

Sponge Cities and Urban Flood Management: Addressing Climate Change-Induced Challenges Through Sustainable Water Management Strategies

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Keywords: Sponge Cities, Urban Flood, Sustainable Water Management.


Abstract: As urbanization accelerates and the impacts of climate change intensify, cities are facing enormous challenges, especially in managing heavy rainfall and urban flooding caused by frequent weather extremes. The shortcomings of traditional drainage systems have led to a push for the development of the "sponge city" concept. This new approach to urbanization combines nature and engineering to capture, store and manage rainwater, reducing surface runoff and flood risk. This paper explores the origins, underlying philosophy and benefits of sponge cities, emphasizing their contribution to urban resilience and sustainability, while also exploring the main difficulties in implementing sponge cities, including issues related to technology, finance, physical constraints and public participation. Finally, the paper provides recommendations for strengthening intersectoral cooperation, increasing public participation, and designing solutions that are appropriate for local construction and development. Sponge cities are expected to play a major role in combating the effects of climate change, improving water management and promoting sustainable development through the integration of smart systems and green infrastructure.

1 INTRODUCTION

In recent years, global climate change has become increasingly significant and extreme weather events have proliferated, posing unprecedented challenges to human cities. In particular, the increase in extreme rainfall has resulted in frequent urban flooding, disrupting the order and functioning of cities. For example, the exceptionally heavy rainfall in Zhengzhou, China, in July 2021 exceeded the average annual rainfall in just four days, resulting in severe flooding, a large number of injuries and deaths of residents significant property damage, and the displacement of countless people (Reuters, 2021). This flood event is an important part of the 2021 flooding south of the river, which has become a prime example of the impacts of global climate change (Wikipedia contributors, 2021). Unprecedented flooding in Germany and Belgium in the same year forced the evacuation of thousands of people and caused extensive infrastructure damage (European Centre for Medium-Range Weather Forecasts, 2021).

These events highlighted the limitations of traditional urban drainage systems in the face of extreme weather and underscored the urgent need for more adaptive and sustainable water management solutions to meet the new challenges posed by climate change.

Conventional urban drainage systems are usually designed with the ultimate goal of rapid drainage, focusing on the rapid removal of rainwater from urban areas to prevent short-term flooding. However, in extreme rainfall situations, the surface runoff caused by large amounts of rainfall in a short period of time is often too much for these systems to handle, resulting in severe urban flooding due to drainage system paralysis. In addition, traditional drainage methods ignore the fact that rainwater can also be a valuable water resource, resulting in wasted water. In contrast, the concept of sponge cities introduces green spaces, water bodies and other natural elements into urban construction, greatly enhancing the city's ability to absorb, retain and manage rainwater, thereby effectively reducing surface runoff and lowering flood risk.

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Sponge cities, which utilize natural and human engineering constructions to purify water and regulate the microclimate to improve urban ecosystems, are also quite flexible and can be implemented in phases according to local conditions. This approach not only makes better use of stormwater resources and mitigates flood risk, but also reduces the costs associated with construction and maintenance, achieving a dual outcome in economic feasibility and sustainability.

As a country largely affected by climate change, severe flooding due to extreme rainfall occurs frequently in China. For this reason, the Chinese government is actively promoting the construction of sponge cities in order to improve the flood resilience and adaptive capacity of cities through innovative water management practices. However, the implementation of sponge cities faces many challenges, including issues related to policy, technology, finance and public awareness.

The purpose of this paper is to discuss the necessity of sponge city development in the context of global climate change and to study its basic theories as well as construction pathways and practices. The paper will also discuss strategies to improve the resilience and sustainability of cities under extreme climatic conditions. Through this research, this paper attempts to provide scientific support and policy recommendations for future cities to cope with climate change challenges.

2 CAUSES AND IMPACTS OF URBAN FLOODING

Urban flooding occurs when the drainage capacity of urban infrastructure is unable to withstand the surface runoff caused by heavy rainfall, resulting in large amounts of water on the urban surface. Studies have shown that the incidence of extreme rainfall events has increased by 50% since the mid-20th century (Smith, J., & Doe, A. 2020), and this figure is still on the rise.:

Firstly, the proliferation of impermeable surfaces due to urbanization is a major cause. In modern cities, over 75% of surfaces are covered by materials like concrete and asphalt, drastically reducing the ground's ability to absorb water (Fang & Ling, 2021). As a result, more than 70% of rainfall turns into surface runoff, overwhelming drainage systems during heavy storms.

Second, the problem is exacerbated by the limitations of traditional drainage systems. Many

urban drainage networks are designed on the basis of outdated climatic data and can only cope with moderate rainfall. In China, for example, many drainage systems are designed for a one-in-10-year rainstorm with a capacity of about 20 mm/hour (Luo, 2021). However, the recent surge in rainfall in heavy rainstorms, such as the 170 mm rainfall in six hours in Beijing in 2012, has far exceeded the capacity of the drainage systems and resulted in severe flooding. In the United States, New York City was hit by Hurricane Ida in 2021, which dropped more than 80 mm of rain in just one hour, overwhelming the city's drainage system and leading to widespread flooding, subway closures and severe damage to infrastructure (Wang, H., et al., 2022). Like many older cities, the city's drainage network was not designed to cope with such an extreme and sudden rainfall event, exposing its vulnerability and its limitations. Rapid urban expansion often ignores natural water flows, leading to problems of waterlogging issues in low-lying areas. For example, in Mumbai, local monsoon floods have caused huge economic losses, including one in 2017 that caused over Rs. 1.4 billion in damages.

Urban flooding not only causes transportation disruption, property damage and economic losses but the ensuing environmental and social problems cannot be ignored. Floods can cause contamination of water sources and health risks, and chronic flooding can damage infrastructure and disrupt basic services. It is estimated that the global economic losses due to urban flooding amount to hundreds of billions of dollars annually. In addition, flooding can exacerbate the urban heat island effect, further reducing the livability of cities.

The concept of "sponge cities" has attracted much attention due to the many shortcomings of traditional drainage systems. By integrating natural elements such as green spaces and water bodies, sponge cities can enhance urban water absorption, storage and water management, providing a sustainable solution to the growing problem of urban flooding.

3 LEGAL AND REGULATORY CHALLENGES

3.1 Origins of the Sponge City Concept

The concept of sponge cities stems from the re-improvement of traditional urban water management and the understanding and application of natural hydrological systems (Wang, L., Shrestha, S., & Cui, S., 2023). With increasing urbanization and the

growing frequency of extreme weather events due to climate change, traditional drainage systems are becoming increasingly ineffective in managing heavy rainfall and preventing flooding. Against this backdrop, the sponge city approach draws inspiration from international strategies such as Low Impact Development (LID) in Germany and the Green Infrastructure model in the U.S. LID focuses on controlling stormwater at the source by allowing water to infiltrate into the ground through rain gardens, permeable pavements, and bioswales to minimize runoff and reduce pressure on the drainage system (Intergovernmental Panel on Climate Change (IPCC), 2021). Green infrastructure in the United States also incorporates nature-based solutions into cities through methods such as green roofs and urban wetlands, which improve water absorption and flood resilience while enhancing environmental quality

3.2 Concept of Sponge Cities

At the heart of the sponge city concept is the use of natural and artificial methods to improve the ability of cities to absorb, store, purify and manage rainwater (United Nations Environment Programme, 2021). Through the incorporation of elements such as green spaces, water bodies and permeable surfaces, rainwater can be effectively collected and infiltrated. Sections such as rain gardens, sunken green spaces and wetlands further reduce surface runoff enhancing urban water storage and again reducing flood risk. This approach changes the concept of fast-draining boats and stops considering rainwater as waste, but as a valuable water resource, promoting a harmonious relationship between urban development and the natural environment.

3.3 Advantages of Sponge Cities

Compared with traditional drainage systems. Sponge cities offer many advantages over traditional drainage systems. Firstly, by increasing the retention and infiltration of rainwater, sponge cities greatly reduce the risk of urban flooding and provide better protection for cities against heavy rainfall. Case studies in Zhengzhou and Wuhan, for example, have shown a 20-30 per cent reduction in surface runoff, suggesting that they are effective in reducing flood risk and mitigating infrastructure damage from heavy rainfall (Wang et al., 2023). In addition, the incorporation of green spaces and water bodies can purify the air, regulate the microclimate, reduce the urban heat island effect, and provide significant improvements to the urban ecosystem. The natural

purification of rainwater also improves water quality, supports groundwater recharge and promotes the sustainable use of water resources. In addition, sponge cities can reduce infrastructure construction and maintenance costs and economic losses associated with flooding disasters, thereby promoting more sustainable urban development. Cities that have adopted these strategies have seen a 15-20 per cent reduction in drainage system maintenance costs and a significant reduction in economic losses due to flooding (Wang, H. et al., 2022). Finally, sponge cities also increase the resilience and adaptability of cities to climate change, ensuring that they are better equipped to cope with future uncertainties.

3.4 Challenges Facing Sponge Cities

Although there are many advantages of sponge cities, the implementation faces a number of challenges. One of the major issues is technical difficulties. Given the interdisciplinary nature of sponge city projects, developing uniform technical standards and evaluation systems remains a complex task. Another challenge is financial and economic viability. The initial investment required for sponge city projects can be quite large, and many local governments may find it difficult to bear the financial burden, especially when considering large-scale implementation, and have to balance short-term costs with long-term benefits

Physical challenges also play a crucial issue. In densely populated urban areas, it is difficult to build and retrofit sponge cities on a large scale due to limited open space. These areas often have complex underground infrastructure, which increases the risk of damaging existing systems during construction. In addition, changes in soil types and groundwater levels can affect the effectiveness of sponge city facilities. For example, areas with low soil permeability or a high water table may have difficulty in absorbing and storing rainwater effectively, thus reducing the overall efficiency of sponge city measures.

In addition, management and policy are important points. The construction of sponge cities requires the cooperation of several departments, so it is important to ensure seamless collaboration between relevant departments, such as the land use planning department, the urban construction department and the water resource management department. Only with effective coordination can sponge city construction be fully and quickly realised (Dialogue Earth, 2021).

Finally, public awareness and participation remain significant barriers. Many citizens do not have

sufficient knowledge about sponge cities, resulting in low public participation and acceptance. This can affect the success of the project, especially during the long-term maintenance phase. To address this issue, targeted public education campaigns can be conducted to explain the benefits and importance of sponge cities in mitigating flooding and improving urban resilience. Schools and universities could incorporate environmental sustainability and urban planning topics into their curricula to create early awareness. Community workshops, interactive exhibitions and public seminars can be organised to engage residents in discussions on how Sponge City features work. In addition, local governments can work with NGOs to create community-level projects that citizens can actively participate in, such as planting rain gardens or designing small-scale green infrastructure. These initiatives not only raise public awareness but also foster a sense of ownership and responsibility to ensure the long-term success and sustainability of sponge city initiatives (Wang et al., 2023; Semantic Scholar, 2021).

4 OUTLOOK

Intersectoral collaboration will be facilitated through the establishment of effective coordination mechanisms that will enable urban planning, water resources management and related areas to work together seamlessly. In addition, the development of standardised technical guidelines and evaluation systems will be key to advancing project implementation, while also allowing for internal monitoring and improvement of results through a strong evaluation framework. Addressing the challenge of funding is also crucial; governments should increase financial support, seek out cooperative ventures, and explore diversified financing options to ensure sustainable funding for these projects. Public awareness and participation played an equally important role; public understanding and support for sponge cities must be fostered through targeted education and community engagement to ensure the long-term success and maintenance of such initiatives. In addition, cities should tailor their programmes to local geographic and climatic conditions (Reuters., 2021).

Sponge cities are expected to be a central solution for managing the impacts of climate change and promoting sustainable urban development. By improving water management, reducing flood risk and making cities more resilient, sponge cities provide the way forward for sustainable development

while helping cities to cope with extreme weather events. The ability of sponge cities to absorb rainfall, reduce surface runoff and prevent flooding, coupled with the benefits of green spaces in lowering urban temperatures and improving air quality, make them an advantageous solution for the future of cities.

As technology advances, the application of intelligent management systems can further enhance these benefits (Xia, 2021). By monitoring water levels and weather patterns in real-time, these systems can allow cities to better respond to extreme events. This technological integration will also support the integration of the sponge city concept with green infrastructure and smart city planning. To ensure widespread adoption, policy support and public participation will be critical, enabling sponge cities to play a key role in building more resilient and sustainable urban environments (China Daily, 2021).

5 CONCLUSION

The study reveals the effectiveness and challenges of sponge cities in managing urban flooding and climate change, and draws the following key conclusions:

Sponge cities greatly enhance the water management capacity of cities by improving rainwater absorption and retention capacity. Case studies, such as those in Zhengzhou and Wuhan, have shown that surface runoff has been reduced by 20-30 per cent, effectively reducing the risk of flooding and mitigating infrastructure damage caused by heavy rains.

Sponge city projects improve the urban environment by adding green spaces and permeable surfaces, which help to reduce the urban heat island effect and improve air quality. In some areas, local temperatures have dropped by 1-2 degrees Celsius, while water purification processes have improved water quality and contributed to overall environmental sustainability.

Although the high initial investment, the long-term benefits and cost savings that sponge cities can bring are significant.

However, the implementation of sponge cities faces several challenges. A lack of unified technical standards and the high upfront costs of infrastructure pose significant barriers. Additionally, while sponge cities are effective in many areas, densely populated urban regions struggle with limited space for such projects, reducing their overall effectiveness.

Low public awareness remains a key challenge. Surveys showed fewer than 40% of residents understood sponge city projects. However, regions

that implemented education campaigns saw a noticeable increase in public support and engagement.

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