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Ecological Design of Community Rain Gardens under the Sponge City Concept: A Case Study of Three Projects on Permeable Pavements and Bioretention Ponds

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Abstract. With rapid urbanization in China, issues such as urban flooding, water scarcity, and water pollution have become increasingly prominent. The sponge city concept offers systematic solutions to these challenges. Community rain gardens, as a key implementation of this concept at the neighborhood scale, utilize ecological design to enable natural rainwater accumulation, infiltration, and purification. This study explores the ecological design strategies and key technical features of permeable paving and bioretention ponds in rain gardens, based on case studies of three representative projects in China: the Shenzhen Guangming Art Center, the Qinhuang Avenue in Xixian New Area, and the Qingshan Lake Greenway in Hangzhou. Findings indicate that permeable paving design must address site-specific challenges, such as balancing bearing capacity with permeability, employing composite infiltration on collapsible loess, and integrating blind pipes with cleanout openings to prevent clogging. Bioretention pond designs also vary considerably: multi-layer media with storage modules in public landscapes, L-shaped waterproof walls with impermeable geotextiles in road medians, and terraced inverted trapezoidal trenches with mixed fillers in ecological corridors. The findings aim to provide theoretical references and practical guidance for sponge community construction in China.

Keywords: Sponge City, Rainwater Gardens, Permeable Pavements, Bioretention Cell, Ecological Design

1. Introduction

The traditional approach to urban construction has altered the underlying surface, leading to increased surface runoff and disruption of the hydrological cycle. It has triggered a range of urban water-related issues. The concept of sponge cities advocates mimicking natural hydrological processes by establishing low-impact development rainwater systems that enable the natural management of rainwater [1]. In the context, community rainwater gardens have emerged as a type of green infrastructure that offers low investment costs, strong ecological functions, and aesthetic value. They have thus become an essential component of sponge city development. Rainwater gardens utilize the synergistic effects of plants, soil, and microbial systems to achieve the infiltration, retention, purification, storage, and utilization of rainwater. This approach effectively

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controls runoff pollution and reduces the burden on urban drainage systems. Permeable paving and bioretention ponds, as the two core technologies of rainwater gardens, play a crucial role in both source reduction and process control.

In recent years, cities such as Beijing, Shenzhen, and Yangzhou have implemented numerous practices across different climatic conditions, accumulating valuable experience in this field. However, numerous studies have addressed the hydrological performance of individual Low-Impact Development (LID) practices. Existing studies rarely compare how permeable paving and bioretention ponds are ecologically designed across different climatic and geological contexts in China. To address these gaps, this study systematically uses representative rain garden case analyses to explore key ecological design strategies for permeable pavements and bioretention ponds. The study aims to promote the precise implementation of the sponge city concept.

2. Theoretical basis and technical framework

2.1. Sponge cities and low-impact development

Sponge cities emphasize that cities should possess the same "resilience" as sponges, enabling them to adapt to environmental changes and cope with natural disasters [1]. The core concept is to utilize LID techniques to mimic natural hydrological processes, thereby achieving source control of rainwater and ecological management.

2.2. Ecological functions of rain gardens in sponge cities

The sponge city aims to build an urban rainwater management system. Within this system, community rain gardens serve as small, decentralized green infrastructure, playing a crucial role in source water management. Compared to large-scale gray infrastructure, rain gardens offer advantages such as flexible layout, low construction costs, and easy maintenance, making them better suited to the spatial characteristics and functional needs of community scales.

Rain gardens play an important ecological role in sponge cities through three main ecological functions: First, through soil infiltration and plant interception, they effectively reduce surface runoff. Authoritative data released by relevant departments show that China's urbanization rate has exceeded 65%. At the same time, weak regulation of rainwater runoff and low water-use efficiency remain major challenges in urban operations [2]. Second, they have a water-quality purification function: rain gardens effectively remove suspended solids, heavy metals, and organic pollutants from runoff through soil filtration and microbial decomposition, thereby improving the efficiency of rainwater use. Third, they have a microclimate regulation function: the vegetation in rain gardens lowers environmental temperatures through transpiration. In addition, rain gardens can provide habitat functions by supporting plant and insect diversity.

2.3. Principles of rain garden design

The design of community rain gardens needs to follow three key principles [2]. The ecological priority principle, which respects natural hydrological processes and uses native plants and permeable materials whenever possible. The functional integration principle combines rainwater management, landscape recreation, and ecological education to improve space efficiency [3]. Third, the adaptive design principle flexibly selects technical combinations based on local climate, soil, and community characteristics. These principles ensure that rain gardens can effectively serve ecological

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purposes while seamlessly integrating into community life, achieving harmonious coexistence between humans and nature. The two key technologies of rain gardens are existing typical ecological design methods for permeable paving and bioretention basins.

3. Permeable paving and bioretention basin design

3.1. Ecological design strategies for permeable paving

Permeable paving is a "breathing" surface that plays a crucial role in the construction of sponge communities. Through special materials and structural designs, it allows rainwater to quickly infiltrate into the ground, replenishing groundwater while reducing surface runoff. The structure of pervious paving typically includes an upper surface layer, a base course, and an underlying sub-base, each with specific material requirements and functional purposes. For structural design, the thickness of each layer and material mix must be determined based on expected loads and rainfall intensity. For sidewalks, a total thickness of 150-200 millimeters is typically used; for driveways, a thicker structural layer (250-300 millimeters) is needed to ensure sufficient load-bearing capacity.

Permeable surfaces now face the risk of clogging and require regular maintenance. Maintenance measures include vacuum cleaning and high-pressure water jet flushing to maintain their permeability. Permeable surfaces are often combined with features such as bioretention ponds to form a complete rainwater management system, achieving source control and rainwater process management. Previous surfaces offer significant ecological benefits: their porous structure helps absorb noise and mitigate the urban heat island effect.

3.2. Ecological design strategies for bioretention ponds

Bioretention ponds are a core component of rain gardens, purifying and retaining rainwater through plants, soil, and microbial systems. They are typically built in low-lying areas to collect and treat runoff water from roofs, roads, and other surfaces.

The design of bioretention ponds must account for factors such as site selection, structure, and plant configuration to achieve a balance between functionality and ecology. A typical bioretention pond structure consists of layers from the top down: a plant layer, a cover layer, a planting soil layer, a filtration layer, and a drainage layer. These multiple layers work together to retain, infiltrate, and purify rainwater.

4. Analysis of representative rain garden cases

Three successful examples of using rain gardens in China were selected: the Shenzhen Guangming Art Center, Qinhuang Avenue in Xixian New Area, and the Hangzhou Qingshan Lake Greenway [4-6]. In-depth analyses were conducted on their permeable paving and bioretention pond technologies.

4.1. Background information

4.1.1. Shenzhen Guangming Art Center

The Shenzhen Guangming Art Center is a cultural landmark built by the Guangming District, covering approximately 130,000 square meters. Its design concept, "Landscape Courtyard Eye," integrates a "return"- shaped layout with the Lingnan stacked courtyard style, creating a central landscape courtyard and the "Eye of Guangming" archway landmark [4]. It has also been awarded

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the National Green Building Three-Star Label, emphasizing low-carbon environmental protection. The project covers about 38,000 square meters and has won the Luban Prize for Chinese Construction Projects.

4.1.2. Xixian New Area Qinhuang Avenue

Xixian New Area is a major north-south arterial road in Fengxi New City and also a national-level sponge city demonstration road. Its core concept is sponge city practices, abandoning traditional drainage models in favor of LID principles. Through permeable paving, sunken green spaces, ecological swales, and rain gardens, it creates a system that integrates infiltration, detention, storage, purification, reuse, and drainage. The main indicator is in line with urban arterial standards, with an annual runoff total control rate of ≥85% [5].

4.1.3. Hangzhou Qingshan Lake Greenway

Qingshan Lake in Hangzhou is located in Lin'an District and is now an ecological and technological innovation landmark featuring "coexistence of lake and city" as a national forest park and Qingshan Lake Science and Technology City. The core concept is the "dual green coexistence" of ecology and technological innovation. By preserving rare aquatic forest landscapes and building greenways around the lake, it aims to return the lake to the people and create a high-quality ecological living area. The key indicators include a total area of about 64.5 square kilometers, a water area of about 10 square kilometers, and a forest coverage rate exceeding 82%. Its core landscape is an aquatic forest covering approximately 1,000 acres [6].

4.2. Applications of rain garden technology

4.2.1. Shenzhen Guangming Art Center: "demonstration-type rain garden system

The technical configuration includes display-type rain gardens, bioretention basins, sunken green spaces, green roofs, vegetated buffer strips, and ecological gravel ditches. These facilities are connected via rainwater that ultimately flows into underground storage tanks for reuse. This design reflects the integration of sponge facilities with the artistic design concept of "mountain-water-pastoral," achieving both functional and landscape value. The project achieved the targets of 74.3% annual runoff volume control rate, 56% non-point source pollution control rate, and 50% permeable pavement rate, meeting Shenzhen's sponge city construction requirements [4].

4.2.2. Xixian New Area Qinhuang Avenue: "curb-style" bioretention system

The core of this technical solution is the safe and efficient use of Low LID facilities under collapsible loess geological conditions. The key technologies include pollution interception troughs and located at curbstone openings, these use recycled construction waste aggregates to filter out impurities, disperse runoff, and dissipate energy. L-shaped reinforced concrete waterproof retaining walls fundamentally address the threat of rainwater infiltration to the stability of roadbeds on collapsible loess foundations [5]. In addition, low-point drainage channels are used to safely channel excess rainwater to regulation ponds during extreme downpours, ensuring system safety.

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4.2.3. Hangzhou Qingshan Lake Greenway: "terraced" ecological retention system

The core features of this ecosystem consist of terraced flower streams, bioretention ponds, wetlands, and permeable paving. The ecological strategy emphasizes adapting to local conditions, cleverly utilizing the existing topographical differences to create terraced flower streams, forming a multi-level rainwater retention and purification system; and by creating flower fields, islands, seas, and slopes, a rich biodiversity conservation network is established. In terms of infrastructure, the main garden paths are paved with permeable concrete covering an area of 2.94 hectares, accounting for 40% of the total paving area, effectively promoting rainwater infiltration [6].

4.3. Comparative analysis

Table 1. Paving type and technical features

Comparative dimension	Shenzhen Guangming Art Center	Xixian New Area Qinhuang Avenue	Hangzhou Qingshanhu Greenway
Pavement Type	Permeable pavement (square/pedestrian area)	Shallow permeable bricks (sidewalk)	Permeable concrete (main garden path) and permeable asphalt
Technical challenges	High Bearing Capacity and Permeability Balance	Complex pipelines and collapsible loess	Large-area continuous paving with anti-clogging properties
Special Techniques	Permeable pavement and ecological gravel channel combination	Fissure and pore permeability composite	Blind pipes with cleanout openings (>40m)

Table 2. Structural design and special measures

Project	Structural Layer Design	Special Measure	Applicable Scenarios
Shenzhen Guangming Art Center	Multi-layer media filtration, phytoremediation, water storage module	Connected in series with green roofs and gravel trenches; underground water storage tank installed at the end.	Public building landscape area
Xixian New Area Qinhuang Avenue	Conveyance-type grass swale, Bioretention grass swale, Rain garden	L-shaped waterproof retaining wall; debris interception channel; impermeable geotextile	Municipal road median
Hangzhou Qingshanhu Greenway	inverted trapezoidal trench, mixed filler, blind pipe	Multiple mixing of filler; pre-backfill water tests	Park green space/ecological corridor

Table 1 and 2 reveals that bioretention pond designs vary significantly according to site functions and geological constraints. The Shenzhen case employs a demonstration-type bioretention pond with a complete multi-layer media system and water storage module. It is well-suited for public building landscape areas where aesthetic and functional integration is required. The Xixian New Area case adopts a segmented transitional design, making it ideal for municipal road medians. The Hangzhou case features a terraced inverted trapezoidal trench approach adapted to park green spaces and ecological corridors.

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5. Discussion

Although community rain gardens demonstrate significant ecological benefits, they still face numerous challenges during actual construction processes.

5.1. Challenges

At the design level, soil selection and improvement, vegetation configuration, and coordination with urban infrastructure pose major difficulties. Rain gardens require strict soil permeability standards, whereas urban soils often suffer from compaction and contamination issues [7]. Regarding maintenance, the lack of long-term maintenance mechanisms leads to functional degradation of facilities, such as plant mortality and soil clogging. Meanwhile, insufficient community participation and poor interdepartmental coordination also hinder the widespread adoption of rain gardens [8].

5.2. Recommendations

To address the design challenges, rain garden projects should adhere to the principle of site-specific adaptation, selecting appropriate technology combinations based on local climate, soil conditions, and community characteristics. The synergistic effect of these two technologies forms a complete stormwater management chain. Successful rainwater gardens should balance ecological functions, landscape effects, and recreational value to enhance residents' sense of fulfillment and participation. Meanwhile, community engagement should be further strengthened by integrating rainwater garden construction with neighborhood governance to establish a positive interaction mechanism. Through the organic integration of technology, management, and community participation, community rainwater gardens will undoubtedly play a greater role in sponge city construction, providing robust support for building sustainable and resilient urban water systems.

6. Conclusion

Through three cases of Shenzhen Guangming Art Center, Qinhuang Avenue in Xixian New Area, and Hangzhou Qingshanhu Greenway, the study explores the ecological design of permeable paving and bioretention ponds in rain gardens. The findings demonstrate that successful rain garden implementation depends on context-specific design strategies. Permeable paving requires tailored solutions balancing load-bearing capacity, permeability, and maintainability. Bioretention ponds adapt structural layering and special measures to site functions and geological constraints. The study also indicates that challenges in soil conditions, long-term maintenance, and community engagement persist.

The study still has limitations. It is mainly based on cases, which may not represent general conditions across China. The study also focuses on technical design aspects, ignoring social and economic factors. Future research should expand the case sample and explore integrated frameworks that combine technical, social, and economic aspects.

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