Application and Trend Analysis of Sponge Cities in Alleviating Urban Waterlogging

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Abstract: As global urbanization intensifies, urban flooding has become a significant issue. The concept of the sponge city, now implemented in China, draws on the experience of various established Western models and is tailored to suit China's unique context. However, as this concept is relatively new, there are still many aspects that remain underdeveloped. This article primarily utilizes a literature review to analyze the current application of sponge cities and the challenges they may face in the future. The findings indicate that four key measures are commonly employed in China's sponge city initiatives: expanding urban green spaces, implementing green roofs, using permeable materials, and enhancing operational management. Given China's vast geographic diversity, a one-size-fits-all approach to managing urban flooding is impractical. However, the use of permeable materials has emerged as the most widespread solution. Although the sponge city concept is still in its early stages and faces numerous challenges, it holds the potential to significantly influence future urban development.

1 INTRODUCTION

Since the 19th century, with the advent of industrialization, rapid population growth, and swift urbanization, scholars have extensively explored the relationship between cities and rivers. Urban waterlogging primarily results from precipitation exceeding the city's drainage capacity. As China's reform and opening up deepened, the urbanization rate surged from 10.64% in 1949 to 57.4% in 2016, exacerbating urban waterlogging issues across the country (Yan etal, 2020). The five main contributing factors include geographical location and urban climate, planning, construction practices, management, and detection systems (Wang, 2022). As urban waterlogging becomes increasingly severe, it poses significant threats to the quality of life, as well as the safety of life and property.

In recent years, significant climate changes and large-scale human activities have exacerbated urban waterlogging, threatening human life and socio-economic development. During urban flooding events, many factors influence river conditions. As the water levels rise, urban obstacles such as vehicles, railways, and industries severely impact water flow, leading to increased losses (Zhu, 2017). For instance, the 1976 Big Thompson Flood in Colorado, USA, resulted in record-high mortality rates due to the vehicles (Albano, 2016).

Urban waterlogging is partly caused by urbanization preventing natural water infiltration, leading to a rapid increase in surface runoff. Many regions have implemented traditional and innovative measures to strengthen urban drainage systems and develop water diversion and storage projects to alleviate urban flooding. Cities like Singapore have built specialized water diversion pipelines and storage facilities to reduce the burden on downstream drainage (Gruntfest, 2020). Additionally, new technologies and concepts such as Low Impact Development (LID) in the United States, Water Sensitive Urban Design (WSUD) in Australia, and Sustainable Urban Drainage Systems (SUDS) in the United Kingdom have appeared (Tortajada, Joshi, 2013). These approaches, often integrated with the local ecological environment, effectively address urban waterlogging issues. By imitating the roles of sponges in natural ecosystems, the idea of a "Sponge City" seeks to improve urban water resource management and flood control while lowering

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pollution and urban waterlogging. Given China's vast land area and diverse geographical conditions, it is not feasible to directly replicate Western governance models. Although China's Sponge City concept was introduced later than Western models, it has incorporated and adapted many Western ideas to better suit China's specific needs.

The features of sponge cities include wetlands, forests, lakes, green roofs, bioretention systems, and permeable pavements (Fletcher,2015). Sponge city technologies and concepts in China focus on enhancing urban permeability. Permeable pavements, which account for 30% of the urban area, effectively mitigate floods caused by heavy precipitation (Liang,2020). However, Due to the complexity of sponge cities, they face lots of challenges when applied to real cities. Sponge city development is a long-term endeavour that calls for increased tolerance and assistance all along the way.

This article primarily explores the key applications of sponge city concepts within urban environments. The impact of urban waterlogging is reduced by the sponge city approach's guiding principles. Firstly, the use of permeable materials on urban roads plays a crucial role in reducing the strain on drainage systems. Secondly, from a sustainable development perspective, integrating natural ecological cycles with urban planning helps to counteract the negative effects of urbanization. In summary, sponge city strategies represent a major direction for future urban development. Although the challenges that exist today, their long-term benefits are undeniable.

2 THE CURRENT DEVELOPMENT OF SPONGE CITIES

Urban water problems have gotten worse in China in recent years due to the country's almost unprecedented level of urbanization. Rapid urbanization has altered land use patterns, resulting in a deteriorating water environment. The hardening of urban land surfaces has reduced water infiltration, increasing runoff, and leading to higher flood peaks and volumes The Chinese government responded by proposing the idea of Sponge City in 2013. (Liu, Jia & Niu, 2017). The Sponge City aims to effectively manage urban rainwater by balancing the natural environment with urban planning. The application of green infrastructure, which includes several processes like retention, storage, purification, and reuse before discharge, is central to Sponge City's tenets. According to studies, these actions can recover 70–90% of precipitation on-site, increasing urban resilience during periods of intense precipitation. (Jiang & McBean 2021).

The material used for the pavement is essential to this idea. For Sponge Cities, a few novel pavement materials have been developed, including permeable cement concrete, permeable asphalt concrete, and others. These materials are distinguished by their porosity, pore size, and related properties. It is possible to modify pore size, connectivity, curvature, and porosity to better fit different urban contexts (Guan, Wang & Xiao 2021). These materials are more expensive than conventional paving materials, but they also have advantages including good noise reduction and water and air purification.

Implementing sponge city principles in urban areas can significantly enhance hydrological performance and has broad applicability. Global variations in seasonal patterns, temperature, precipitation, and the frequency of severe weather events, such as heavier rainfall, are already signs of the consequences of human-caused climate change. The rapid expansion of urban areas has exacerbated water security issues and catastrophic flooding, a stark contrast to the 1980s when 60% of the population lived in rural regions (Jiang & McBean, 2021). This increased urbanization intensifies the risks associated with extreme weather. A key advantage of the sponge city approach is its ability to balance precipitation and drainage effectively, promoting greater water infiltration.

3 APPLICATIONS OF SPONGE CITIES IN MITIGATING URBAN FLOODING

In Sponge Cities, many measures are implemented to reduce urban flood disasters, with many similarities to LID and SUDS. The four major measures in the sponge city concept are mainly contiguous open green spaces, green roofs, porous design and management.

3.1 Contiguous Open Green Spaces

Green spaces in urban areas offer numerous benefits, both ecological and economic. Human's mental health could be improved by green environments. Research from Midtown Manhattan provides evidence that sociocultural features of urban living, such as disorganization, may impact mental health (Galea, Ahern, Rudenstine, Wallace & Vlahov 2005). Economically, areas with more green space generally have higher property values and reduced heating and cooling costs. Importantly, the extent of green space in a city determines the overall health of its ecosystem.

In the concept of Sponge Cities, green spaces typically include public parks, sports fields, vacant lots, road verges, and similar areas. Research by Richard and others indicates that major gradients of urban densification and topography are significant factors influencing the availability and quality of urban green spaces (Davies, Barbosa, Fuller, R, Tratalos, Burke, Lewis & Gaston 2008). As populations grow rapidly, urban areas cannot avoid high-density modern buildings. In Sponge City, governments should prioritize housing policies that reduce high-density construction and preserve existing trees and large shrubs within development areas.

3.2 Green Roofs

Green roofs in Sponge Cities are primarily used for rainwater collection on rooftops. In China, many cities experience significant rainfall, so green roofs not only help collect rainwater but also effectively reduce the building's water costs. A case study by Weiyu presented a green roof model and tested it on their school dormitory (Zhan, Ye, Wu, Yan & Zhu 2023). Their model could save approximately 227,500 yuan annually in water costs. The model’s principle involves collecting rain from the roof through a system that includes a base layer, thermal insulation layer, screed layer, waterproof layer, irrigation system, planting soil layer, and vegetation layer. This green roof model captures rainwater and uses it and vegetation to supply water for the building’s toilets and reduce rooftop runoff. Therefore, the widespread use of green roofs can significantly help in water conservation and managing heavy rainfall in the area.

In green roofs, various materials are used, each with its own characteristics. Spraying polyurea as a waterproofing material can effectively prevent roof cracking and extend the roof's lifespan. Porous PVC drainage plates, known for their excellent cost-effectiveness and drainage performance, ensure that rainwater is quickly diverted, preventing water accumulation. For example, the application of polyurea through spraying can efficiently mitigate roof cracking, while the porous PVC drainage plates provide great economic advantages and physical characteristics. According to Data Envelopment Analysis by Lijuan Huang, spraying polyurea waterproof material is one of the best ways to green roofs (Huang, He, Tang, Fu & Li 2020). In conclusion, green roofs play a necessary role in the Sponge City concept such as contributing to rainwater management, energy savings, and environmental improvement.

3.3 Porous Design

This aspect is crucial for porous design in the concept of Sponge Cities. To meet Sponge City requirements, pavement materials need to have properties such as permeability, retention, purification, evaporation, and drainage (Guan, Wang & Xiao 2021). This presents a challenge for pavement engineering. Previously, many cities used permeable vegetation, but this has gradually been replaced due to development needs. Additionally, this change has worsened the urban heat island effect and increased urban flooding.

The concept of permeable pavements is designed to absorb and retain water when it rains and to evaporate it when there is no rainfall (Brunetti, Šimůnek & Piro 2016). This design helps reduce flood risks and mitigate the urban heat island effect. Although this concept is advanced, it poses challenges for material development. Permeable asphalt concrete, permeable cement concrete, permeable bricks, and novel materials utilizing polymer binders are just a few of the permeable pavement materials that are currently accessible. (Guan, Wang & Xiao 2021). These materials are characterized by their porosity, pore size, pore distribution, connectivity, and curvature. Engineers choose materials based on local soil and terrain conditions. Despite the promising nature of the porous design, these materials are significantly more expensive than traditional ones, and there is a need to develop new materials with better load-bearing capacities.

3.4 Management

In addition to utilizing the technologies in Sponge Cities, effective management is also crucial. An efficient management system can optimize the various technologies used in Sponge City. Thu Thuy Nguyen and colleagues propose a comprehensive management model with several key components. First, it is important to strengthen monitoring and evaluation systems to collect a range of data promptly. Tools for decision support must be created by researchers to implement Sponge Cities sustainably. These tools can help decision-makers and designers effectively allocate suitable technologies and resources. Next, urban ecosystem services should be assessed, including biodiversity, urban cooling, and overall ecosystem health, to determine their economic benefits. Standards for implementing Sponge Cities should then be established. Due to the great geographic diversity of China, each city is unique, and rules should be adjusted to account for local conditions to ensure that Sponge City technologies effectively reduce flood risks and the negative effects of the urban heat island effect. Finally, developing and promoting Sponge City construction should be based on comprehensive data. The concept of sustainable development is a mainstream development idea in the 21st century, making the advancement of Sponge City applications inevitable.

4 FUTURE PERSPECTIVES

The Sponge City concept is relatively new in China, and it addresses urban water issues and effectively improves the ecological environment. However, implementing this concept presents several challenges, particularly in technology, funding, and policy. From a technical perspective, incomplete data collection across different regions has resulted in imperfect models for many sponge cities. For example, while some permeable pavement materials have performed as expected, many still fail to withstand heavy loads. Future iterations will require developing new materials with both higher permeability and greater load-bearing capacity. In terms of funding, insufficient financial resources have been one of the major obstacles to implementing sponge cities in China. The research and deployment of many emerging technologies, such as green materials for green roofs, demand significant investment. Additionally, some technologies are still underdeveloped, leading to high maintenance costs. A lack of management experience has further contributed to escalating costs. Regarding laws and policies, the lack of close cooperation between government entities and the inadequate integration of relevant agencies have hindered progress. Many policies remain fragmented, which is limiting community participation and reducing the potential for public-private partnerships. The Chinese government could involve more private enterprises to mitigate the financial and operational pressures on government entities. Overall, although the sponge city concept is innovative and promising, it also has many unpredictable challenges. As the benefits of sponge cities develop gradually, achieving sustainability and realizing their full potential benefits may need long-term investment and continuous development.

5 CONCLUSION

The concept of sponge cities is relatively new in China. The application of sponge city has grown rapidly in recent years and made it increasingly well-known. This article presented the key measures adopted by sponge cities and the challenges might face in the future. Urbanization and climate change have led to a rise in the frequency of urban flooding. Therefore, it has prompted the need for innovative solutions like the sponge city approach, which integrates established methods such as WSUD, SUDS, and LID. Key strategies include the development of interconnected green spaces, the use of green roofs, porous urban structures, and advanced water management systems. Expanding urban green spaces enhances local ecosystems and offers multiple benefits. Green roofs not only collect rainwater but also contribute to urban greening. Among these measures, porous design is especially effective, because it mitigates the hardening of urban surfaces by incorporating permeable materials. Overall, these strategies play a key role in promoting sustainable urban development. However, the sponge city concept is still in its early phases and faces a few challenges, especially when it comes to materials and technology. While China's approach is well-suited to its specific needs, there is still a lot of work ahead. Therefore, the long-term benefits are clear and hard to ignore.

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