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Sponge City As A Civil Engineering Solution To Climate Change That Improves Urban Flood Resilience

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***Abstract*—Climate change and urbanization drive the demand for water management to make cities more water resilient. Climate change brings heavy precipitation and causes urban flooding, with conventional construction of cities no longer suitable given the rising risk of flooding. Characterized by constructing cities as large sponges that absorb and treat water, the idea of sponge cities is a solution to stormwater control and drainage water management, which can be achieved by creating water absorbing areas, increasing permeable surface, and integrating stormwater and drainage systems. To assess flood resilience, evaluation indicators have been introduced to measure the effectiveness of sponge cities. A case study was also provided in this review to demonstrate how the concept of sponge cities was put into practice.**

Keywords—sponge city, low-impact development, climate change, flood resilience

I. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), cities worldwide are facing a rising number of severe flood events exacerbated by the force of climate change. The concept of sponge cities has been proposed to solve urban flooding, through developing a more sustainable and ecological water management system. Some of the existing urban drainage systems cannot withstand the increasing flood events and require a new approach to water management. Sponge cities were first proposed in China as an idea to mimic natural hydrological processes to accommodate the increasing water risk in urban areas associated with climate change [1]. By adopting natural-based solutions, sponge cities can collect, store, and treat the rainwater, lengthen the rainfall durations, and reduce runoff and soil loss. Constructing sponge cities is an effective way to prevent flooding. This article aims to provide insights into flood management in urban areas under climate change and urbanization, and the factors associated with urban flood resilience. It also explores the concept and current construction of sponge cities and how sponge cities maintain a balance between the urban ecosystem and the welfare of people living in the city. Subsequently, a case study was introduced to provide practical examples of the construction of sponge cities that has led to sustainable urban planning.

II. Effects of Climate Change on Urban Resilience

Accelerating urbanization and ongoing climate change expose urban populations to more environmental issues than before. Extreme weather events such as storms and floods are increasingly occurring in urban areas. Research has shown that from 2020 to 2030, the extent of urban areas exposed to flood events will increase by 2.7 times [2]. As suggested by the Center for Climate and Energy Solutions, human activities in cities contribute significantly to climate change, for which electricity generation and heating (31%), transportation (15%), and manufacturing (12%) account for more than half of all greenhouse gas emissions. Those forces of change, including climatic and anthropological factors, emphasize urban resilience to extreme weather events as a crucial issue in urban planning.

Conventional urban planning is designed to meet human needs and for convenience but lacks consideration for environmental conservation, with which those urban designs have difficulty adapting to climate change and population growth. For example, impermeable pavements, roads, parking lots, and roofs do not allow water to flow underground after heavy rains. Flooding occurs more frequently due to less capacity to store rainwater. Additionally, urban streams reach higher peak discharge, and have larger runoff volume [3]. Traditional urban designs not only increase the risk of flooding but also reduce the amount of water that can be extracted in urban areas, as less rainwater is allowed to filter through the urban soil and be stored in aquifers. Moreover, the adverse impact of the inappropriate use of impermeable urban surfaces in conventional urban designs is aggravated by the high frequency of heavy precipitation in the context of climate change.

Human activities exacerbate the impacts of climate change. The reduction of urban greenspaces results in less carbon dioxide captured by plants and less cooling effect of plants on the environment. The decrease of urban permeable

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areas and the replacement of natural green coverings by pavements and buildings deprive urban areas of their ability to absorb and insulate heat, resulting in the phenomenon of urban heat islands (UHI). The urban temperature in the city is higher than that of the surrounding rural areas. UHI increase the duration and intensity of heat waves, directly influencing the health and comfort of city residents [4]. Besides, UHI change the precipitation patterns in urban areas [5]. The increase in extreme precipitation due to global warming and UHI emphasize the importance of developing a new paradigm of urban designs to adapt and mitigate the risks and uncertainties caused by extreme precipitation.

III. The Concept of Sponge Cities

Urban resilience is required to cope with the hazards caused by climate change. Sponge cities are designed to create an absorbent urban environment where rainwater can flow down into the soil and drain more effectively, and be collected in aquifers for later cleaning and reuse. The concept of sponge cities was initially implemented in China, a country with severe water problems. It was reported by the Office of State Flood Control and Drought Relief Headquarters in 2013 that there was a total of 641 cities in danger of flooding. In addition to the case of sponge cities, alternative eco-friendly strategies for rain management include low-impact development (LID) in the United States (US), sustainable development urban drainage system (SUDS) in the United Kingdom (UK), water sensitive urban design (WSUD) in Australia, and well-balanced hydrological system (WBHS) in Japan [6]. Despite their different names, they all represent the same core idea of ecological stormwater management.

A variety of measures can be taken to achieve the goal of constructing sponge cities. The construction activities of sponge cities includes the follows [7]: (1) Constructing sponge buildings and communities, including green roofs, rain gardens, rainwater harvesting systems, and rainwater drainage galleries. (2) Constructing sponge roads and squares with permeable porous materials. (3) Constructing sponge parks and greenspaces, including artificial wetlands, rain gardens, and vegetated infiltration basins. (4) Protecting and remediating the nature and ecology of the environment by increasing wetland areas, maintaining natural flow regimes of rivers, reducing impermeable surfaces, and dredging urban rivers and lakes. (5) Improving the connectivity of urban water system to allow unimpeded flows. (6) Constructing modern drainage systems or reconstructing the existing ones to satisfy adequate discharge and flood-control standards. (7) Separating stormwater and sewage pipeline networks.

Based on the seven components, specific approaches are used to adapt to each city's unique climate, geography, and demographics. Through these approaches, sponge cities can facilitate the infiltration, stagnation, storage, purification, utilization, and discharge of water, thereby mitigating the risk of flooding and flood-related hazards. Apart from reducing water-related disasters and improving urban water quality, the construction of sponge cities also allow us to mitigate the effect of UHI [8], enrich biodiversity, and provide greener, healthier, and more enjoyable urban spaces (Figure 1).

IV. Evaluation Indicators of Flood Resilience

Resilience as a measure of the effectiveness of sponge city construction, or LID in general [9], is defined as the capacity of a system to absorb water, to reorganize the city

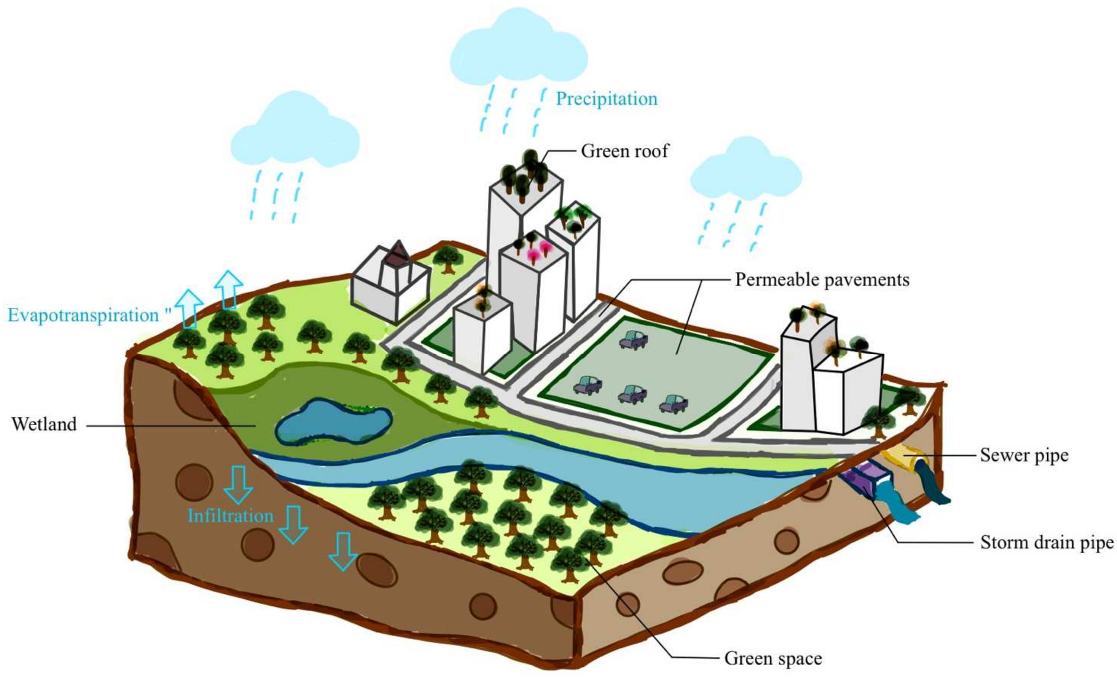

Figure 1. Schematic diagram of a sponge city

from disturbances caused by flooding, and to maintain its functions, structure, identity, and feedback.

The flood resilience index (FRI) can be used to evaluate urban resilience. The index indicates the ability of the assessed area to accept the disturbances and recover from flooding. Five dimensions are considered in the FRI: natural, physical, social, economic, and institutional dimensions [10, 11]. Each dimension is composed of different variables (Table 1). The natural dimension represents the location of the urban area. The physical dimension describes the assessment of the building environment, such as urban density and infrastructure. The social dimension evaluates the factors related to the community, including health status, flexibility, knowledge, and available resources. The economic dimension is relevant to the economic and urban growth of the city, including economic capacities, income resources, employment rate, and population growth. The institutional dimension is determined by how the authorities cope with disasters through flood management plans, policies, mitigation measures, and evacuation plans.

The linear aggregation method is preferred for the FRI. It takes the following form Eq. (1). A zero value of FRI is considered a low resilience level, 100 indicates a high resilience level, and 50 represents a medium resilience level.

$$FRI = \frac{NRI + PRI + SRI + ERI + IRI}{5} \qquad (1)$$

Natural Resilience Index (NRI); Physical Resilience Index (PRI); Social Resilience Index (SRI); Economic Resilience Index (ERI); Institutional Resilience Index (IRI)

V. The Implementation of Sponge Cities in China

A survey conducted by the Ministry of Housing and Urban-rural Development (MOHURD) indicated that 62% of the cities in China experienced urban flooding from 2008 to 2010 [12]. Proposed initially in China in 2012, the concept of sponge cities has already been adopted in many cities in China, aiming to decrease flood risks and improve water quality. The Chinese government launched a sponge city program (SCP) to support the development of sponge cities in 2014 [13], during which a total investment of US$ 12.2 billion was planned over the first three years for the construction of sponge cities in the first batch of 16 pilot cities (e.g., Jinan, Hebi, and Wuhan) [1, 14, 15]. The estimated construction area of sponge cities for the selected 16 large cities with frequent flood events was approximately 450 km^2 (average investment of US$ 14-21 million km^{-2}) [16]. The design and construction plans for sponge cities differed from city to city and were determined by local climatic and hydrological conditions. 14 pilot cities for the second batch (e.g., Beijing, Shanghai, and Ningbo) were assigned in 2016, with the hope to include a wider variety of climatic and environmental conditions.

The ambition of SCP was large and could be described as short, medium, and long-term goals [14]. The short-term (2015-2018) goal of SCP was to put the concept of sponge cities into practice in the selected pilot cities. The medium-term (2018-2020) goal of SCP was to develop a standard for sponge city construction and establish an early warning system, with an expectation to have over 20% of the urban areas recycle 70% of rainfall. The long-term (2020-2030) goal was to integrate the concept of sponge cities in urban development, planning, and construction, with a target to make more than 80% of the urban areas able to absorb, retain, and reuse 70% of rainwater.

Jinan, the first pilot city to implement the concept of sponge cities in China, is located in the Yellow River floodplain that is known for suffering from severe hydrological issues of water-logging and pluvial logging. The construction of a sponge city in Jinan included introducing LID systems and drainage systems to manage stormwater. Jinan had already made some achievements after being constructed as a sponge city. According to the evaluation by Song et al. [15], the annual rainfall capture of Jinan city was 77.4%, the drainage pipeline capacity was improved, and the risk of flooding was reduced effectively [17]. The areas with high flooding risks decreased by approximately 45% of 50-year return period rainfall events with 24-hour rainfall duration. These results indicated a considerable improvement in flood reduction in Jinan, with which the successful experience can be used as a reference for the construction of future sponge cities. It was demonstrated in the case of Jinan and other urban areas included in the SCP that the construction of sponge cities can indeed contribute to flood management, reduce runoff pollution, and improve water sustainability [18].

Dimensions of FRI	Targets	Variables
Natural dimension	Describes the space where the city of interest is located	Elevation, location
Physical dimension	Assesses the building environment	Urban density, infrastructure, building materials
Social dimension	Describes the factors related to community	Health status, flexibility, knowledge, available resources
Economic dimension	Evaluates the economic and urban growth	Economic capacities, income resources, employment rate, population growth
Institutional dimension	Describes the plans of the city to cope with disasters	Flood management plans, policies, mitigation measures, evacuation plans, awareness programs

Table 1. Five dimensions of flood resilience index (FRI)

Some challenges remain for the implementation of sponge cities in SCP. Despite the public generally supports government investments in sponge cities to reduce flood risks, headwinds for the implementation of SCP include immature regulations, government interventions, and vague water boundaries. The perceived performance of sponge cities might be blighted by the reasons mentioned above if the flood-control infrastructure and the regulations of sponge cities are not better integrated. Therefore, the maintenance of green infrastructure in sponge cities is important for the attraction of long-term investments and the accomplishment of the ultimate goal of flood reduction [14].

VI. Discussion

With the impact of climate change and rapid urbanization, the conventional engineering methods of urban construction are no longer appropriate for many cities, especially when considering flood management. The concept of sponge cities is a shift from typical technical construction to a more sustainable and ecological solution to urban flooding. The assessment of flood resilience plays a vital role in the progress of urban flood risk management. The FRI includes five dimensions. In addition to natural conditions surrounding the urban area of interest, the FRI as well takes economic, social, and institutional factors into account. Based on this perspective, the assessment of flood resilience for sponge cities shifts from the conventional pure engineering method to understanding conditions related to economic changes, human activities, and institutional strategies.

Compared to the traditional water management system, sponge city is a nature-based solution to urban water problems. The case study in China has shown the capability of sponge cities to improve water absorption capacity and water self-purification. In the context of climate change, the frequency and intensity of floods are gradually increasing. Although the specific measures of constructing a sponge city should be adapted to regional characteristics of each city, the core concept has always been the same.

VII. Conclusion

The concept of sponge cities provides a sustainable way of urban water management to reduce flooding risks and improve water quality. Moreover, sponge cities can provide a healthier and more enjoyable urban environment that benefits both nature and humans. The concept of sponge cities should be applied more widely to achieve sustainable urban water management, which serves as a practical solution to water-related risks caused by climate change and urbanization.

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