established internationally[5], focusing on the connectivity and network con-struction of water and green spaces, there remains insufficient discussion regarding the dynamic coupling mechanisms and synergistic pathways between "hydrological regulation and habitat networks". Domestic research has primarily concentrated on optimizing individual functions, such as the application of sponge city technologies and habitat restoration design. Systematic investigation into the collaborative mechanisms, quantitative evaluation, and implementation strategies for the complex functions of blue-green spaces remains in its nascent stages, with a notable lack of empirical studies that integrate the context of historical linear water regeneration.

In this context, the Catharijnesingel regeneration project in Utrecht, the Netherlands, serves as a case study for comprehensive analysis[6]. In recent years, the canal, which had been pre-

## Column introduction

The current City Observer column offers a comprehensive analysis of the Catharijnesingel Canal Park in Utrecht, the Netherlands, which has transformed the historically grey canal infrastructure into a vibrant blue-green space. The park integrates "hydrological management" with "ecological restoration" to enhance the city's stormwater resilience, biodiversity, and the quality of public spaces. Furthermore, it serves as a valuable model for the integration of spatial planning, ecological considerations, and community benefits in high-density urban renewal projects.

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viously buried to accommodate urban transportation construction, was restored through a "blue-green renaissance" strategy and transformed into a linear park featuring ecological regulation, biological habitats, and public recreational functions. Through systematic design, the project achieves a profound integration of hydrological regulation and habitat networks, offering valuable insights into enhancing urban resilience and promoting ecological and social benefits through blue-green synergy in densely built environments. This case exemplifies the internal mechanisms underlying the synergy of blue-green infrastructures and provides both theoretical guidance and practical approaches for ecological construction in urban renewal projects in China.

# 1 Case background and collaborative path

## 1.1 Design strategy of Catharijnesingel Canal Park

Catharijnesingel Canal Park (Fig.1), situated in the historic center of Utrecht, the Netherlands, represents a prominent urban blue-green space restoration project[7]. The primary objective of this initiative is to reconstruct and restore a historic canal that had been buried during transportation infrastructure development in the middle of the 20$^{th}$ century, transforming it into an urban waterfront area that provides both ecological service functions and public recreational values. The project successfully achieves a synergistic integration of hydrological regulation and habitat network through innovative ecological design approaches, thereby establishing a resilient urban infrastructure capable of withstanding extreme weather events while delivering multiple ecosystem services[8]. Urban eco-hydrological regulation services constitute a critical component of ecosystem services, playing a vital role in managing surface runoff and maintaining hydrological balance. These functions are essential for mitigating the risks associated with heavy rainfall and urban flooding, ultimately enhancing urban resilience[9].

The restoration of the canal structure around the old city of Utrecht is an important part of the Master Plan for the Station Area. Approximately 50 years ago, the canal was filled for the construction of a ten-lane motorway. To restore the historical context, alleviate traffic congestion, create public spaces, and systematically enhance the city's ecological resilience, the original, historical water structure is restored by re-excavating the canal. Consequently, the historic center of Utrecht is once again fully surrounded by water and vegetation. The project area now has a green and sloping character in which ecology, water recreation and traffic have been carefully integrated. Thanks to the nature-friendly foreshores, there is more space for flora and fauna and a lot of greenery has been brought back into the city.

For the layout of Catharijnesingel and the extension of the Zocherpark that runs alongside it, the designer has made well-considered choices concerning the type of traffic flow. Pedestrians are given priority over other kinds of traffic, but only where it is desirable and not primarily in all situations. The extensive walking route along the canal invites recreational and sporting use. One walks past grasslands, conversation pieces (art objects that encourage interaction about climate adaptation or the history of the place), numerous seating areas, and a variety of greenery.

The proposal to utilize the canal park as a new habitat for living organisms plays a crucial role in enhancing urban resilience by improving the city's capacity to withstand high temperature, storms, and floods. Furthermore, the integration of water recycling and vegetation contributes to carbon sequestration and pollution reduction. In the planting plan, a variety of species are used: from evergreens to richly flowering species that create a year-round experience. In combination with the openness of the water and grasslands, the planting groups provide beautiful vistas and sightlines. The water line is a cultivated line, in which the reflection of the park is purposefully mirrored. The reflection of tall plants and trees is used to create a visual unity between the canal and the park.

The primary objective of the design is to reestablish the city's connection with water, thereby restoring its historical relationship and creating public spaces for residents to engage in leisure, sports, and aquatic activities (Fig.2). The design reintroduces greenery into the urban environment through expansive walking trails, recreational and sports spaces, and nature-friendly foreshores. Emphasizing climate adaptation, the project enhances the city's resilience to extreme weather events, including high temperature, storms, and floods, by restoring canal water bodies, implementing porous design, and diversifying vegetation. Furthermore, the introduction of various native and adaptive plant species fosters the development of new habitats for small organisms such as birds and insects[10].

## 1.2 Spatial implementation of collaborative design

**1.2.1** Meandering of river channel morphology. River channels serve as critical bonds between terrestrial and aquatic ecosystems, performing multiple essential functions including flood control, drainage, water purification, and providing biological habitats[11]. The canal park abandons the traditional design of straight gutters and removes the original hard ground cover to emulate the complex morphology of natural rivers. The river is redesigned with a flat layout featuring gently varying curves. The banklines are intentionally shaped with irregular protrusions and recesses, which not only enhance aesthetic appeal but also create diverse flow velocity conditions—characterized by slower flow on the inner bends and faster flow on the outer bends. These variations in flow velocity offer suitable habitats for aquatic organisms with differing behavioral preferences. Additionally, the meandering channel increases flow resistance, effectively reducing flow velocity and mitigating erosive forces on the shoreline[12]. The extended flow path also prolongs water residence time within the park, facilitating the sedimentation and purification of suspended particles.

**1.2.2** Diversification of river cross-sections. A single vertical concrete embankment is replaced with a combination of gentle slopes, stepped revetments, and partial vertical revetments. Various types of revetments are designed, including gentle slope grasslands, stone cage revetments, and wooden platforms, all aimed at supporting hydrophilic and biological habitats. The design approach involves treating the shoreline as a natural soil slope, facilitating the natural spread of vegetation from land to water, creating a longitudinal sequence of alternating shallow and deep water zones, and establishing step-like or gently sloping areas that can be periodically inundated above normal water levels. This configuration significantly expands the interface between land and water, forming a continuous gradient from deep water to shallow water, and from wet to dry conditions. Additionally, gentle slopes and beaches serve as supplementary flood storage areas during heavy rainfall, enhancing rainwater regulation and storage capacity, while providing optimal habitats for the foraging and breeding of amphibians and waterbirds.

**1.2.3** Transformation of river basement. Pebbles, boulders, and dead wood are strategically placed within the riverbed to create "ecological reefs". Ecological modifications involve altering riverbed and shoreline substrates by substituting concrete with porous materials or employing natural earthen slopes stabilized by plant root systems. Porous revetments function to physically capture suspended particles as water flows over them. The addition of gravel, fallen logs, tree roots, and other natural materials to the riverbed generates microhabitats that serve as attachment sites, shelters, and foraging grounds for aquatic insects, fish, and small crustaceans. Furthermore, these structures provide space for plant root development, thereby contributing to the establishment of a stable ecosystem[13].

**1.2.4** Construction of continuous communities by planting combinations. Native plant species are carefully selected and arranged along water level gradients to establish continuous vegetation filter belts, thereby simultaneously facilitating water purification and providing habitat. The design team models natural succession processes to develop a comprehensive vertical sequence comprising aquatic vegetation, wetland herbaceous layers, shrub layers, and tree layers. These vegetation strata are not isolated, but interconnect and transition seamlessly. This spatial configuration transforms the plant community from a background into an active, synergistic system that performs essential functions in hydrological regulation and habitat provision. In conjunction with the "reshaping of channel morphology", this approach collectively establishes the canal park as a dynamic, self-regulating, and resilient ecosystem.

## 2 Synergistic mechanism of "hydrology and habitat"

### 2.1 Core strategies

**2.1.1** Public space activation. The activation of public spaces facilitates the transformation of ecological value into tangible social value. Ecosystem services contribute to enhancing the quality of public spaces, while the vitality of these spaces supports ecological sustainability. Elements such as clear water bodies, hydrophilic interfaces, microclimates generated by evapotranspiration, and habitat network functions are directly experienced as core components within public spaces. Consequently, ecological benefits transcend abstract metrics to become vibrant environments where citizens can directly perceive ecological health and environmental aesthetics. The dynamism of public spaces promotes sustained social engagement and the ongoing maintenance of ecological infrastructure. In this context, citizens transition from mere users of ecosystems to active guardians. This societal feedback loop is essential for maintaining the long-term synergistic mechanism of hydrology and habitat, thereby fostering a public ethos that prioritizes the protection of ecological health during park utilization.

**2.1.2** Hydrological regulation efficiency and its ecological contribution. Hydrological mechanisms influence vegetation growth, structure, spatial patterns, and community distribution through processes such as flooding, wave action, and water flow[14]. Integrating hydrological regulation with the fulfillment of habitat requirements involves more than merely controlling water volume, and entails the creation of flow diversity. The meandering of river channels and the formation of shoal and deep pool sequences serve to delay floods while generating a range of flow velocities and depths. These dynamics suggest that engineered hydrological regulation can create diverse habitats and provide suitable living conditions for various aquatic organisms, thereby directly enhancing aquatic biodiversity. Additionally, the filtration capacity of ecological revetments, along with the pollutant absorption and degradation performed by aquatic plants and rhizosphere microorganisms, can systematically improve water quality[15]. In this context, water purification through hydrological regulation is not an ultimate goal but a necessary prerequisite for restoring highly sensitive habitats and facilitating the return of specific organisms.

**2.1.3** Habitat network efficiency and its hydrological feedback. A diverse array of native plant species has been introduced in the canal park to provide food for pollinating insects, including bees and bumblebees. Concurrently, efforts to restore water flow and improve aquatic ecosystems are underway, exemplified by initiatives such as the well-known fish doorbell project in Utrecht, which aims to facilitate fish migration and enhance the vitality of underwater ecology. These measures create habitats and migration corridors for birds, insects, and aquatic organisms, thereby promoting urban biodiversity. Within this habitat network, plants function not merely as passive ornamental elements but as active soil stabilizers, analogous to natural water pumps and filters. Through their biological activities, they sustain and enhance hydrological regulation with minimal energy expenditure. Healthy plant communities foster the proliferation of soil microorganisms, which contribute to the improvement of soil aggregate structure and the formation of a stable pore network. This biologically influenced porous soil acts as an efficient spongy body, significantly enhancing soil infiltration and water retention capacities, thereby strengthening the site's rainwater retention function at its source. Furthermore, the dense vegetation community optimizes the hydrological cycle by intercepting rainfall through tree canopies, reducing groundwater levels via transpiration, and mitigating erosion through root stabilization of bank slopes.

### 2.2 Synergistic benefits

**2.2.1** Microclimate regulation of green sponge. The project integrates the restoration of natural

**Fig.1 Catharijnesingel Canal** (photo source: https://www.gooood.cn/catharijnesingel-utrecht-okra.htm)

**Fig.2 Catharijnesingel Canal Park water system** (photo source: https://www.gooood.cn/catharijne singel-utrecht-okra.htm)

river channels, permeable pavements, soil, and extensive vegetation root systems to form a distributed green sponge system. This system effectively delays runoff, facilitates infiltration, and purifies rainwater, thereby significantly reducing the burden on the municipal drainage network and enhancing the city's resilience to heavy rainfall events. Additionally, the expansive water bodies absorb substantial heat through evaporation, while the dense vegetation community continuously releases moisture into the atmosphere via transpiration, which dissipates heat from the surrounding environment and effectively lowers local temperatures. Consequently, this system not only addresses urban flooding issues but also mitigates the urban heat island effect to a considerable extent.

**2.2.2** Connection of fragmented green spaces by ecological corridors. The canal functions as a blue ecological corridor, restoring connectivity to a landscape previously fragmented by urban roads and linking isolated patches of parks and green spaces in central Utrecht. By designing diverse habitats, these parks not only serve as refuges for various species but also establish secure migratory and dispersal pathways. Birds, insects, amphibians, and small mammals utilize this corridor to move, facilitating gene flow and enabling access to new food sources and habitats. This project optimizes the urban landscape pattern by transitioning from a "patch-based" model to a "networked" model. Such enhanced connectivity significantly improves the stability and resilience of the entire urban ecosystem[16].

**2.2.3** Enhancement of vitality and identity through hydrophilic design. The park mitigates both physical and psychological barriers between individuals and the water by incorporating a natural shoreline design featuring a gentle slope, a hydrophilic platform, and a waterfront footpath. This design fosters a novel hydrophilic experience that encourages activities such as walking, cycling, boating, resting, and socializing, thereby transforming the area from a mere transportation corridor into a dynamic urban public space. Public engagement and appreciation promote sustained social attention and provide intangible protection for the park. Consequently, spaces valued by the community demonstrate greater resilience against destruction and inappropriate development, thereby ensuring the long-term sustainability of ecological benefits.

**2.2.4** Synergistic model. Optimized hydrological systems constitute the fundamental physical framework for habitat networks. The availability of clean water, variability in flow rates and water depths, and the presence of healthy soil moisture gradients directly influence the composition and abundance of plant communities. These plant communities subsequently provide essential resources such as food, water, and shelter for diverse animal species, thereby fostering rich biodiversity. Moreover, established habitat networks reciprocally enhance hydrological functions through their biological activities. For instance, plant roots stabilize bank slopes and improve water quality, while soil microorganisms and fauna enhance soil structure and increase infiltration capacity. Additionally, a well-functioning food web plays a critical role in maintaining the ecological balance of aquatic environments.

The high-quality ecological environment shaped by hydrology and habitat constitutes an appealing public space. This ecological value is directly reflected in perceived social benefits, offering citizens venues for leisure, physical activity, environmental education, and spiritual well-being. Consequently, it fosters public vitality and cultivates a profound sense of place attachment among individuals. Blue-green spaces are intricately interwoven both horizontally and vertically. Hydrological and ecological systems mutually reinforce and depend upon one another, ultimately providing integrated ecosystem services whose combined value significantly surpasses the sum of their individual contributions.

# 3 Conclusions and implications

## 3.1 Main conclusions

The design path and fundamental mechanisms employed to achieve synergistic interaction between "hydrology and habitat" at Catharijnesingel Canal Park illustrate that integrated blue-green infrastructure is essential for the enhancement of urban ecosystem services. This project effectively restores the historical canal into a self-regulating and continuously evolving living system. At the spatial practice level, the integration of macro-scale river morphology remodeling, meso-scale continuous plant community alignment, and micro-scale habitat fine-tuning collectively constitute a three-tiered technical framework to achieve synergistic interaction. Each tier facilitates the functional coupling of hydrological regulation and biological habitat in terms of both physical structures and ecological processes.

The system operates through a virtuous cycle mechanism. An optimized hydrological environment underpins the existence of the habitat network, while a healthy biological community and its associated physical structures reinforce and enhance hydrological functions through their life activities. Ultimately, Catharijnesingel Canal Park not only improves urban climate resilience by functioning as a green, sponge-like entity and connects fragmented habitats as an ecological corridor, but also promotes community well-being as a center of public vitality. This park serves as a comprehensive model for the ecological renewal of densely populated global cities, demonstrating a viable approach to constructing resilient, healthy, and livable urban environments through collaborative design.

## 3.2 Successful experience of the collaborative design of Catharijnesingel Canal Park

Catharijnesingel Canal Park offers a replicable and comprehensive framework for the systematic planning, design, and evaluation of historic urban areas and densely built environments confronting analogous renewal challenges. Urban blue-green spaces must achieve an integrated harmony among hydrological processes, ecological functions, and human activities. Such spaces should not be regarded merely as isolated water management or park projects but as complex, dynamic systems[17]. Through innovative design strategies, water security is maintained by the ecosystem, which in turn is strengthened by the presence of healthy water. This synergistic cycle collectively contributes to the development of an urban park that is both more resilient to climate change and richer in biodiversity.

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(To be continued in P18)

**Table 3 Three development stages of the theory of architectural space narrative**

| Phase | Time | Key event | Main features |
|---|---|---|---|
| Early budding stage | The 1960s and 1970s | Roland Barthes published *Elements of Semiology*, introducing a semiotic framework for analyzing the transmission of meaning in architectural elements[9-10]; Christian Norberg-Schulz authored *Genius Loci*: *Towards a Phenomenology of Architecture*, highlighting the intrinsic relationship between architectural space and the significance of human existence[11-12]. | These studies began to transcend the constraints of traditional architectural research by incorporating semiotic and phenomenological perspectives, emphasizing that architectural space is not merely a physical entity but also serves as a narrative medium embodying history, culture, and emotions. |
| Development stage | The 1980s and 1990s | Long Diyong published *Spatial Narratology*, systematically integrating spatial dimensions into the narratological research framework[13]; Frank Owen Gehry designed the Guggenheim Museum Bilbao, demonstrating the applicability of spatial narrative theory through deconstructivist modeling and spatial sequencing[11]. | The theory of space narratology has swiftly emerged as a significant guidance for innovation in architectural design; numerous practical cases, including the Guggenheim Museum Bilbao, have demonstrated the theory's effectiveness in real-world applications. |
| Mature stage | From the early 21st century to the present | Interdisciplinary research has become standard practice, with fields such as sociology, psychology, and cultural studies being thoroughly integrated; the utilization of digital technologies, including virtual reality (VR) and augmented reality (AR), in the narrative design of architectural spaces is increasingly prevalent. | The ongoing advancement of both theoretical and practical approaches has propelled the narrative of architectural space into a mature and flourishing phase; enabled by digital technologies, including VR and AR, this progression transcends the constraints of physical space, facilitating the creation of immersive narrative experiences. |

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