Innovative Renovations for Environmental Enhancement in Old Urban Residential Communities: Sponge Smart City Approach

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Abstract: As China's urbanization enters a phase focused on enhancing the quality of the existing built environment, old residential communities commonly face challenges such as aging infrastructure and poor living environments. These issues not only affect residents' daily lives but also pose obstacles to sustainable urban growth. Conducting systematic renovations of these communities is a crucial component of promoting high-quality urban development. To address the core difficulties in renovating old residential communities and to improve the quality and practical effectiveness of these renovations, this paper takes the deep integration of the Sponge City and Smart City concepts as its central theme. It investigates and constructs a systematic, innovative renovation plan aimed at improving the environmental quality of old residential communities, integrating advanced technologies like IoT sensors for real-time monitoring and adaptive management. The goal is to help these communities move away from the traditional "rapid drainage" model and transition towards an integrated water management approach emphasizing "retention, infiltration, purification, utilization, and drainage." This research provides scientifically sound and feasible technical pathways and management methods, offering practical reference experience for urban renewal practices guided by green and low-carbon principles, as well as for the implementation of the national "carbon peak and carbon neutrality" strategy, thereby fostering more resilient and eco-friendly urban spaces.

Keywords: Sponge City; Smart City; Renovation of Old Residential Communities; Low Impact Development (LID); Stormwater Management; Water Resource Recycling; Ecological Resilience; Green Infrastructure

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1 Introduction

Old residential communities with long construction histories, outdated infrastructure, and substandard living environments have become key targets in urban renewal initiatives. It is estimated that the total investment for comprehensive renovation of old residential communities nationwide has exceeded 4 trillion RMB, providing strong momentum for sustainable urban development. Constructing resilient cities capable of effectively withstanding natural disasters and possessing systemic resilience has become a key strategic orientation for urban development in China. [1]

Building “resilient cities” capable of effectively resisting disasters and maintaining systemic resilience has become a core strategic direction in China’s urban development. This paper innovatively establishes an integrated, full-life-cycle rainwater management system based on the principles of “infiltration, retention, storage, purification, utilization,

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and discharge," promoting deep coupling between hydrological cycles and urban spatial structures. Furthermore, guided by landscape ecology theory, we propose an "eco-landscape collaborative design" approach that organically integrates sponge city facilities with landscape architecture—enhancing stormwater regulation capacity while strengthening biodiversity service functions, ultimately creating multifunctional public spaces that combine aesthetic value with ecological conservation benefits.

2 Water Resource Challenges and the Rise of the Sponge Smart City Concept

2.1 Current Status of Water Resources and Urban Water Issues in China

Over the past two decades, rapid urbanization in China has accelerated transportation development, leading to a gradual increase in the proportion of impervious road surfaces within built-up areas. Impervious roads now account for approximately 20% of urban developed land [2].

Urban water resource and environmental problems are characterized by significant complexity and multi-factor interactions. They can easily trigger water safety risks such as urban flooding, and lead to surface runoff carrying large amounts of light pollutants, resulting in serious non-point source pollution. In old residential communities with low drainage standards, limited green space, and continuous degradation of ecological functions, these issues have become prominent constraints on improving living environments and achieving high-quality urban development. Urban water resource challenges present a high degree of complexity. On one hand, rapid urbanization has triggered a surge in water demand, leaving many cities facing resource scarcity. On the other hand, under traditional 'fast discharge' stormwater management models, extensive impervious surfaces hinder rainwater infiltration and cause rapid surface runoff concentration. This not only easily triggers urban waterlogging but also risks the mixing of rainwater and sewage, exacerbating flooding issues because the drainage system struggles to cope with the immense volume during heavy rains [3].

2.2 In-Depth Analysis of the Sponge Smart City Concept

In China, the "Sponge City" concept represents a new generation of urban stormwater management models and a novel urban construction philosophy, offering remarkable benefits at environmental, economic, and social levels [4].

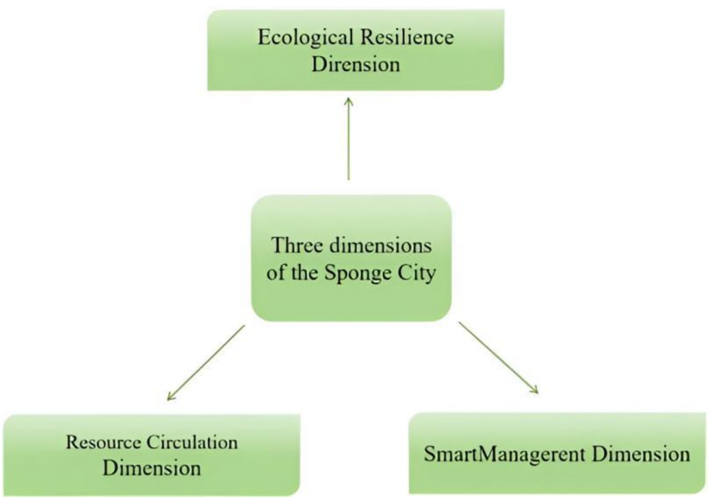

Figure 1 Three dimensions of the Sponge City

Three Core Dimensions:

Ecological Resilience Dimension: By expanding urban "sponge bodies," natural rainwater retention, infiltration, and purification functions are strengthened, effectively enhancing buffering capacity and adaptability to extreme rainfall events, thereby increasing resilience of urban aquatic ecosystems.

Resource Circulation Dimension: The core initiative promotes wastewater reuse. Specifically, collected rainwater is purified and used for non-potable purposes such as landscaping irrigation and street cleaning, achieving rainwater resource utilization goals. This reduces pressure on municipal water supply systems and significantly improves water cycling efficiency.

Smart Management Dimension: Leveraging IoT sensing devices, real-time and precise monitoring of key hydrological parameters—such as rainfall, runoff, and water quality—is conducted. Integrated with big data, cloud computing, and artificial intelligence technologies, a unified smart water management platform is established to simulate flood risks, enable intelligent scheduling of water facilities, and optimize maintenance operations. This transforms urban water management from traditional experience-driven approaches to modern precision governance.

3 Environmental Status and Diagnosis of Core Problems in Old Residential Communities

As integral components of urban built-up areas, old residential communities exhibit typical and concentrated environmental challenges, reflecting micro-scale manifestations of various “urban maladies.”

3.1 Insufficient Drainage Capacity and Combined Sewer Systems

Most old communities were constructed under outdated drainage design standards, featuring undersized pipes, improper slopes, sedimentation, and structural damage, severely reducing drainage performance. A widespread issue is combined sewer systems, where rainwater and sewage share the same pipelines. During storms, large volumes of rainwater mix with sewage, causing untreated mixed discharges into natural water bodies—one of the main causes of river and lake blackening and odor.

3.2 Extensive and Inefficient Water Resource Utilization

Municipal tap water supplies most public landscaping irrigation and street cleaning needs, resulting in low water use efficiency. Meanwhile, abundant potential rainwater resources remain underdeveloped and are treated merely as burdens requiring rapid disposal via direct discharge.

3.3 Degraded Ecological Quality and Lack of Public Spaces

Historical construction constraints have left many old communities with insufficient green space and monotonous vegetation structures, significantly weakening ecological regulation functions. This exacerbates summer heat island effects and generates rapid surface runoff during rainstorms, triggering localized ponding and flood risks.

4 Innovative Renovation Strategies Based on the Sponge Smart City Concept

4.1 Refined Reconstruction of Separate Stormwater and Sewage Systems

This is fundamental for addressing water pollution and flooding. Renovation steps include: first, conducting comprehensive pipeline surveys and diagnostics; second, scientifically calculating and designing independent stormwater and sewage networks; third, fully separating building downspouts; fourth, rectifying misconnected sources such as balcony washing machine wastewater to ensure sewage enters sewage pipes. Underground pipeline upgrades should consider site conditions, employing both excavation and trenchless techniques, alongside necessary pretreatment facilities.

4.2 Diversified Integration of Green Infrastructure

(1) Green Roofs and Vertical Greenery

Flat roofs with adequate structural load capacity can be retrofitted as green roofs to retain rainwater, slow runoff, and provide thermal insulation. Building walls and fences can feature vertical greenery to increase vegetation cover and enhance aesthetics.

(2) Rain Gardens and Bioretention Facilities

Rain gardens collect roof and ground surface runoff, using soil infiltration and plant filtration to purify water, while shallow depressions temporarily store rainwater for gradual groundwater recharge, thus reducing peak discharge. In August 2003, the International Rainwater Catchment Systems Association (IRCSA) conference was held in Heim, Germany. At this conference, the definition and concept of rain gardens were broadened and expanded, leading to the proposal of a generalized definition: any landscape green space system that relies on scientific techniques or natural methods to collect, utilize, and treat rainwater, while simultaneously achieving high landscape quality, may be defined as a rain garden. [4-5] Statistics show that a 1,000 m^2 rain garden can capture about 300 m^3 of rainwater during a 50 mm storm event [6].

(3) Sunken Green Spaces and Permeable Pavements

Sunken green spaces refer to green depressions lower than the surrounding hard-surfaced ground. They possess a certain retention volume, can treat surface runoff from gray spaces such as roads and plazas, reduce the pressure on urban drainage networks, and serve as ecological zones that prevent pollutant diffusion while purifying rainwater runoff. [7] Additionally, converting some paved plazas and parking areas into permeable pavements significantly increases infiltration, reducing runoff at the source. Typically, the design of sunken green spaces is relatively monotonous, offering limited improvement to the ecology and environmental aesthetics of residential communities. Therefore, it is necessary to enhance their ecological and landscape value through design aesthetics and the arrangement of landscape plants within the green spaces [8]. Furthermore, plant selection must prioritize species that can adapt to aquatic environments while possessing drought resistance. Since the water volume in sunken green spaces is closely tied to rainfall—exhibiting alternating periods of high and low water levels—the plants must tolerate both conditions [9]. Additionally, species characterized by developed root systems, rapid growth, and succulent stems and leaves are better equipped to perform these functions [10]. Employing a multi-layered community structure combining arbors, shrubs, and grasses can create a green space landscape rich in seasonal variations.

(4) Collaborative Eco-Landscape Design

Plant selection is critical for successful green infrastructure implementation. Native species with drought/flood tolerance and strong purification capabilities should be prioritized. Scientific planning should establish mixed community structures combining trees, shrubs, and herbaceous plants. This not only creates visually appealing landscapes with rich seasonal variation but also enhances biodiversity and ecosystem stability.

4.3 Intelligent Operation, Maintenance, and Long-Term Management Mechanisms

Detailed surveys of topography, drainage systems, and soil conditions are conducted to understand ponding patterns, runoff pathways, existing facility performance, and ecological status—providing a basis for ecological restoration. The technical route follows "Survey & Analysis → Scheme Design → Technical Validation → Implementation Optimization → Long-term Operation," integrating multidisciplinary methods and digital technologies into a closed-loop process.

First, field measurements collect topographic data,

The traditional two-dimensional linear drawings of land terrain results are transformed from paper-based representations into more intuitive three-dimensional model graphics [11], drainage network layouts, soil infiltration coefficients, meteorological records (e.g., Kunming's average annual rainfall and storm intensity), and resident water-use habits to build a multidimensional database covering flood risk points, runoff paths, and operational statuses. Next, modular designs integrate separate sewers, green roofs, rain gardens, and sunken greenspaces based on sponge city principles.When designing an integrated green roof for green buildings, it is essential to prioritize safety principles by rationally planning the landscape layout to prevent personnel from falling and eliminate all potential safety hazards [12]. BIM technology, with its capabilities of parametric modeling, data integration, and visual simulation, provides a pathway to overcome traditional design bottlenecks in green buildings. Through BIM, the entire digital workflow of "design—simulation—optimization—control" for green buildings can be realized, driving the transformation of design from "passive compliance" to "active optimization." [13].

During construction, a "local pilot → phased advancement" strategy is adopted, prioritizing sponge retrofits in representative zones while deploying IoT sensors to collect real-time data on infiltration rates, pipe pressure, and water quality. Adjustments to construction parameters are made by comparing data with design models.To ensure the comprehensiveness and accuracy of monitoring, sensors for water level, flow rate, temperature, and other parameters are deployed to establish an integrated sky-ground-water sensing network. This network supports high-concurrency data acquisition and real-time transmission, effectively safeguarding system performance while enhancing the safety and reliability of operational processes [14]. Post-project, a dynamic performance evaluation and smart O&M platform is developed using cloud computing to assess long-term ecological, economic, and social benefits. A tripartite "government–market–resident" collaboration mechanism enables automatic fault warnings, intelligent task assignment, and public feedback, forming a sustainable "Design–Construction–Monitoring–Evaluation–Optimization" pathway.BIM technology, centered around digital models, provides robust technical support for visual design, construction process simulation, and refined management and control by systematically integrating geometric information, technical parameters, and management data throughout the entire project lifecycle. Meanwhile, leveraging distributed storage and powerful computing capabilities, cloud computing effectively breaks down barriers between regions and systems, establishing an efficient and flexible platform for data sharing and collaborative work among multiple stakeholders [15]. This provides a replicable standardized solution for sponge retrofitting of old communities.

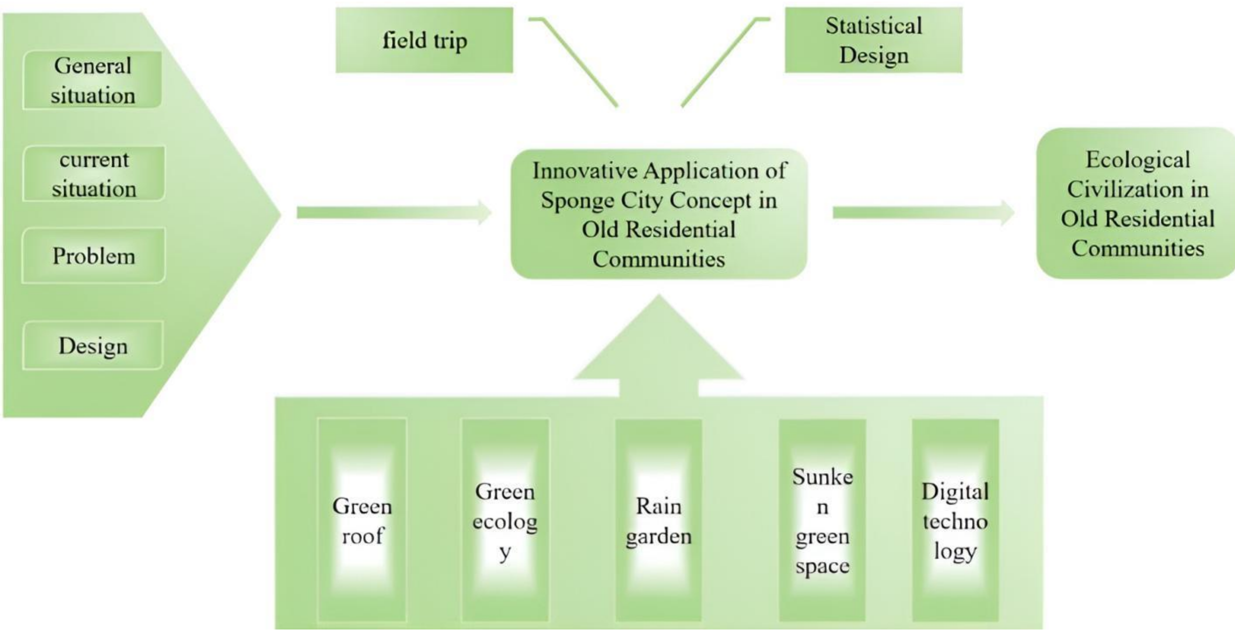

Figure 2 Renovation process flowchart

5 International and Domestic Practice Insights and Conclusions

In summary, renovating old residential communities under the sponge smart city concept is a multidisciplinary, comprehensive project. Unlike conventional retrofitting, its focus is not merely repairing drainage systems but upgrading water systems, ecosystems, and governance models holistically. Implementing stormwater-sewage separation, installing green infrastructure, adopting permeable paving, and establishing intelligent operation platforms can effectively resolve flooding, water pollution, and water scarcity in old communities, enhancing ecological resilience and improving living environments. Since 2015, pilot city initiatives in China have accumulated localized experience in retrofitting complex built environments. By protecting the ecological integrity of river channels, banks, and wetlands, it is possible to enhance urban ecological benefits and water purification capacity, thereby providing robust support for sustainable urban development .

For long-term success, coordinated efforts across multiple domains are essential. Policy-wise, relevant standards must be refined and inter-departmental cooperation strengthened. Technologically, low-cost, easy-to-maintain sponge solutions suited to high-density built environments should be developed. Financially, reliance solely on government funding must shift toward diversified financing channels. Managerially, digital-based long-term O&M

mechanisms should be established for routine maintenance. Only through such integrated efforts can the sponge smart city concept take root throughout the entire lifecycle of old community renewal, laying a solid micro-level foundation for China's green, low-carbon, safe, and smart urban development.

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