Developing urban waterfront greenways for multi-objective sustainability in Chengdu

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ABSTRACT

As an ecological restoration approach, greenway construction can effectively address issues such as environmental pollution, ecological degradation, and natural resource scarcity in central urban areas. While most of the literature has analyzed the value of greenways primarily from ecological perspectives, a growing body of research and case studies focus on creating high-quality spaces tailored to spatial users and enhancing social values. Further exploration is needed on how greenway network design can improve not only ecosystem quality but also the vibrancy of public spaces and cultural sustainability. This paper proposes a greenway design framework centered around waterfront greenways, based on field research and in-depth interviews, aiming to balance objectives in ecological restoration, public space vitality, and cultural sustainability. Using the Jinjiang River area in Chengdu, China, as a case study, this paper elaborates on multi-objective-oriented greenway design strategies. The problem diagnosis framework and design strategies established in this study may prove useful for future interventions in high-density urban areas, and the proposed methodology could serve as a model for ecological restoration in other areas.

Keywords: Waterfront greenway, ecological restoration, sustainable development, urban regeneration

1. INTRODUCTION

Rapid urbanization and high-density urban construction have resulted in a series of urban issues. Uncontrolled construction has placed a significant burden on the urban natural ecology system. The proliferation of impervious surfaces and man-made structures, especially in the central urban areas, has fragmented the ecological network. Moreover, pollution caused by high density further exacerbates the deterioration of the ecosystem. In the face of increasing global attention to issues of urban sustainability, ecological restoration has emerged as one of the pivotal strategies to address urban challenges. Studies on ecological restoration have also increased over the past 30 years[1].

The widely accepted definition of "ecological restoration" was proposed by the Society for Ecological Restoration (SER). Ecological restoration is the process of assisting in the recovery of an ecosystem that has been degraded, damaged, or destroyed[2]. Chinese academics similarly define ecological restoration as the restoration of the structure and function of an urban ecosystem to its natural state before disturbance[3]. While this definition is descriptive and biased towards natural and environmental science, the emergence of practical projects and more in-depth theoretical research suggests that the meaning of ecological restoration should be further elaborated and expanded. Scholars such as Shuding et al.[4], Rohwer[5], and others have continued to explore and discuss the concept and practice of ecological restoration. Higgs[6] emphasizes that the goal of ecological restoration in the 21st century should focus on improving human well-being, which obviously includes social and cultural considerations, thereby enhancing the quality of life in areas undergoing ecological restoration. Building on this notion, Martin[7] proposes redefining ecological restoration by incorporating perspectives from both social and scientific fields and considering the viewpoints of diverse groups. This endeavor underscores the importance of broadening the scope of ecological restoration beyond the realm of the natural environment and placing greater emphasis on human-centered projects. Klaus further points out that ecological restoration approaches should take into account local history, site conditions, and the needs of citizens[8]. Fu et al.[9] closely associate ecological restoration with sustainable development, proposing a 'landscape pattern—ecosystem service—sustainable development' framework to evaluate the multifaceted impacts of ecological restoration.

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Little[10] explains greenway as "an open space along natural corridors such as riversides, valleys and ridge lines, or along artificial corridors such as abandoned railway lines, ditches and scenic roads for recreational activities." They serve as open space links connecting parks, nature reserves, scenic spots, historic sites, and high-density residential areas. Ahern[11] prefers a more comprehensive concept, referring to greenways as the intentional planning, design, and management of interconnected parcels of land tailored to serve diverse objectives. These greenways incorporate various functions and typologies adaptable to different environmental, cultural, and social contexts. Jongman and Pungetti[12] point out that greenways constitute the connectivity framework itself of the ecological network. Tan[13] summarizes the greenways in Singapore as park connectors, referring to greenways linking the main public places such as parks, nature reserves and other places of interest. This concept clearly emphasizes the connectivity attributes of greenways. Fabos[14] also defines greenways as corridors that have ecological significance, recreational functions or historical and cultural values.

Overall, there are several mainstream similarities in the definitions of greenways in existing studies. For example, greenways are typically linear spaces that often serve as connectors and are integral parts of ecological networks. However, the specific emphasis varies across different fields, depending on the geographical and environmental context where the greenways are situated. Similarly, with the advancement of theoretical research and the demands of practical design projects, there is a need for new interpretations and expansions of the greenway concept, particularly considering its spatial attributes along with ecological, social, and cultural influences. Currently, as urban challenges become increasingly pressing and urban renewal unfolds across various dimensions, this comprehensive urban spatial structure holds significant development potential.

In the last decade, greenway design has evolved into an international movement. Before 2009, China's exploration of greenway design remained at the theoretical level. The implementation of the Pearl River Delta Greenway in 2009 that marked the beginning of greenway planning and design practice in China. Qin and Wei[15] have divided the development of greenways in China into three stages: the first stage (1985-2006) was the initial phase when the concept of "greenway" first emerged in China; the second stage (2006-2009) was the intermediate phase, during which many scholars in China studied greenways theory, integrating it with local characteristics. The third stage (from 2009 to present) represents the current stage of development. In 2009, the formulation and implementation of the outline of the general planning of the Pearl River Delta Oasis Network symbolized China's progress in this field, marking the transition from theoretical exploration to practical development.

The planning and design of greenway have always been topics worthy of discussion. Linehan[16] proposes the landscape eco-network method, which assumes that the basic framework of the greenway system is formed by wildlife protection and corridor constitution. Network theories and graph theories are then utilized to analyze the habitats of target species and determine the optimal greenway route. This approach proves effective in designing the most suitable greenway routes. Additionally, Lawrence[17] introduces an ecological framework for evaluating waterfront greenways, applying it to the design of a greenway in the South Saskatchewan River Basin in Canada. His framework manages waterfront greenways through resource evaluation and spatial structure assessment. Furthermore, Miller[18] utilizes GIS technology to plan and construct the greenway network in Prescott River Town, Arizona, USA. He employs a suitability analysis theory and designs a riverfront greenway primarily focused on ecological protection. In addition, Damien[19] uses Torrens River Linear Park in Australia as a case study and demonstrates a four-part planning process for waterfront greenways: planning organization, public participation or consultation, overall development planning, and implementation planning. These frameworks provide general guidelines for waterfront greenway planning, with specific processes varying depending on the project. Suitability research methods are significant in determining greenway function and location, albeit requiring considerable time and effort to gather sufficient data during the initial stages. Therefore, a greenway network design framework can enhance both efficiency and effectiveness. For multi-objective greenway projects, especially those focused on sustainable development, which require the integration of diverse areas, a comprehensive framework is essential. The central concept revolves around balancing multiple objectives and maximizing the utility of greenway spaces. Shan et al. investigated people's preferences for greenways from the perspective of environmental perception and suggested that more open designs should be adopted and the accessibility of greenways should be enhanced[20]. Liu et al.[21] identified greenway characteristics from the perspective of human perception and established connections between different design features and human emotional responses, indicating that greenways with high consistency between internal and external environments are more likely to evoke positive emotions.

In studies conducted on greenways, some scholars emphasize the positive effects of greenways on the urban ecosystem, while others provide summaries of greenway network design strategies in specific cases. Additionally, some studies focus on the ecological effects of greenways and their role and effectiveness in restoration processes. Despite many

scholars proposing a broader definition of greenways, relevant cases demonstrating greenway design frameworks and strategies with multiple objectives remain scarce. This study aims to explore further possibilities for greenways, particularly in addressing ecological, social, and cultural challenges in a coordinated manner adapted to local conditions. Taking the waterfront greenway design of the Jinjiang River Area in Chengdu, China, as an example, this paper proposes a greenway design framework centered around waterfront greenways based on the Public Space and Public Life Survey (PSPL) method, aiming to balance objectives in ecological restoration, public space vitality and cultural sustainability. To further complement and enhance the functions of greenways in the field of urban ecology, ecological, social, and cultural design considerations are incorporated, enabling waterfront greenways to not only achieve the goal of ecological restoration but also comprehensively promote the vitality and cultural sustainability of urban public spaces (Figure 1).

Figure 1. Greenway as the carrier and core for multi-objective sustainability.

2. METHOD

Using the Public Space and Public Life Survey (PSPL) method as an assessment approach for evaluating the quality of urban public spaces and the conditions of citizens' public life, this study employs a combination of qualitative and quantitative research methods to understand user behavior patterns. The objective is to use these findings as a foundation for redesigning and enhancing urban spaces and greenways to improve the quality of public areas and fulfill the needs of citizens' public life (Figure 2).

Figure 2. Opinions of residents and public life in public space in the Jinjiang River area.

The PSPL method was initially proposed by Jan Ghel in the 1960s. The PSPL method targets urban public spaces, focusing on the users and their activities within these spaces. The application of the PSPL method involves conducting a spatial diagnosis of the current situation before proposing strategies. It consists of four primary approaches: mapping, on-site counting, direct observation, and interviews[17]. Mapping techniques are used to record the locations and activities of people within the space at different times, reflecting the usage patterns and characteristics of public spaces. Furthermore, interviews are conducted to determine the actual needs of the users, and observational methods are used to identify and document the current conditions and issues that hinder effective use of the space. In the case study of the Jinjiang River area, interviews and direct observation are predominantly employed, supported by other methods, to comprehensively evaluate and analyze space quality from various perspectives. Moreover, the PSPL method facilitates participatory design by providing insights and reference points for greenways and public space design from the perspective of users.

The design framework can be summarized as follows (Figure 3):

- This study conducts on-site observations, immersive experiences, and in-depth interviews with residents and users to gain insights into the current conditions and renewal needs of the area. Methods, such as mapping, are then utilized to aid in the analysis.
- This study then diagnoses the existing issues of the area from various aspects such as environmental quality, landscape conditions, traffic systems, public space systems, cultural functions, etc.
- Following this, a design framework integrating ecological restoration and cultural sustainability is proposed based on survey findings. Strategies are developed to address the identified issues, with greenways serving as a primary component.
- Finally, this study implements improvements across various domains using comprehensive strategies and actions, including establishing a sponge city, promoting sustainable biodiversity, fostering effective connections, enhancing cultural sustainability, and more.

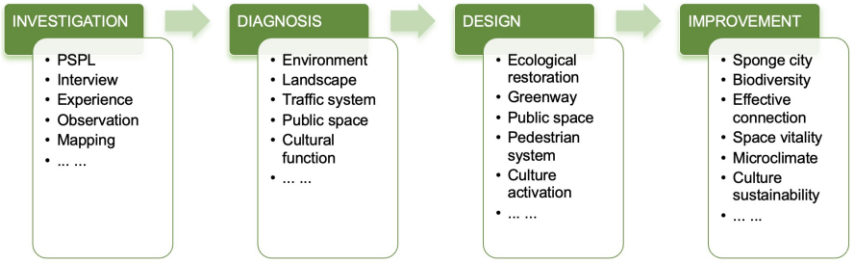

Figure 3. Framework of the urban waterfront greenway design.

3. CASE STUDY

3.1 Study area

Chengdu, located in the southwestern region of China, is of significant historical and economic importance as the birthplace of ancient civilization and a pivotal point along the Yangtze River economic belt. The Jinjiang River area, located in the heart of Chengdu City, Sichuan Province, has been historically referred to as the "Chengdu Mother River" due to its vital role in irrigating Chengdu Plain and sustaining 70% of Chengdu's population (Figure 4). However, rapid urbanization and agricultural irrigation have led to a steady decrease in annual runoff within the Jinjiang River Basin, resulting in significant ecological degradation and water quality deterioration, transforming the river into an organically polluted water body. Consequently, comprehensive restoration and improvement of the water environment in the Jinjiang River Basin have become urgent priorities. The central district such as the Mengzhui Bay area serves as the focal point for functional optimization. "The Jinjiang Green Axis Planning of the Tianfu Greenway" advocates for the transformation of Jinjiang into a picturesque waterfront corridor with flowing green waters and vibrant surroundings. This area is a subsidiary component of the Millennium Scroll Area within the Tianfu Greenway Landscape Axis Planning, boasting distinctive landscape features, and holds economic and cultural significance. Waterfront greenway systems could serve as the primary strategic foundation to achieve these goals.

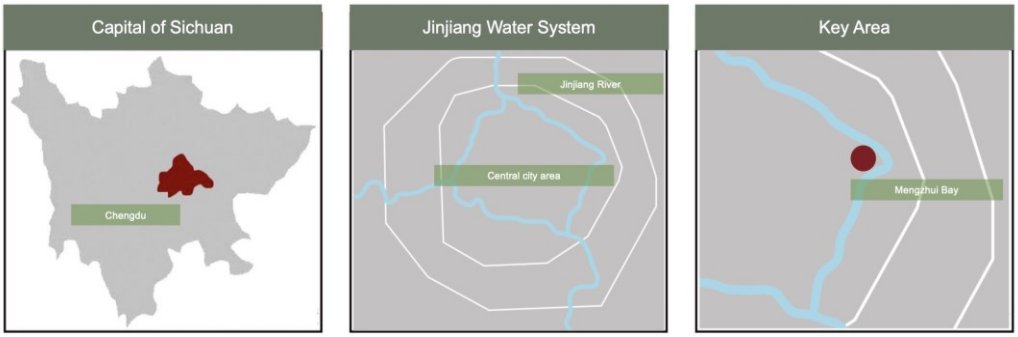

Figure 4. Study area.

3.2 Problems diagnose

Following the mentioned methods and design process framework, the first step is to identify the issues within the case study area, categorizing the issues within the case study area, as well as summarizing. Mainly, these include three aspects: ecological environment and landscape issues, public space and transportation infrastructure concerns, and cultural and social challenges.

(1) Pollution ecological environment and fragmented landscape structure

Since the 1980s, the water quality of the Jinjiang River has significantly deteriorated due to rapid economic development and population growth. Given the high population density in the central urban area, the annual total water consumption is substantial, with daily sewage production reaching 82.91 million tons. About 8.7% of untreated sewage, mainly domestic and industrial wastewater, is directly discharged into urban pipelines, causing severe water pollution in this section of the river basin. In response, the Chengdu Municipal Government initiated pollution control measures by 1990s, resulting in significant improvements in water quality. Despite the ecological purification function of the upstream living water park, with a daily purification capacity of 200 m^3, industrial pollution continues, resulting in noticeable odors in the downstream shallow water areas. Immediate action is needed to tackle water ecological pollution in the Jinjiang River.

In addition to the pressing pollution issues, the landscape structure of the Jinjiang River area appears fragmented due to a lack of well-coordinated overall planning. Furthermore, the escalating utilization of urban water resources and disturbances to the water environment are contributing to the decline and degradation of vegetation within aquatic ecosystems, fragmentation of animal habitats, disruption of microclimate, alteration of suitable habitat spatial patterns, and severe degradation of urban ecological landscapes. Following an analysis of ecological resources and water-green networks in the region, it is evident that constructed green spaces such as the Mengzhui Bay Stadium and Riverside Zone are insufficient and of low quality. Particularly in the southern communities, the green spaces are failing to establish effective linkages. Moreover, a significant number of rigid revetments line the riverbanks, resulting in fragmented and monotonous greenery on both sides of the river. Consequently, the environment during the dry season becomes impoverished, hindering the formation of a cohesive landscape axis.

(2) Inadequate public space and disordered traffic system

The situation of public space is one of the most important parts of providing high-quality public life for both locals and visitors. However, the public space and traffic situation in this area is not optimistic (Figure 5). A deficiency of public space is primarily observed in high-density residential areas and along riverbanks. While linear public spaces exist along both sides of the river, there is insufficient public expansive space within communities to meet residents' recreational needs. Additionally, riverside public service facilities are incomplete, with many in disrepair or semi-abandoned.

The traffic situation in the residential areas surrounding the district is also chaotic. There are numerous poorly maintained roads and a lack of circulation systems. Vehicles are parked haphazardly, leading to significant inconvenience for residents. Moreover, the area experiences heavy traffic flow, exacerbating the mixing of pedestrians and vehicles, consequently compromising the integrity of pedestrian waterfront corridors.

Communities and streets are obstructed by tall walls, while urban green spaces are separated by fences. The landscape along both banks of the Jinjiang River is inaccessible, leading to the disruption of riverside microclimates and hindering the realization of ecological and economic benefits. Moreover, the prime scenic area opposite the Tianfu Tower has been

unlawfully occupied, with buildings on the southern side in a state of disrepair. In areas with the highest population density, the removal and reconstruction of temporary and long-standing structures are necessary.

(3) Inadequate cultural development and unbalanced social structure

As one of the downtown areas, the surroundings of Mengzhui Bay possess rich cultural resources and development potential, with the site adjacent to the historic Sisheng Temple cultural district. However, during the rapid urban development and large-scale construction, the spatial structure that holds urban memories has been damaged. The original traditional cultural spaces have gradually vanished as indigenous residents have been relocated. There is currently a shortage of existing cultural facilities.

The unbalanced social population structure further constrains the vitality of the region. As community aging becomes increasingly prevalent, the number of inactive individuals has been rising. The current situation fails to adequately meet the demands for outdoor activities, particularly in the predominantly elderly southern residential areas. Observations show that the majority of individuals engaging in exercise along the riverside landscapes and residential areas were elderly. From lighting and ventilation to outdoor spatial environments, these areas fail to cater to the needs of younger demographics. Consequently, as they mature, many children move away from these neighborhoods.

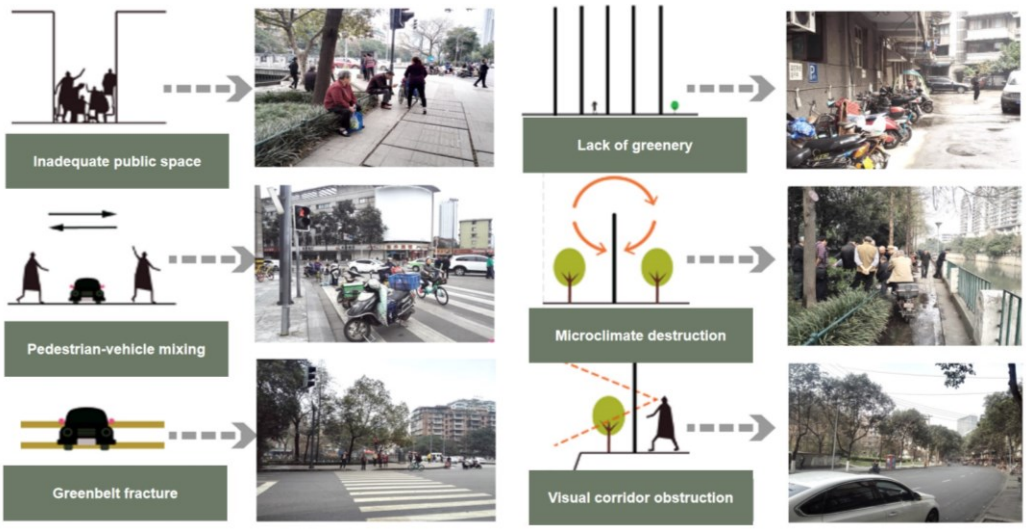

Figure 5. Problems in existing urban public space.

4. STRATEGIES AND DISCUSSION

Considering all the problems mentioned above, a series of strategies based on the greenway network design are proposed to provide opportunities for change from a more systematic view. These targeted yet mutually supportive strategies can be divided into three aspects: ecological restoration, public space optimization, and cultural sustainability strategies.

4.1 Ecological restoration strategies

The water quality issue of the Jinjiang River is a long-standing ecological problem in the area and is also a crucial factor in determining whether the entire region can be comprehensively enhanced. Strategies related for ecological restoration are applied to the water systems within the greenway system, including the following main strategies: water storage and utilization, water division and collection, purification, and regeneration (Figure 6).

(1) Aquatic plant self-purification

This study aims to control source water quality, prevent pollution at its source, and implement measures for intensity control in key areas. Several technologies are integrated to enhance the self-purification capacity of water. These include habitat restoration for animals and plants, natural shoal reconstruction, wetland restoration, increased wetland construction, and diversified landscape design. Different plant species exhibit varying purification effects on water quality, and combinations of plants can be implemented accordingly. The current water quality of the Jinjiang River is purified through the biosorption and decomposition processes facilitated by aquatic plants and microorganisms, thereby

achieving the goal of ecological pollution control.

Close to Chenghua Park, the rainwater park is designed to improve the urban microclimate and create various characteristic landscape areas. The rainwater garden not only effectively infiltrates rainwater but also serves multiple functions. It can efficiently remove suspended particles, heavy metal ions, organic pollutants, and other harmful substances from runoff. Integrated within the green landscape of the composite community, it provides a high-quality habitat for animals and promotes plant transpiration. Moreover, it helps regulate humidity and air temperature, thereby enhancing the microclimate. The rainwater garden not only offers a visually appealing environment but also boasts simple and cost-effective maintenance and management.

(2) Sponge city design

The method involves laying sponges on the ground and repair of pipes underground to control water pollution simultaneously. Surface runoff is collected and treated through the implementation of planned green spaces, permeable leisure squares, permeable roads, and green-roofed buildings. Adhering to the principles of water-sensitive urban design, a rainwater collection system is designed for the entire site. Rainwater is collected or discharged, purified, and reused to prevent secondary pollution of urban rivers. In the underground portion, in conjunction with the construction of a comprehensive pipeline network, water storage tanks and regulating pools are employed to distribute, filter, and store rainwater.

(3) Sustainable ecological design

Sustainable ecology primarily emphasizes water purification and biodiversity enhancement, establishing three water purification processes: filtration, sedimentation, and ecological purification within the design framework. The upstream Jinjiang water is directed into the rainwater park and subsequently recirculated into the Jinjiang River. Impurities and pollutants in the river are filtered using mesh ropes and regularly removed. The flow rate is slowed down through the use of eco-islands and meandering coastlines, facilitating the sedimentation of particulate matter and water purification. Additionally, ecological revetments, sewage purification treatment systems, and wetland systems are employed to further enhance water quality.

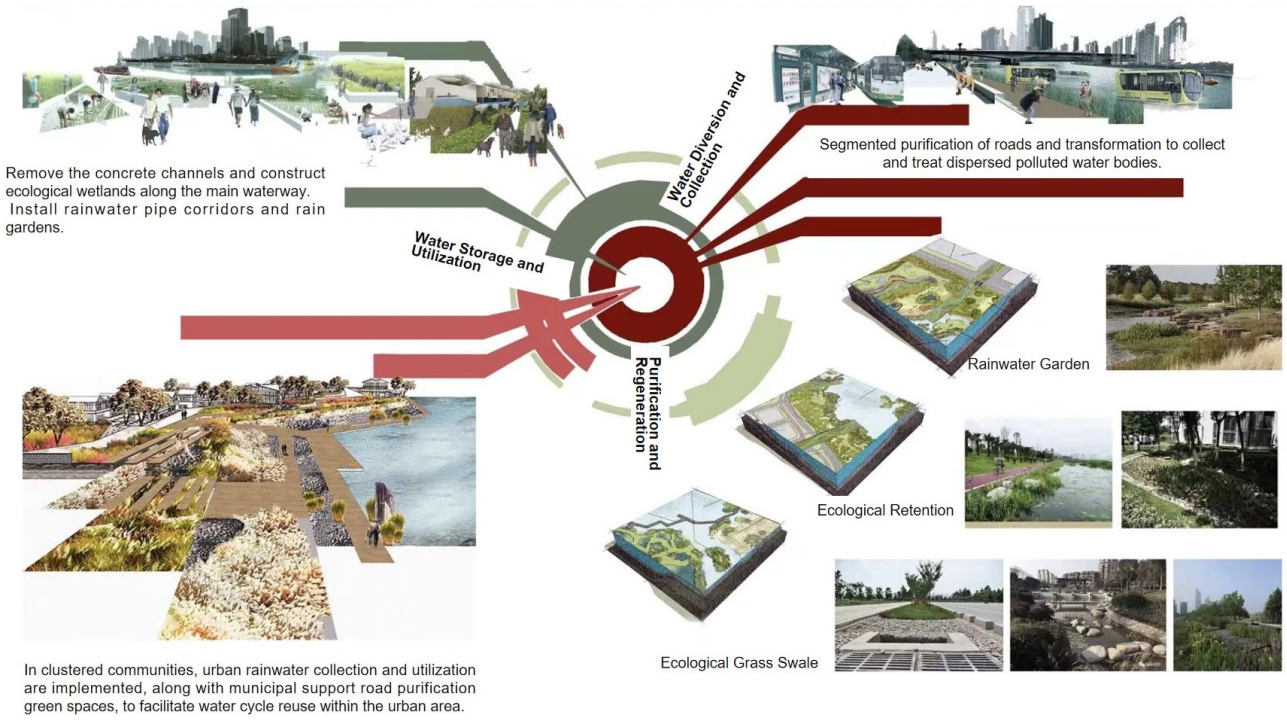

Figure 6. Ecological restoration strategies.

4.2 Public space optimization strategies

(1) Establishing public spaces for waterfront recreation

To enhance urban green spaces and recreational opportunities, Chenghua Park, the original community courtyards, and the existing low-level green spaces can be utilized to establish a new network. This initiative aims to increase connectivity and accessibility for pedestrians. It involves enhancing greenery along the riverbanks and incorporating hydrophilic platforms to create a continuous pedestrian system. Additionally, removing dilapidated buildings along the riverbank and opening up the river interface can be considered. Furthermore, designing underground hydrophilic leisure spaces and expanding recreational areas, integrating features such as basketball courts, football fields, skateboard parks, or picnic lawns, can create sunken areas capable of purifying stagnant water during rainy periods and facilitating leisure activities on sunny days.

(2) Connecting the pedestrian network to facilitate communication

To enhance connectivity, the plan involves connecting the riverside pedestrian corridor, designing the riverside landscape bridge, establishing a loop for healthy running, riverside tour loop, and multi-level three-dimensional riverside landscape. In the central area of the site, at the intersection of Xinhua Avenue and Binhe Road, there exists currently a mixed pedestrian-vehicle bridge with a width of about 40 meters. This strategy aims to connect the two sides of the riverside and the surrounding commercial buildings to form a landscape bridge. Its purpose is to enhance the accessibility for people in riverside walking and meet the needs of outdoor activities such as transportation, landscape appreciation, and relaxation. Additionally, it seeks to link the rear business district with the southern residential area, thereby reducing spatial and service disparities between the two areas and expanding the service coverage of the business district.

(3) Constructing a composite waterfront greenway system

The waterfront greenway is designed as an axis to serve as a continuous urban green corridor and develop the riverside public space network. A series of public spaces along the axis should be interconnected to enhance accessibility for people. Ecological greenways can be arranged along the riverbank to create a pedestrian-friendly system. By opening up landscape corridors leading to the riverbank, the city can establish a multi-axis and multi-branch greening system, thus significantly enhancing the urban environmental quality. Emphasis should be placed on the connectivity and accessibility of green spaces to meet citizens' recreational needs. Simultaneously, this approach can improve accessibility to the riverside and provide a multi-level, diversified, green open waterfront space. Various artificial embankments, such as stepped descending steps and natural embankments, should be utilized. Gentle lawns and hydrophilic platforms should be incorporated in areas where the waterfront is dominated by green spaces. Building layouts in construction zones can be arranged in an enclosed, open, or semi-open manner facing the riverside. This approach can prevent the disruption of river ecological wetlands by urban construction areas and integrate waterfront landscapes into the cityscape, thereby enhancing the quality of the urban landscape.

4.3 Cultural sustainability strategies

(1) Providing more spaces for cultural functions

The greenway spaces along with the Jinjiang River can provide venues and areas for a variety of cultural activities through design. For example, utilizing the elevation difference along the riverbank as a public outdoor performance platform, by adding squares suitable for public cultural activities. Leveraging the advantages of waterfront spaces as locations for cultural venues can attract more residents and tourists. In the revitalized area, thorough research on the existing urban cultural structures is conducted. By preserving iconic landscapes and protecting the original cultural characteristics in the renovated spaces, the cultural sustainability of the area is promoted.

(2) Preserving the original community's cultural characteristics

To address the issues of unbalanced social structure and the lack of vitality in old communities, introduce greenway network as a link between old and new cultures can infuse new vitality. Reshaping the culture of new communities must be built upon the inheritance and affirmation of the original community's cultural characteristics. Through the construction of greenway systems, new urban focal points are created, increasing participation, especially among the retired population in existing communities. This fosters a new community culture that integrates with greenway development while preserving and maintaining the original community culture (Figure 7).

Figure 7. Cultural sustainability strategies.

5. CONCLUSION

In summary, different areas of the greenway network are responsible for multi-objective sustainability for regeneration of the whole district. The eco-landscape area is responsible for water purification and creating a favorable microclimate, while the riverside scenic area and hydrophilic areas cater to recreational and leisure activities. Community and commercial areas primarily focus on guiding and managing the flow of people. The main axis of the landscape development aligns with the riverside, connecting the key landscape nodes within the designated area, each serving the functions of ecology, landscape, and leisure. Additionally, by linking multiple smaller nodes on both sides and considering the diverse needs of community and commercial areas, a comprehensive leisure and recreation loop is formed, offering various sightseeing experiences. To complement the existing urban road infrastructure, the vehicle system is designed to enhance longitudinal traffic flow between Xinhua Avenue and Wucheng Avenue within the community, catering to the demands of the original mixed vehicle section and facilitating the smooth movement of both people and vehicles within the community, thereby establishing a cohesive riverside greenway system.

However, this study also has certain limitations that need to be addressed and advanced in future research. Firstly, the proposed waterfront area framework centered on greenway design is primarily applicable to redevelopment scenarios; for the planning and design of new areas, other factors need to be considered. Secondly, although multiple objectives were set, the effectiveness of achieving these different objectives requires corresponding evaluation and balance. Additionally, the cost-effectiveness of utilizing spatial strategies in greenway design for redevelopment needs to be assessed.

In high-density urban centers, a series of urban issues require diverse solutions. Space, as a primary component of urban construction and renovation, naturally offers advantages in providing multifaceted strategies. Although greenway systems have traditionally been valued for their ecological and scenic roles in previous research and practice, they actually hold greater potential. This study proposes to systematically integrate various considerations and strategies through greenway system design, thus avoiding the isolation of improvement measures and enhancing the overall efficiency of urban environmental enhancement. The case of the Jinjiang River area provides a design framework oriented towards ecological, social, and cultural sustainability, offering valuable insights for sustainable development and renewal in central urban areas.

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