

OJO SEGUN SUNDAY

**IMPLEMENTING SPONGE CITY CONCEPTS IN PRACTICE: LEARNING
FROM THE CASE OF SHENZHEN, CHINA**



**UNIVERSIDADE DO ALGARVE
Instituto Superior de Engenharia
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Master in Urban Water Cycle

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Declaration of authorship of the work

I hereby declare to be the author of this work, which is original and unpublished. Authors and works consulted are properly cited in the text and included in the reference list.

(Ojo Segun Sunday)

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RESUMO

As inundações urbanas constituem um dos principais desafios enfrentados pelas cidades em acelerado processo de urbanização, particularmente em contextos marcados por elevada densidade populacional e crescente variabilidade climática. Na China, este fenómeno tem sido agravado pelas alterações climáticas e pela impermeabilização intensiva dos solos urbanos, exigindo respostas integradas e sustentáveis por parte das autoridades locais. Neste contexto, a presente dissertação centra-se na análise do programa Sponge City em Shenzhen, uma das cidades-piloto nacionais, com o objetivo de avaliar de que modo as soluções baseadas na natureza têm contribuído para a resiliência urbana face às inundações, bem como para benefícios ambientais e sociais mais amplos.

Partindo de uma abordagem de estudo de caso, a investigação recorre a métodos mistos que combinam análise documental, dados hidrológicos secundários, revisão reflexiva da literatura e análise preliminar de séries temporais de eventos de inundações. A investigação estrutura-se em torno de três dimensões analíticas: (1) resiliência urbana e desempenho hidrológico, (2) impactos ambientais e infraestruturais, e (3) governação e desafios de implementação. Estas dimensões permitem compreender, de forma articulada, os resultados e limitações do programa Sponge City em Shenzhen, à luz de quadros teóricos como a Teoria da Resiliência, a Gestão Integrada dos Recursos Hídricos (IWRM) e a abordagem dos Serviços dos Ecossistemas.

Os resultados empíricos evidenciam uma redução significativa do escoamento superficial e das cheias urbanas nos distritos intervencionados, com valores de mitigação superiores a 40% em zonas-piloto, de acordo com simulações hidrológicas e dados de monitorização. Estes resultados confirmam a eficácia das soluções de baixo impacto (Low-Impact Development – LID), tais como bacias de retenção, pavimentos permeáveis e zonas húmidas artificiais. A par da redução dos volumes de água, registaram-se melhorias na qualidade da água, com diminuições mensuráveis nos níveis de azoto, fósforo e matéria orgânica dissolvida. Estas alterações são consistentes com os princípios ecológicos que orientam o conceito de cidade-esponja, baseado na replicação de funções naturais de absorção, infiltração e depuração da água no espaço urbano.

A segunda dimensão da análise incide sobre os impactos ambientais e infraestruturais decorrentes da implementação do programa. Observou-se um aumento da cobertura vegetal e da conectividade ecológica em parques urbanos requalificados, como o Parque Ecológico de Mangais de Futian, com efeitos positivos ao nível da biodiversidade e da regulação microclimática. Em algumas áreas de elevada densidade populacional, foram registadas descidas de temperatura local na ordem dos 2–3°C, refletindo os benefícios multifuncionais das infraestruturas verdes. Além disso, a reconversão de espaços degradados em zonas de lazer e parques multifuncionais contribuiu para melhorar a qualidade de vida urbana e a perceção pública da sustentabilidade hídrica.

Contudo, a investigação revela também desafios persistentes no domínio da governação. A fragmentação institucional, traduzida em mandatos sobrepostos e ausência de mecanismos formais de coordenação interdepartamental, tem comprometido a implementação eficaz e a manutenção das infraestruturas verdes. Distritos mais antigos como Luohu e Futian enfrentam dificuldades acrescidas na adaptação de zonas densamente urbanizadas, onde os constrangimentos espaciais e as limitações técnicas dificultam a adaptação de infraestruturas convencionais às exigências do modelo de cidade esponja. Por outro lado, a dependência quase exclusiva de financiamento público, aliada à escassa participação do setor privado, coloca em causa a sustentabilidade a longo prazo dos investimentos realizados. A análise mostra ainda que os sistemas de monitorização permanecem insuficientemente desenvolvidos, com cobertura desigual e ausência de uma plataforma centralizada de dados, o que dificulta a gestão adaptativa e a avaliação baseada em evidência.

Em termos metodológicos, a dissertação destaca-se pela integração de diferentes tipos de fontes e metodologias de análise, embora enfrente limitações relevantes. A ausência de dados espaciais limitou uma análise mais aprofundada da equidade territorial e da associação entre diferentes variáveis. De igual forma, a ausência de dados primários recolhidos no terreno limitou a capacidade de validação empírica direta dos resultados. Estas limitações, reconhecidas de forma crítica no trabalho, abrem caminho para futuras investigações mais abrangentes e interdisciplinares.

Apesar destas lacunas, a investigação cumpre os objetivos delineados, contribuindo de forma substantiva para o conhecimento sobre a operacionalização de soluções baseadas na natureza no contexto chinês. O caso de Shenzhen é analisado não apenas como exemplo de inovação infraestrutural, mas também como laboratório de governação urbana face às alterações

climáticas. A análise comparativa com outras cidades como Wuhan, Xi'an ou Pequim sugere que, embora Shenzhen se destaque em termos de visibilidade pública e inovação tecnológica, partilha desafios estruturais ao nível da fragmentação institucional e da replicação em zonas urbanas consolidadas.

Do ponto de vista das implicações políticas, os resultados sugerem a necessidade de reforçar a integração dos princípios das cidades-esponja nos regulamentos urbanísticos e nos códigos de construção, promovendo incentivos à participação privada e à gestão comunitária das infraestruturas. A utilização de tecnologias digitais, como sensores IoT e painéis interativos, deve ser expandida para apoiar a monitorização em tempo real e melhorar a transparência na gestão urbana da água. Finalmente, é fundamental garantir que a abordagem não se limita aos aspetos técnicos, mas integra as dimensões sociais da resiliência, promovendo o envolvimento das comunidades e a apropriação cidadã dos espaços urbanos requalificados.

Palavras-chave: Cidade-Esponja, Shenzhen, inundações urbanas, estudo de caso, resiliência hidrológica, infraestrutura verde, adaptação climática.

ABSTRACT

Urban flooding represents an increasingly critical challenge in China's rapidly urbanising regions, where high-density development and climate variability exacerbate hydrological vulnerabilities. This dissertation presents a case study of Shenzhen, one of China's national pilot cities for the Sponge City programme, to assess how nature-based infrastructure contributes to urban flood resilience and environmental sustainability.

Adopting a mixed-methods case study approach that combines hydrological data synthesis, flood event mapping, and policy review, the research analyses the contribution and governance of sponge interventions in Shenzhen's. Drawing on secondary data from 2006 to 2020, the study identifies trends in flood frequency, pollutant reduction, and surface runoff mitigation, particularly in areas with concentrated Sponge City deployment. The analysis highlights significant hydrological and environmental outcomes, including reductions in peak flows and enhanced pollutant filtration, while also revealing persistent challenges related to institutional coordination, technical capacity, and long-term maintenance.

Despite constraints in accessing primary spatial and monitoring data, the study provides an empirically grounded and policy-relevant evaluation of Shenzhen's transition toward climate-adaptive stormwater management. The findings contribute to the theoretical and applied understanding of nature-based solutions in rapidly urbanising contexts and offer a framework to support the scaling and adaptation of Sponge City strategies in other climate-vulnerable cities.

Keywords: Sponge City, Shenzhen, urban flooding, case study, hydrological resilience, green infrastructure, nature-based solutions, climate adaptation.

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LIST OF ACRONYMS

BERT	Bidirectional Encoder Representations from Transformers
BiLSTM-CRF	Bidirectional Long Short-Term Memory with Conditional Random Fields
CNKI	China National Knowledge Infrastructure
ESDA	Exploratory Spatial Data Analysis
GIS	Geographic Information System
IoT	Internet of Things
IWRM	Integrated Water Resources Management
LID	Low Impact Development
LISA	Local Indicators of Spatial Association
NDVI	Normalized Difference Vegetation Index
NLP	Natural Language Processing
PPP	Public–Private Partnership
SCP	Sponge City Programme
SoA	State of the Art
SWMM	Storm Water Management Model
TC	Tropical cyclone

1

INTRODUCTION

Urban water management challenges have intensified with rapid urbanization, requiring adaptive solutions that integrate ecological sustainability with infrastructure resilience. The accelerating pace of urban expansion, combined with the growing impacts of climate change, has significantly disrupted natural hydrological cycles. The widespread coverage of impervious surfaces, such as roads, rooftops, and pavements, limits rainwater infiltration, increases surface runoff, and contributes to urban flooding, water scarcity, and environmental degradation. Historically, cities have relied on grey infrastructure systems prioritizing quick water evacuation through centralized drainage networks and engineered flood control structures. While these systems provide more immediate control, they often neglect long-term sustainability, resulting in problems such as groundwater depletion, water pollution, and ecological imbalance (Jiang et al., 2017).

To address these shortcomings, the ‘Sponge City’ concept has gained traction as an innovative and ecologically sensitive urban water management strategy (CNN, 2024). This approach integrates nature-based solutions that mimic natural hydrological processes, promoting stormwater retention, infiltration, purification, and reuse within the urban landscape. Interventions such as permeable pavements, bioretention cells, rain gardens, green roofs, and constructed wetlands play a central role in reducing runoff volumes, filtering pollutants, and enhancing groundwater recharge (Li et al., 2019). At the forefront of this movement is Shenzhen, a rapidly urbanizing city in southern China. With a high population density and increasing exposure to hydrological risks, Shenzhen presents a compelling case for evaluating how Sponge City principles are operationalized in practice. Its designation as a

national demonstration city further underscores its relevance to contemporary discussions on climate adaptation and sustainable urban planning (Yin et al., 2021).

Despite the growing literature on Sponge Cities, there remains a critical gap in empirical evaluations of their real-world performance, particularly in terms of flood mitigation and long-term ecological benefits. While many studies explore the theoretical underpinnings of nature-based solutions, fewer investigations assess the on-the-ground implementation and outcomes in specific urban contexts (Ma & Jiang, 2023).

Shenzhen provides an opportunity to bridge this gap by offering a detailed case from which lessons can be drawn about the effectiveness, challenges, and scalability of sponge strategies in urban settings. Shenzhen is part of the Shenzhen River Basin and is defined by numerous small, rain-fed rivers and streams organised into nine major watersheds, which collectively drain the urban area and its surrounding catchments into the Pearl River Delta (Fu et al., 2023). The nine main watersheds are: Maozhou River, Shenzhen River, Longgang River, Guanlan River, Pingshan River, Daya Bay, Dapeng Bay, Shenzhen Bay, and the Pearl Estuary watershed. These watersheds play a critical role in flood risk management, water quality control, and the sustainable management of urban water resources. Rapid urbanization and industrial growth have severely polluted these river systems, reduced their environmental capacity, and damaged local ecosystems. In response, the city has implemented comprehensive management strategies, including pollution control measures and large-scale ecological restoration projects such as the Sponge City initiative.

This study is therefore guided by the central research question: To what extent has the Sponge City initiative in Shenzhen improved urban resilience and sustainable water management in the context of rapid urbanization and climate change?

To investigate this question, the research aims to: analyse the theoretical foundations of Sponge City strategies and their relevance to urban sustainability; assess the practical outcomes of Sponge City implementation in Shenzhen using planning documents and empirical assessments; and evaluate the broader implications of such strategies for future urban water governance.

To achieve these objectives, the study adopts a methodological framework that blends qualitative and quantitative tools. A reflexive literature review forms the conceptual backbone of the research, involving critical engagement with academic literature on sustainable urban water management, resilience, and nature-based infrastructure solutions (Jiang et al., 2018). Complementing this theoretical inquiry is a case study analysis of Shenzhen's Sponge City Programme, drawing on urban planning reports, policy documents, and technical evaluations

to trace the city's implementation trajectory (Li et al., 2019). In tandem, the study uses descriptive quantitative analysis to selected indicators. Altogether, this multi-method approach ensures a holistic assessment that captures both the conceptual evolution of Sponge City thinking and its material effects on the urban fabric. Through this lens, the study not only investigates the success of Shenzhen's water-sensitive infrastructure but also contributes to the broader discourse on adaptive and sustainable urban design in the face of global environmental change.

This dissertation is organized into five integrated chapters that collectively explore the principles of Sponge City development, their application in Shenzhen, and broader implications for sustainable urban water management.

The opening chapter introduces the research background, defines the central problem and objectives, and briefly presents the methodological approach, laying the groundwork for the study's overall direction. The second chapter provides a comprehensive review of the existing literature, tracing the evolution of urban water management from conventional grey infrastructure to the adoption of green, nature-based solutions. It examines theoretical frameworks surrounding urban resilience and sustainable development, offering a conceptual lens through which Sponge City strategies are understood. The third chapter outlines the research methodology, explaining the rationale behind the case study selection, the reflexive literature review process. It also discusses the data sources and analytical techniques used to assess policy and infrastructure performance. The fourth chapter presents and interprets empirical findings, evaluating the effectiveness of Shenzhen's Sponge City interventions in areas such as stormwater absorption, flood mitigation, and ecological restoration. It further explores policy implications and offers context-sensitive recommendations for improving implementation. The final chapter draws the study to a close by summarizing key findings, reflecting on methodological limitations, and proposing future directions for Sponge City development both within China and in other rapidly urbanizing regions worldwide.

2

LITERATURE REVIEW

2.1 THE RISE OF SPONGE CITY CONCEPT

Water management has played a crucial role in shaping the development of cities, responding to the growing demands of expanding urban populations and evolving environmental challenges. Historically, early civilizations implemented basic water supply and drainage systems to facilitate access to clean water and prevent flooding. Roman aqueducts, Mesopotamian canal networks, and the advanced irrigation systems of the Indus Valley exemplify early engineered solutions that focused primarily on water distribution and sanitation (Jiang et al., 2017). While effective in their time, these systems did not emphasize long-term sustainability, leading to unintended consequences such as water source depletion and soil degradation.

With the onset of industrialization in the 19th and 20th centuries, cities rapidly expanded, leading to an increasing reliance on grey infrastructure, including concrete drainage networks, underground pipelines, and engineered flood barriers. These technological advancements provided solutions for sanitation and flood control; however, they also contributed to environmental degradation. The widespread replacement of natural landscapes with impervious surfaces altered hydrological cycles, increasing runoff, reducing groundwater recharge, and exacerbating urban flooding issues (Nguyen et al., 2019).

By the late 20th century, urban planners recognized the limitations of conventional water management systems, leading to a shift toward Integrated Water Resources Management (IWRM), which emphasizes a holistic approach that considers the interconnections between water, land use, and ecosystem health (Jiang et al., 2017). Alongside IWRM, the emerging climate adaptation movement underscored the need for resilient urban

water infrastructure to mitigate the impacts of intensified rainfall, rising temperatures, and extreme weather events (Li et al., 2019). This evolving discourse laid the foundation for Sponge City principles, which prioritize stormwater absorption, filtration, and reuse rather than simply channelling water away from urban areas (Yin et al., 2021). These principles are operationalized through specific infrastructure components, such as permeable pavements, constructed wetlands, and rain gardens, each designed to perform critical hydrological and ecological functions, as summarized in Table 2.1.

Table 2.1 - Key Infrastructure Components of Sponge Cities and Their Functions

Sponge City Component	Function	Main Benefits
Permeable Pavements	Allow stormwater infiltration	Reduces runoff, enhances groundwater recharge
Constructed Wetlands	Filters and stores stormwater	Improves water quality, supports biodiversity
Rain Gardens & Bio-Retention	Captures and cleans stormwater	Supports urban biodiversity, prevents pollution

Source: Own Elaboration.

Green roofs, which feature vegetated surfaces on buildings, assist in stormwater absorption and temperature regulation (Ma & Jiang, 2023). Permeable pavements replace traditional concrete roads and sidewalks, allowing water to infiltrate the ground and reduce runoff accumulation (Chan et al., 2018). Rain gardens and bio-retention systems provide stormwater storage and pollutant filtration, creating urban pockets of biodiversity (Liu & Jensen, 2018). Constructed wetlands mimic natural wetlands to treat stormwater and improve water quality (Qiao et al., 2020), while rainwater harvesting systems collect water from rooftops and drainage points for sustainable reuse (Rentachintala et al., 2022). Lastly, stormwater detention basins and floodable parks slow down stormwater movement, preventing flash floods and reinforcing urban flood resilience (Jiang et al., 2017). In light of this diversity of components, it is important to explore the theoretical frameworks that inform and support the implementation of Sponge City principles.

2.2 THEORETICAL INSPIRATIONS FOR SPONGE CITY PRINCIPLES

The Sponge City initiative is underpinned by several key theoretical frameworks that collectively provide a robust foundation for its hydrological, ecological, and urban resilience

strategies. At the heart of this initiative is Resilience Theory, which explores how urban systems can adapt to disturbances, such as flooding, heat stress, and water scarcity, while maintaining essential functions (Ahern, 2011). Sponge Cities operationalize this by incorporating infrastructure that can absorb, store, and reuse stormwater, thereby enabling urban areas to withstand and recover from extreme weather events more effectively, thus promoting long-term sustainability. Complementing this is the Ecosystem Services Theory, which emphasizes the critical benefits delivered by natural systems, including climate regulation, water purification, and flood mitigation (Gómez-Baggethun & Barton, 2013). Sponge Cities strategically harness these services by integrating elements such as wetlands, permeable surfaces, and green spaces into urban environments.

These features naturally regulate hydrological cycles and contribute to improved environmental conditions, making cities more liveable and ecologically balanced. The principle of Integrated Water Resources Management (IWRM) also plays a central role in Sponge City design. IWRM advocates for the coordinated management of water, land, and environmental resources to achieve sustainable outcomes (GWP, 2000). Sponge Cities reflect IWRM ideals by decentralizing water systems, treating stormwater as a valuable resource rather than waste, and minimizing reliance on traditional drainage infrastructure (Jiang et al., 2017). This approach fosters cooperation between urban development and ecological conservation, ensuring water sustainability across sectors.

Finally, Urban Green Infrastructure Theory supports the integration of vegetation-based solutions, such as bioswales, rain gardens, and constructed wetlands, into the urban landscape to enhance stormwater management, boost climate resilience, and improve urban aesthetics and health (Tzoulas et al., 2007). Sponge Cities embody this theory by replacing impermeable materials with multi-functional, water-sensitive infrastructure that not only manages runoff but also contributes to cooling, biodiversity, and human well-being.

Although these theoretical perspectives are often mobilized in a complementary fashion, they are grounded in distinct epistemologies and institutional logics that may not always align in practice. Resilience Theory, for instance, foregrounds adaptive capacity and systemic robustness, yet its implementation in urban planning has been criticized for lacking normative clarity and for masking social inequalities under the guise of flexibility (Gómez-Baggethun & Barton, 2013). Similarly, while the Ecosystem Services framework provides a persuasive rationale for integrating natural processes into urban infrastructure, it can encourage a technocratic and economic valuation of nature, sidelining ethical, cultural or

community-based understandings of ecological relationships (Gómez-Baggethun & Barton, 2013).

In parallel, IWRM promotes a paradigm of integrated decision-making across sectors, but its operationalization is frequently hampered by fragmented institutional arrangements, overlapping mandates, and entrenched sectoral silos, especially in rapidly urbanizing contexts (Jiang et al., 2017). Moreover, the normative assumption of coordination often clashes with political realities, in which water governance is contested and asymmetrical. Urban Green Infrastructure Theory, although offering concrete design solutions, can also suffer from being depoliticized or reduced to surface-level greening strategies, unless firmly embedded in broader socio-environmental planning frameworks.

These theoretical tensions do not undermine the relevance of the Sponge City approach but rather highlight the need for reflexivity in its application. A critical engagement with these frameworks allows for a more context-sensitive, inclusive and politically aware implementation of Sponge City principles, one that acknowledges not only ecological processes but also governance dynamics, social equity, and institutional constraints. In this light, the study of empirical cases becomes particularly valuable for understanding how these conceptual models are negotiated, adapted or resisted in different urban environments.

Grounded in these conceptual foundations, a growing number of cities have started experimenting with Sponge City practices. The following case studies offer insight into how these principles are applied in real urban contexts.

2.3 LEARNING FROM PRACTICAL IMPLEMENTATION OF SPONGE CITIES

The Sponge City Programme (SCP), introduced by the Chinese government in December 2013 and inspired by Professor Kongjian Yu (Yu, 2016), is an urban stormwater management strategy that employs Blue-Green Infrastructure to restore natural water cycles through the accumulation, filtration, purification, storage, and reuse of rainwater, while also delivering environmental and social co-benefits. The initiative, launched collaboratively by the Ministries of Finance, Water Resources, and Housing and Rural-Urban Development, began with 16 pilot cities in the first batch and 14 in the second. In October 2015, the government issued guidelines (General Office of the State Council, 2015) requiring that 20% of urban areas incorporate sponge features—such as rain gardens, swales, wetlands, ponds, and permeable paving—with targets rising to 70% by 2020 and 80% by 2030, necessitating both retrofitting of existing areas and integration into new developments. Pilot projects were

rolled out in 2015 and 2016, with cities like Zhenjiang, Jiaxing, and Xiamen in the first batch and Shenzhen, Shanghai, Tianjin, and Beijing in the second, supported by national policies and financial mechanisms, including a public-private partnership (PPP) model introduced by the Central Ministry of Finance.

China's Sponge City initiative has been piloted in several major urban centres, offering valuable insights into the practical application of nature-based water management strategies. Among these, Wuhan, Xiamen, and Shenzhen stand out as illustrative case studies, each representing a distinct approach shaped by local geography, urban form, and planning priorities.

Wuhan, situated along the Yangtze River, has long been vulnerable to seasonal flooding due to its low-lying terrain and monsoon climate. In response, the city adopted large-scale ecological interventions as part of its SCP. Projects such as the Zhanggong Dyke Wetland Park exemplify this approach, combining constructed wetlands, rain gardens, and permeable pavements to enhance water absorption and reduce flood risk. These multifunctional landscapes not only mitigate flooding but also support biodiversity conservation and provide recreational space for residents (Yin et al., 2021).

In contrast, Xiamen, a compact coastal city, faced the challenge of integrating Sponge City principles into an already dense urban fabric. With limited space for expansive green infrastructure, the city focused on retrofitting existing residential areas. Rainwater harvesting systems, bio-retention cells, and permeable surfaces were introduced to manage stormwater within confined environments. This approach demonstrates the adaptability of Sponge City strategies to high-density settings, where spatial constraints necessitate innovative, small-scale interventions (Jiang et al., 2017).

Shenzhen presents a third model, shaped by rapid urbanization and complex hydrological conditions. As one of China's fastest-growing cities, Shenzhen has embraced a data-driven approach to Sponge City planning. The use of GIS-based hydrological modelling has enabled planners to identify flood-prone zones and strategically deploy stormwater absorption features such as vegetated swales, constructed wetlands, and permeable pavements. The Futian Mangrove Ecological Park stands as a flagship example, integrating ecological restoration with flood mitigation in a high-density urban context (Li et al., 2019). Shenzhen's emphasis on spatial analysis and digital planning tools highlights the potential of technology to enhance the precision and effectiveness of Sponge City interventions. Given its unique combination of rapid growth, environmental vulnerability, and technological innovation, Shenzhen has been selected as the primary case study for this research. Its experience offers a

compelling lens through which to examine the real-world performance, governance dynamics, and spatial outcomes of Sponge City implementation in a megacity context.

Despite the promise shown in these pilot cities, the broader implementation of Sponge City strategies continues to face various obstacles, while also opening new avenues for innovation and sustainability.

2.4 CHALLENGES AND OPPORTUNITIES FOR SPONGE CITY IMPLEMENTATION

Despite the growing enthusiasm for Sponge City development, its implementation across urban landscapes remains fraught with challenges. While the concept holds immense promise for sustainable water management, cities often encounter a complex mix of technical, financial, institutional, and social barriers that can hinder its widespread adoption. One of the most immediate hurdles lies in the technical complexity of adapting Sponge City strategies to diverse urban environments. Each city presents unique geographical and climatic conditions, requiring tailored hydrological modelling and specialized infrastructure design. Without adequate planning and expertise, interventions may fall short, leading to drainage inefficiencies, localized flooding, or underperforming filtration systems (Li et al., 2019; Nguyen et al., 2019). These risks are particularly pronounced in retrofitting older urban areas, where existing infrastructure may not easily accommodate nature-based solutions.

Financial constraints also pose a significant obstacle. While Sponge City infrastructure can yield long-term economic and environmental benefits, the upfront costs of installing permeable pavements, constructed wetlands, and rainwater harvesting systems are often substantial. Municipal budgets, especially in rapidly urbanizing regions, tend to favor conventional grey infrastructure due to its lower initial investment requirements (Rentachintala et al., 2022). This short-term cost logic can delay or limit the integration of more sustainable alternatives. Institutional and policy-related barriers further complicate implementation. Many existing regulatory frameworks are still geared toward traditional drainage systems, making it difficult to incorporate green infrastructure into formal planning processes.

Fragmented governance structures and limited inter-agency coordination can result in inconsistent standards, duplicated efforts, or stalled projects (Jiang et al., 2017). Without a unified vision and collaborative mechanisms, the holistic nature of Sponge City planning is difficult to achieve. Public engagement is another critical, yet often overlooked, dimension. In many cities, residents remain unaware of the benefits that Sponge City interventions can

bring—not only in terms of flood control, but also in improving public spaces and environmental quality. This lack of awareness can lead to resistance, particularly when projects involve changes to familiar streetscapes, green spaces, or drainage systems. Without targeted education and outreach, community involvement in maintaining and supporting these systems remains limited (Yin et al., 2021).

Finally, climate adaptation introduces an additional layer of complexity. Sponge City designs must be responsive to local climate conditions, whether that means managing storm surges in high-rainfall regions or prioritizing water conservation in arid zones. The increasing unpredictability of weather patterns further underscores the need for flexible, adaptive infrastructure that can evolve with changing environmental pressures (Ma & Jiang, 2023; Jiang et al., 2017). Addressing these challenges requires more than technical fixes. It calls for integrated policy reforms, innovative financing models, capacity-building initiatives, and inclusive public engagement. Cities like Shenzhen, Wuhan, and Xiamen have begun to chart this path, offering valuable lessons on how Sponge City principles can be refined and scaled to meet the demands of a rapidly urbanizing and climate-vulnerable world (Yin et al., 2021).

At the same time, the Sponge City concept offers a wide range of opportunities for enhancing urban resilience, sustainability, and well-being. The Sponge City initiative presents a significant shift in urban water management, offering numerous opportunities for cities to strengthen flood resilience, improve water conservation, and restore ecological balance. As urbanization intensifies, these nature-based solutions provide a long-term strategy to mitigate climate change impacts and infrastructure vulnerabilities (Ma & Jiang, 2023). One of the primary benefits of Sponge Cities is flood risk reduction, particularly in high-density urban areas that experience extreme rainfall and drainage overloads. By incorporating permeable pavements, rain gardens, and wetlands, stormwater is absorbed rather than rapidly discharged into overburdened drainage systems, preventing flash floods and infrastructure damage (Jiang et al., 2017). This adaptive measure reduces the financial burden associated with flood recovery efforts.

Another major opportunity lies in enhanced urban water security. Sponge Cities promote rainwater harvesting and groundwater recharge, allowing cities to store and repurpose stormwater for irrigation, cooling, and non-potable municipal uses (Li et al., 2019). This approach minimizes reliance on traditional freshwater sources, benefiting cities facing seasonal droughts or declining groundwater levels (Yin et al., 2021). Beyond hydrological benefits, Sponge Cities contribute to biodiversity conservation and ecological restoration. Green spaces and urban wetlands serve as natural habitats for wildlife, improving air and water

quality while promoting a healthier urban environment (Qiao et al., 2020). Additionally, these features provide social and recreational benefits, integrating parks and green corridors that enhance urban aesthetics and create walkable, liveable spaces (Liu & Jensen, 2018).

Technological advancements offer further opportunities to optimize Sponge City design and functionality (Zhou, 2022). Geospatial analysis, artificial intelligence-driven hydrological modelling, and smart monitoring systems allow urban planners to precisely map flood-prone areas, improving stormwater absorption strategies (Li et al., 2019). Sustainable materials, such as high-performance permeable concrete and modular green infrastructure, enhance durability while reducing maintenance costs (Siddiqui et al., 2025). On a broader scale, Sponge Cities have the potential for global adaptation, making them relevant for regions dealing with urban flooding, water scarcity, and heat stress. Lessons from Shenzhen, Wuhan, and Xiamen can inform international urban sustainability strategies, providing scalable and customizable models for cities seeking to integrate climate-responsive infrastructure (Yin et al., 2021).

To fully capitalize on these opportunities, urban policymakers must prioritize interdisciplinary collaboration, integrate Sponge City principles into zoning laws, and establish financial incentives for sustainable investments. With a growing global emphasis on resilient cities and environmental sustainability, Sponge Cities serve as a leading model for innovative urban water management, ensuring long-term liveability and climate adaptation.

3

METHODOLOGY

3.1 RESEARCH DESIGN

This chapter presents the research design adopted in the study, detailing the overall methodological approach, data sources, analytical strategies, and considerations regarding validity and limitations. The aim is to clarify how the investigation was structured to address the central research question: To what extent has the Sponge City initiative in Shenzhen improved urban resilience and sustainable water management in the context of rapid urbanization and climate change? The study adopts a qualitative case study design, supported by a reflexive literature review and document analysis. The methodological approach is therefore structured around the use of secondary data sources to conduct an in-depth qualitative analysis of Shenzhen's SCP.

The research adopts a qualitative case study methodology to explore the implementation and effects of the Sponge City initiative in Shenzhen. This approach allows for a comprehensive and context-sensitive examination of complex social and institutional phenomena, especially when the boundaries between the phenomenon and its context are not clearly defined (Yin, 2018). The case study design is particularly suitable for research questions that seek to explain 'how' or 'why' certain interventions work in real-life settings. It provides an empirical framework to examine a contemporary event within its real-world context, relying on multiple sources of evidence and allowing for triangulation.

A reflexive literature review was conducted to examine the theoretical and empirical foundations of Sponge City practices, following some basic principles of a systematic approach (Tranfield et al., 2003; Okoli and Schabram, 2010). Sources were identified through iterative searches on Web of Science, Google Scholar, ScienceDirect, and CNKI. Selection criteria included thematic relevance, publication quality, and geographic or conceptual

alignment with the case of Shenzhen. The literature reviewed covers topics such as sustainable drainage systems, urban ecological infrastructure, flood risk management, and climate-resilient urban planning.

Complementing the literature review, a qualitative document analysis was performed using a range of official planning documents, technical reports, municipal strategies, and hydrological assessments. These documents were used to understand the implementation phases, policy frameworks, spatial priorities, and institutional challenges associated with Sponge City projects in Shenzhen. Examples include flood hazard mapping reports, the Water Resources Bureau's annual bulletins, and documents from pilot zone evaluations. Materials selected were mainly in English, but some data and documentation were accessed in Chinese.

Given the complexity of urban water management systems and the context-specific nature of Sponge City implementation, a case study design was deemed appropriate for capturing the multidimensional features of the Shenzhen experience. To ensure methodological clarity and rigour, the study follows the framework proposed by Yin (2018), which outlines five essential components for conducting case study research. These are presented in the next section, providing the conceptual and analytical scaffolding for the investigation.

3.2 CASE STUDY METHODOLOGY AND JUSTIFICATION

According to Yin (2018), a case study should include five key components: (1) a clearly defined research question; (2) propositions, if applicable, that guide data collection; (3) a unit of analysis; (4) a logical linkage between data and the propositions; and (5) criteria for interpreting the findings. In this study, the unit of analysis is the city of Shenzhen, specifically its institutional, infrastructural, and ecological efforts under the Sponge City initiative. The research does not follow an experimental or comparative logic but aims to interpret and contextualize the measures taken in Shenzhen within broader frameworks of sustainable urban water management and climate adaptation.

The central research question guiding this case study is: To what extent has the Sponge City initiative in Shenzhen improved urban resilience and sustainable water management in the context of rapid urbanization and climate change? This question reflects the dual concern with environmental performance and institutional effectiveness, and is aligned with broader scholarly debates on nature-based solutions in urban governance. It frames the investigation

within the intersecting domains of infrastructure adaptation, ecological restoration, and climate resilience.

Consistent with Yin's (2018) recommendations, this case study is structured around a set of propositions that inform both the data selection and the analytical lens. First, it is assumed that the Sponge City model promotes urban resilience by mitigating flood risk and enhancing ecological functions. Second, it is posited that the implementation of green infrastructure contributes to improved water management outcomes in rapidly urbanizing contexts. Third, the study explores the idea that institutional coordination, governance capacity, and policy coherence are critical factors that shape the success of Sponge City strategies. These propositions provide a conceptual foundation for the interpretation of documentary and literature-based evidence.

The unit of analysis in this research is the city of Shenzhen, specifically in its role as a national pilot city within China's Sponge City initiative. This focus allows for a bounded examination of policy design, infrastructure implementation, and governance arrangements within a single urban context. Shenzhen's rapid urban growth, complex hydrological challenges, and high political visibility make it an especially relevant site for studying the operationalization of Sponge City principles.

In the absence of original empirical data collection, the logical linkage between the research propositions and the evidence base is established through a systematic review of secondary sources. These include peer-reviewed literature, technical reports, policy documents, and planning guidelines issued by municipal and national authorities. The integration of these sources allows for triangulation across different types of knowledge and supports a multi-dimensional interpretation of how Sponge City measures have been conceptualized, implemented, and evaluated in Shenzhen. Particular attention is paid to the coherence between policy goals and observed outcomes, as reported in official documentation and academic assessments.

3.3 ANALYTICAL FRAMEWORK

This research is structured around an analytical framework designed to align the research objectives with appropriate data sources and analytical strategies. The framework reflects the propositions outlined in the previous section and operationalises them through a set of thematic dimensions. These dimensions guide the organisation and interpretation of secondary data, ensuring a coherent response to the research question: To what extent has the

Sponge City initiative in Shenzhen improved urban resilience and sustainable water management in the context of rapid urbanisation and climate change?

The analysis is structured around four interrelated dimensions: (1) Theoretical and conceptual foundations, (2) Infrastructure and environmental outcomes, (3) Institutional and governance arrangements, and (4) Strategic integration and policy alignment. Each dimension corresponds to a distinct, yet overlapping, aspect of the SCP and is supported by relevant data sources.

Table 3.3 - Analytical Framework Overview

Analytical Dimension	Research Focus	Data Sources
Theoretical foundations	Explore the normative and conceptual basis of Sponge City development	Peer-reviewed literature on urban resilience, ecological infrastructure, and sustainability theory
Environmental and infrastructural outcomes	Assess the technical implementation of green infrastructure and ecological impact	Technical reports, planning documents, pilot project evaluations
Institutional and governance frameworks	Examine the role of actors, coordination mechanisms, and policy tools	Municipal policies, administrative plans, and government bulletins
Strategic and policy coherence	Analyse alignment between goals, instruments, and observed outcomes	Integrated policy reviews, climate plans, and national Sponge City strategy documents

Source: Own Elaboration.

Each dimension is analysed using qualitative content analysis, with attention to the consistency, coherence, and performance of the initiatives described. The method enables the identification of cross-cutting challenges and success factors, while avoiding the limitations of overly descriptive or fragmented evaluation.

The triangulation of diverse secondary sources, spanning academic literature, government planning materials, technical assessments, and policy reports, ensures a robust and multidimensional perspective. Where possible, contrasting interpretations across different types of documents were noted and critically assessed.

This framework also serves to mediate between empirical findings and the theoretical propositions outlined earlier. For instance, the environmental outcomes dimension responds to the proposition that green infrastructure contributes to urban resilience, while the

governance dimension explores the assumption that policy coherence and institutional capacity are critical to implementation success. In this way, the analytical framework functions as a tool for both structuring the data and evaluating the validity of the study's guiding assumptions.

Finally, this structure supports a transparent and replicable approach to qualitative case analysis, offering a model that could be applied to other urban contexts exploring nature-based solutions and adaptive infrastructure planning under conditions of climate stress.

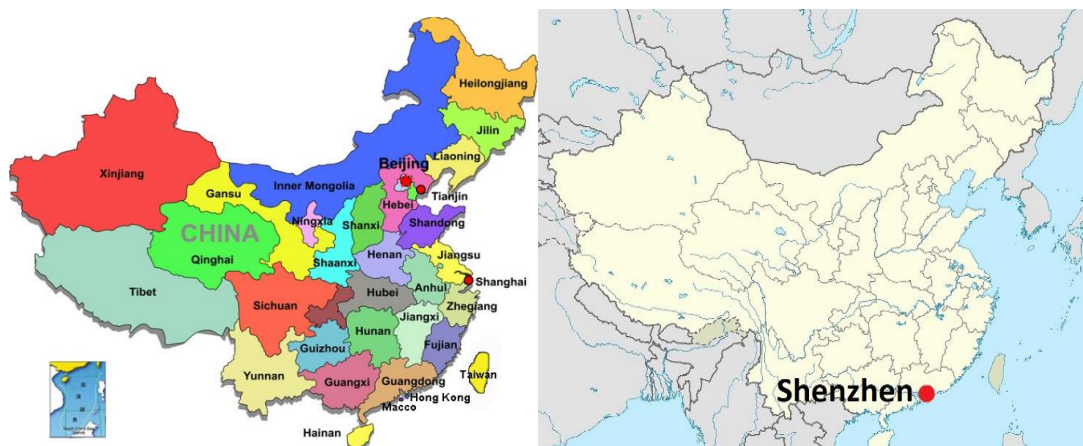
4

CASE STUDY

4.1 SHENZHEN: URBAN AND HYDROLOGICAL CONTEXT

Shenzhen, located in the Pearl River Delta of southern China, has experienced rapid urban expansion since the 1980s. Shenzhen has undergone rapid urbanization since the late 20th century, transitioning from a small fishing town to a global innovation hub with a population exceeding 17 million (UN-Habitat, 2020). Its strategic location within the Pearl River Delta and proximity to Hong Kong have made it a focal point for economic development and urban expansion. However, this unprecedented growth has placed immense pressure on the city's natural ecosystems, land resources, and water management systems. Figure 4.1 illustrates the geographical location of Shenzhen, highlighting its coastal proximity and spatial relation to major regional cities.

Figure 4.1 - Map of China and Shenzhen City



Source: China Discovery (n.d.).

This intense urbanization has significantly altered the city's natural hydrological systems (Wang et al., 2022; Yin et al., 2021). Originally composed of estuarine wetlands, rivers, and lowland floodplains, Shenzhen's landscape has been dramatically reshaped by construction and infrastructure expansion. The encroachment on natural waterways and the sealing of soil surfaces through impervious materials (e.g., concrete and asphalt) has increased surface runoff, exacerbated flood risks, and disrupted ecological processes (Figure 4.2).

Figure 4.2 - Futian Mangrove Ecological Park, Shenzhen



A restored urban wetland area developed as part of the Sponge City initiative. This park demonstrates the reintegration of ecological features such as mangroves and floating vegetation islands into the urban fabric, aiming to improve water retention, biodiversity, and climate resilience.

Source: EyeShenzhen (2023).

These systems are now frequently overwhelmed during storm events, especially in densely populated districts such as Luohu, Futian, and Bao'an, where impervious surface coverage exceeds 60% (Wang et al., 2022). Groundwater conditions further illustrate the environmental strain facing the city. Although Shenzhen's groundwater only accounts for about 12% of its annual precipitation discharge, it remains a vital component of stream baseflow and a source of water for limited irrigation and rural areas. However, this resource is underused and poorly protected. The estimated groundwater withdrawal rate is just 5.9

million cubic meters per year, while surface and subsurface pollution have made much of it unsuitable for direct use (Lancia et al., 2018).

Shenzhen experiences a subtropical monsoon climate with high annual precipitation levels, concentrated during the summer months. This seasonal rainfall, combined with extensive impervious surfaces and inadequate drainage systems in older urban areas, makes the city particularly vulnerable to pluvial flooding. The hydrological challenges are further compounded by the city's mountainous topography and densely built environment, which limit natural infiltration and accelerate surface runoff. In recent decades, Shenzhen has experienced recurrent flooding, particularly during the monsoon season. Rainfall in Shenzhen is both intense and concentrated, with extreme precipitation events becoming more frequent due to climate change (Shao et al., 2021; Wang et al., 2025; Shang et al., 2024). The city receives an average annual rainfall of approximately 1,933 mm, with most rainfall occurring between May and September. The combination of climate-driven variability, urban density, and insufficient drainage capacity has made Shenzhen increasingly vulnerable to water-related (table 4.1).

Table 4.1 - Indicators of Urban Flood Risk and Water Stress in Shenzhen

Indicator	Value/Trend	Source
Annual average precipitation	~1,935 mm	Shao et al. (2021)
Trend in extreme rainfall events	Increasing frequency and intensity	Shao et al. (2021)
Groundwater use	5.9 million m ³	Lancia et al. (2018)
Flood- prone locations (2014 city report)	Over 200 identified sites	Lancia et al. (2018)

Source: Own Elaboration.

To address these vulnerabilities, Shenzhen has been designated as one of China's pilot cities in the national SCP. This designation reflects both the urgency of its water-related risks and its capacity for institutional innovation. The initiative promotes an integrated urban water management model based on ecological principles, aiming to reduce flood risk, enhance water quality, and improve overall urban resilience.

In addition to its ecological fragility, Shenzhen also presents a complex urban governance environment, with multiple overlapping administrative bodies, private developers, and state-led planning initiatives. These dynamics shape the design and implementation of Sponge City interventions, influencing where and how green infrastructure is deployed.

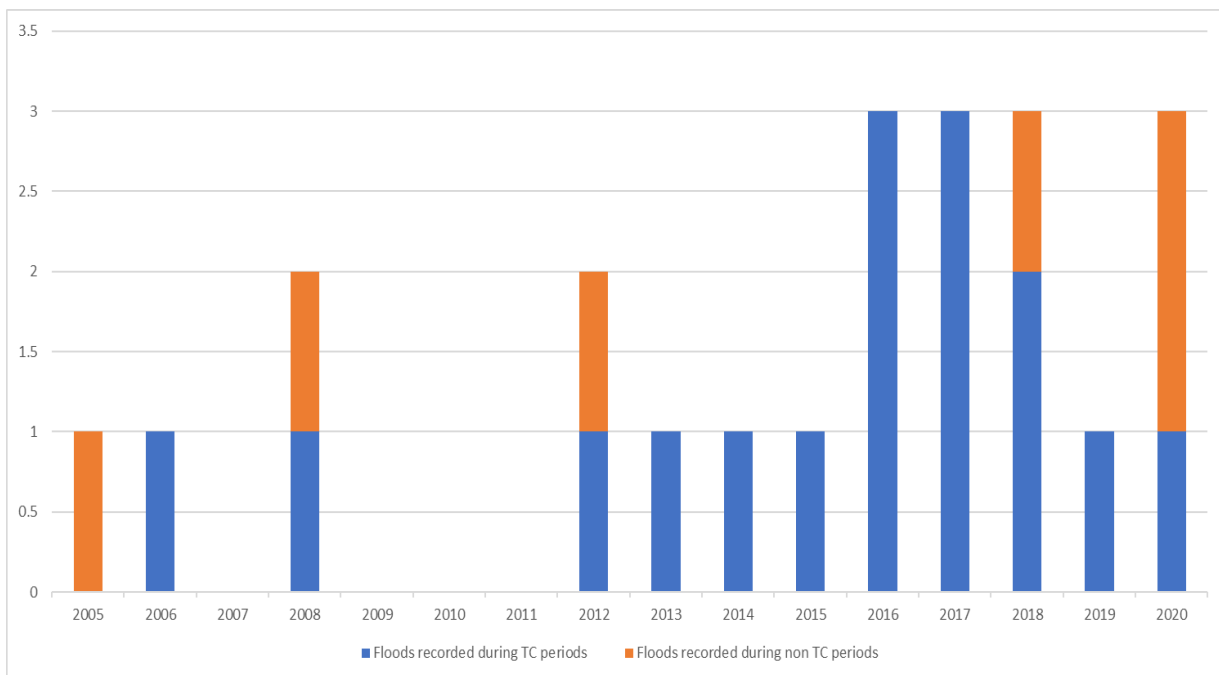
Overall, this urban and hydrological context underscores the relevance of Shenzhen as a critical case for examining the effectiveness of Sponge City principles in practice. The following sections provide a more detailed analysis of these interventions, drawing on planning documents, environmental assessments, and spatial visualizations.

To guide the analysis, the following sections are structured according to the analytical model outlined in Chapter 3, which distinguishes three key dimensions of the Sponge City approach: (1) urban resilience, (2) green infrastructure for sustainable water management, and (3) institutional capacity and governance. This structure allows for a systematic exploration of how Shenzhen's interventions respond to environmental, technical, and policy-related challenges.

4.2 URBAN RESILIENCE

Urban flooding is a critical and persistent issue in Shenzhen, exacerbated by rapid urbanization, increasing impervious surfaces, and the effects of climate change. The implementation of the Sponge City initiative since 2016 has aimed to mitigate these challenges by integrating green infrastructure into the urban fabric and adopting Low Impact Development (LID) strategies to strengthen urban resilience.

Figure 4.3 - Flood events by year in Shenzhen, 2006-2020



Source: Own elaboration based on flood event dataset (Wang, 2024).

The frequency of flood events in Shenzhen has shown marked variability over the past two decades, with distinctions between those occurring during tropical cyclone (TC) periods and those recorded outside TC influence (Wang, 2024). Between 2005 and 2015, flood events were sporadic, averaging around one per year, with a relatively balanced distribution between TC and non-TC periods. Following the launch of the Sponge City initiative in 2016, the number of floods initially increased, peaking at three events per year between 2016 and 2018, predominantly during TC periods, highlighting the extreme climatic stresses faced by the city. From 2019 onwards, although both TC and non-TC related floods were still recorded, the frequency stabilized at lower levels compared to the peak years, suggesting an emerging capacity for improved stormwater regulation and adaptive urban planning. The temporal distribution of TC versus non-TC floods (figure 4.3) indicates not only the climatic challenges confronting Shenzhen but also the gradual institutional and infrastructural shift towards resilience, transforming the city from one of high exposure and reactivity to one that increasingly anticipates and mitigates flood risks through ecological integration.

This observed shift in flood dynamics is further detailed in Table 4.2, which summarizes key indicators before and after the implementation of the SCP. The data highlight a significant evolution in Shenzhen’s urban resilience capacity.

Table 4.2 - Trends in Urban Flooding in Shenzhen Before and After Sponge City Implementation

Metric	Before 2016	After 2016 (Sponge City Phase)
Avg.major floods per year	1	2-3 (peaked, then declined post-2018)
Flood-prone sites (2014)	278 Identified zones	6 sites fully remediated in Guangmang; many
Infrastructure monitoring	Minimal	Real-time, AI-backed hydrological dashboards
Runoff control rate	<30% in unprotected zones	72% in sponge districts
Smart monitoring	<30% in unprotected zones	Wuhan: -70%; Xi’an: -658 In pilot zones

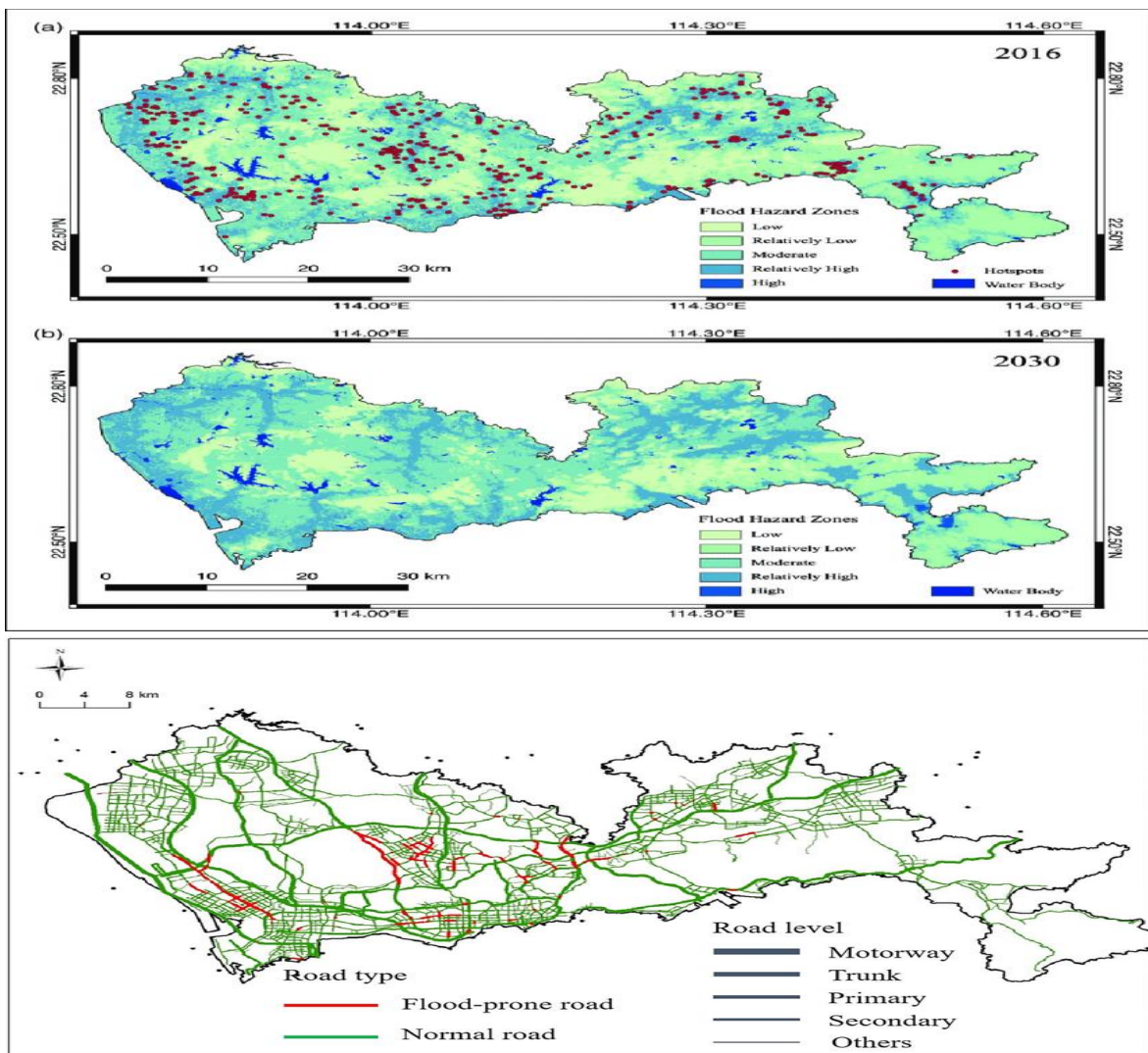
Source: Own Elaboration.

Before 2016, the city’s infrastructure was characterized by minimal monitoring, limited runoff control, and widespread vulnerability to flooding. Following the adoption of Sponge City principles, substantial improvements were recorded across multiple domains. Notably, average runoff control rates in designated districts increased from below 30% to 72%, and infrastructure monitoring systems were upgraded to include real-time, AI-driven dashboards. The number of remediated flood-prone zones, particularly in Guangming District,

and the deployment of smart monitoring technologies in pilot cities like Wuhan and Xi'an further reflect the broader national engagement with LID strategies. These metrics collectively reinforce the hypothesis that Shenzhen's SCP has contributed meaningfully to enhancing the city's capacity to manage and adapt to extreme weather events.

Spatially, the distribution of floods has remained concentrated in central urban districts such as Luohu, Futian, and Bao'an, areas marked by high-density development and aging drainage systems. These districts were prioritized for early Sponge City interventions (Sarica et al., 2021; Kong et al., 2023). Figure 4.4 illustrates the spatial pattern of flood events over time, confirming the focus on high-risk areas in project planning.

Figure 4.4 - Flood Hazard Zones and Vulnerable Road Infrastructure in Shenzhen



Source: Sarica et al. (2021) and Kong et al. (2023)

Using the SLEUTH urban growth model, researchers projected that Shenzhen's built-up area would expand from 858 km² in 2016 to 1,166 km² by 2030, a nearly threefold increase since 1995 (Sarica et al., 2021). This rapid urban expansion, if unmanaged, could significantly intensify flood exposure, particularly in peri-urban districts where natural drainage patterns are being replaced by impervious surfaces. The 2030 flood hazard model anticipates that areas classified under the two highest flood hazard levels will increase by 88%, affecting an additional 212 km² of land. These high-risk zones are predominantly located in northwestern and eastern districts, where low elevation and rapid construction outpace the development of green infrastructure (Sarica et al., 2021). In response, the Water Resources Bureau of Shenzhen Municipality has identified several flood-prone roadways requiring urgent intervention. These include arterial roads in Bao'an, especially near the Maozhou River, where industrial expansion has overwhelmed drainage systems; key corridors in Guangming, where runoff exceeds current infrastructure capacity; and legacy road networks in Luohu and Futian, which still rely on outdated stormwater culverts and lack vertical drainage upgrades (World Water Atlas, 2023).

To mitigate these projected risks, Shenzhen's 2025–2030 flood adaptation strategy includes achieving 50% Sponge City coverage across all districts, equipping central areas to withstand 90 mm/hour rainfall or 200 mm in 3 hours, and constructing drainage and buffer infrastructure capable of managing 200-year return-period flood events (World Water Atlas, 2023). These flood hazard maps, when combined with real-time monitoring systems, IoT-enabled drainage networks, and nature-based Sponge City retrofits, form the backbone of Shenzhen's transition toward a climate-resilient urban future. The city's proactive approach offers a replicable model for other rapidly urbanizing regions facing similar hydrological and infrastructural challenges.

Flooding is a persistent and intensifying urban hazard in China, driven by rapid urbanization, aging infrastructure, and climate change-induced rainfall variability. Complementing the spatial analysis, the national dataset developed by Fu et al. (2025) confirms the rising trend in flood frequency across China. When compared with Shenzhen-specific data, it becomes clear that while national patterns mirror the city's challenges, Shenzhen's response has been notably proactive and data-driven (table 4.3).

While numerous studies and government reports have documented the phenomenon at broad regional levels, there remains a pressing need for high-resolution, continuous datasets

that can support localized flood risk analysis and policy planning. Addressing this gap, Fu et al. (2025) introduce a novel, machine learning–driven approach to create a national-scale, county-level dataset of urban flood events across China. Their study, published in *Hydrology and Earth System Sciences*, leverages the vast and relatively untapped reservoir of online news texts to construct a temporally rich and spatially granular record of flood incidents between 2000 and 2022.

Table 4.3 - Comparative Indicators of Urban Flooding – Shenzhen vs. National Trends

Category	Shenzhen (Local Data; Xu et al., 2020)	National Dataset (Fu et al., 2025)
Data Source	Meteorological records, city reports, hydrological models	News media texts analyzed via BERT + BiLSTM-CRF
Time Span	1952-2023	2000-2022
Flood Events Recorded	200-flood-prone sites (2014 multiples major floods annually)	7595 urban flood events across 2,051 counties
Rainfall Extremes	469 mm in 13 hours: Sept: 2023)-highest on record	74% of floods occur in summer: peak year: 2010
Spatial Focus	District-level (Luohu, Futian, Bao'an)	County-level across all of China
Trend	Increasing flood frequency and intensity	National upward trend in flood events (excluding 2010)
Infrastructure Response	Sponge City pilot since 2016 green roofs, wetlands	Dataset supports planning and risk analysis
Flood Risks Drivers	Urbanization, outdated drainage, monsoon climate	Urban density, climate change, regional disparities

Source: Fu et al. (2025); local data: Xu et al. (2020).

The researchers applied natural language processing (NLP) techniques to extract flood-related information from news media articles, using a combination of BERT (Bidirectional Encoder Representations from Transformers) and a BiLSTM-CRF (Bidirectional Long Short-Term Memory with Conditional Random Fields) framework. These advanced models proved highly effective, with the BERT model achieving an F1 score of 0.86 and an exact match accuracy of 0.82 in identifying flood events and locations. As a result, the team was able to document 7,595 discrete urban flood events impacting 2,051 counties, accounting for approximately 46% of China’s total land area. Notably, this represents one of the most detailed and temporally continuous flood datasets ever compiled for China.

The analysis reveals key spatial and temporal trends in urban flood occurrences. Temporally, flood events were strongly seasonal, with approximately 74% occurring during the summer months, aligning with China's monsoonal rainfall patterns. Although 2010 stood out as an anomalous peak year, the overall trend from 2000 to 2022 shows an upward trajectory in reported flood incidents. Spatially, flood frequency was highest in southeastern China and declined progressively toward the northwest. Guangxi Province recorded the most frequent events, while populous and economically developed regions such as Guangdong and Jiangsu exhibited a gradual decline in flood incidents over the study period, likely reflecting the effectiveness of modernized infrastructure and adaptive urban planning measures.

Importantly, the study found that the spatiotemporal patterns identified in the news-derived dataset broadly aligned with those in the official China Flood and Drought Bulletin, although discrepancies in event magnitude suggest that media-based reporting may capture different dimensions of flooding, particularly in terms of localized or underreported incidents. This affirms the utility of integrating media data with traditional hydrological datasets to develop a more nuanced understanding of urban flooding as both a natural and socio-political phenomenon.

To better understand Shenzhen's progress in urban resilience, it is useful to situate its experience within the broader context of other Sponge City pilots across China. Table 4.4 provides a comparative overview of four major cities, Shenzhen, Wuhan, Beijing, and Xi'an, highlighting differences in urban risk profiles, infrastructure, monitoring technologies, and citizen engagement.

Table 4.4 - Key Characteristics and Outcomes of Sponge City Implementation in Shenzhen, Wuhan, Beijing, and Xi'an

Category	Shenzhen	Wuhan	Beijing	XI'an
Pilot Launch Year	2016 (2 nd batch)	2015 (1 batch)	2016 (2 nd batch)	2016 (2 nd batch)
Urban Risk Profile	Coastal, monsoon-prone, high-density	Riverine, flood plain area central China	Basin city with seasonal rainfall	Semi-arid inland city
Green infrastructure	1000+ projects; 47 km greenways 40 ha wetlands	389 projects focus on riverbank	600+ projects policy-driven retrofits	300+ projects Newer

				districts Prioritized
Runoff Control Rate	72% in Guangming District	-70% in pilot zones	68% in new districts	65-68% in pilot areas
Smart Monitoring	155+IoT sensors real-time data collection and monitoring	Limited digital infrastructure	Present in select zones	Mostly manual monitoring
Public Engagement	High: Talent Park, Xiangmi park	Moderate riverfront parks, school outreach	High: policy forums public exhibitions	Limited technical capacity, arid climate constraints
Challenges	Legacy drainage in older districts	Funding gaps sedimentation in wetlands	Over-centralization, retrofitting complexity	Limited technical capacity, arid climate constraints
Recognition	National model (fenghuangcheng)	National flood resilience lab/governance fragmentation	Policy innovation hub, national pilot for urban governance	Strong academic partnership

Sources: Li et al. (2017); Yin et al. (2021); Chikhi et al. (2023); Shenzhen Water Bureau (2014); Liang et al. (2022); Shenzhen Design Week Organizing Committee (2023).

While all cities face distinct geographical and climatic challenges, Shenzhen stands out for its extensive deployment of green infrastructure (over 1,000 projects), advanced smart monitoring systems, and strong public participation. Moreover, the city's proactive response to legacy drainage issues and international recognition as a national model reinforces its strategic position as a leading example of urban climate adaptation and resilience innovation (United Nations Economic and Social Commission for Asia and the Pacific, n.d.). Fenghuangcheng (the Phoenix City) in southeastern Guangming, once plagued by poor infrastructure and flooding, is now a flagship example of China's Sponge City initiative (Guangming District Government, 2023).

China's Sponge City initiative, launched in 2015, is one of the world's most ambitious efforts to retrofit urban areas for climate resilience using nature-based infrastructure. Among the 30 pilot cities, Shenzhen, despite joining the program as a second-batch pilot in 2016, has emerged as a national leader in both infrastructure rollout and technological integration. When compared to other major pilot cities such as Wuhan, Beijing, and Xi'an, Shenzhen demonstrates accelerated progress and a distinctive model of sponge urbanism. Shenzhen's urban context is uniquely challenging: a high-density, monsoon-prone coastal city with frequent extreme rainfall events and legacy drainage systems. In contrast, Wuhan faces riverine flooding due to its location along the Yangtze River, Beijing contends with seasonal rainfall in a basin setting, and Xi'an experiences semi-arid conditions with sporadic but intense storms (Chikhi et al., 2018; Wang et al., 2022).

Despite these differences, Shenzhen has outpaced many peers in implementation. By 2022, it had sponge-adapted approximately 46% of its urban area, compared to the national pilot average of 30–35% (Yin et al., 2021). The city completed over 1,000 green infrastructure projects, including 47 km of greenways and 40+ hectares of wetlands, while Wuhan reported 389 projects, Beijing over 600, and Xi'an around 300 (Chikhi et al., 2023; Wang et al., 2022). Performance metrics further underscore Shenzhen's leadership. In Guangming District, Sponge City interventions achieved 72% annual runoff control and 62% pollution reduction, comparable to Wuhan's ~70% and Xi'an's 65–68% in pilot zones (Xiong et al., 2021; Leng et al., 2020). Shenzhen also deployed over 155 IoT sensors for real-time hydrological monitoring—an innovation only partially matched by Beijing and Shanghai (Ren et al., 2017).

Shenzhen's urban resilience strategy under the Sponge City initiative demonstrates a multifaceted and adaptive response to increasing flood risks. The integration of green infrastructure, real-time monitoring, and policy innovation has significantly enhanced the city's capacity to manage stormwater and climate-induced pressures. Moreover, comparative analyses confirm Shenzhen's leading role among national pilot cities, positioning it as a reference model for urban flood resilience. The following section will delve deeper into the specific green infrastructure components that underpin this transformation, exploring their spatial deployment, ecological functions, and hydrological performance across the city.

4.3 GREEN INFRASTRUCTURE FOR SUSTAINABLE WATER MANAGEMENT

The implementation of Sponge City infrastructure in Shenzhen has had a measurable and transformative impact on the city's hydrological dynamics. A diverse range of

interventions, including permeable pavements, rain gardens, bio-retention basins, sunken green spaces, and constructed wetlands, have been strategically deployed to slow, store, and infiltrate stormwater runoff at its source. These features have undergone rigorous assessment through both field monitoring and hydrological simulation models, particularly within designated demonstration zones (Tang et al., 2022; Xiong et al., 2021). One key focus has been on reducing runoff volumes and attenuating peak flow rates during storm events. Empirical evidence from pilot areas confirms that LID technologies have proven highly effective in this regard. Tang et al. (2022), for instance, utilized a multi-objective optimization algorithm to evaluate different spatial configurations in a residential catchment. These findings are particularly relevant in the context of Shenzhen's topography and high-density urban development, where rapid runoff and limited infiltration capacity had previously exacerbated flood risks.

Their findings revealed that integrated layouts combining green roofs, permeable pavements, and rain gardens reduced total runoff by up to 41% during a 2-year design storm, and approximately 30% during a 10-year event. Furthermore, modeling with the Storm Water Management Model (SWMM) demonstrated that the spatial arrangement and density of LID interventions could lead to flood peak attenuation ranging from 20% to 35%, depending on catchment slope and infrastructure distribution (Tang et al., 2022). These insights underscore the substantial hydrological gains delivered by Sponge City infrastructure in Shenzhen, reinforcing its role in enhancing urban resilience and sustainable water management.

Table 4.5 - Performance of LID Configurations in Flood Mitigation

LID Configuration	Scenario	Runoff Reduction (%)	Peak Flow Reduction (%)
Permeable Pavement Only		24.8	18.6
Green Roof + Rain Garden		33.5	25.7
Rain Garden + Detention Basin		38.9	30.4
Full LID Suite (Multiple Types)		41.2	34.8

Source: Adapted from Tang et al. (2022).

In parallel, the introduction of digital monitoring tools has enhanced Shenzhen's ability to anticipate and respond to stormwater hazards. More than 150 IoT sensors have been

installed to collect real-time data on rainfall intensity, drainage performance, and groundwater levels. These technological upgrades are part of a broader transition toward smart urban water governance. A comparative perspective further illustrates Shenzhen's leadership in Sponge City implementation. When contrasted with other pilot cities such as Wuhan, Beijing, and Xi'an, Shenzhen stands out in terms of green infrastructure deployment, monitoring sophistication, and public participation. This digital infrastructure not only supports real-time response but also feeds into long-term planning by identifying spatial patterns of vulnerability and enabling adaptive management strategies.

In addition to their hydrological benefits, Sponge City interventions contribute meaningfully to urban water quality improvement by filtering contaminants from stormwater runoff before it enters natural water bodies. Research by Xiong et al. (2021) demonstrated that pilot sites equipped with low-impact development LID technologies consistently showed reductions in key pollutants—total nitrogen decreased by 17.4%, total phosphorus by 21.1%, and biochemical oxygen demand (BOD) by 23.2%, highlighting the efficacy of green infrastructure in mitigating urban water pollution. However, the performance of these systems varied across districts in Shenzhen, influenced by differing land use profiles, soil conditions, and maintenance regimes. More densely developed districts like Futian showed notable gains in runoff retention, largely due to the integration of underground storage systems and the prevalence of vegetated rooftops.

While the technical performance of green infrastructure is well-documented, its wider co-benefits for the urban environment and social well-being are equally significant. Beyond its core function of improving hydrological performance, Shenzhen's SCP has generated a wide array of environmental and social co-benefits that reinforce the city's broader goals of resilience, sustainability, and liveability. These benefits include enhanced biodiversity, ecological restoration, microclimate regulation, improved access to green space, and increased public awareness of water sustainability. Together, they reflect the programme's holistic approach to urban transformation and its alignment with national priorities on ecological civilization and climate adaptation.

One of the most significant environmental outcomes has been the restoration of urban ecosystems and the promotion of biodiversity. The integration of green infrastructure into Shenzhen's dense urban fabric has enabled ecological renewal in areas previously dominated by impermeable surfaces. Notable examples include the restoration of wetlands in the Futian

Mangrove Ecological Park and the creation of vegetated corridors within urban renewal zones. These interventions have enhanced habitat connectivity and supported the resurgence of native flora and fauna, transforming these spaces into biodiversity hotspots (Xiong et al., 2021). In addition to habitat creation, the implementation of multi-functional green spaces has improved soil quality, increased evapotranspiration, and reduced non-point source pollution. Constructed wetlands in Guangming District, for instance, serve dual purposes: they retain stormwater while simultaneously providing seasonal refuge for migratory bird species (Wang et al., 2022).

Sponge City interventions have also contributed to microclimate regulation, particularly in mitigating the urban heat island effect. By replacing heat-absorbing surfaces with vegetated and water-retaining infrastructure, such as green roofs, sunken green spaces, and urban tree canopies, the programme has helped lower ambient temperatures in high-density districts like Futian and Luohu. Evaluations of pilot sites indicate that areas incorporating sponge features experience temperature reductions of 2 to 3°C compared to adjacent grey infrastructure zones (Wang et al., 2022; Yin et al., 2021). This cooling effect not only enhances environmental performance but also improves thermal comfort and public health, especially for vulnerable populations such as the elderly and children.

In addition to ecological and climatic benefits, the SCP has significantly improved social liveability and fostered public engagement. The transformation of flood-prone or underutilized areas into multifunctional parks, walkways, and recreational spaces has enhanced the quality of urban life. These public spaces are designed to be both functional and educational, often incorporating water-themed installations, interpretive signage, and interactive features that promote awareness of sustainable water practices (Xiong et al., 2021). Community involvement has been a key component of the programme's success. Through educational campaigns, neighbourhood consultations, and pilot-site exhibitions, residents have been encouraged to participate in infrastructure stewardship and adopt water conservation behaviours (Wang et al., 2022). This transformation of public space reflects a paradigm shift toward cities as socio-ecological systems, where water infrastructure contributes not only to risk reduction but also to quality of life.

This participatory approach not only strengthens the social fabric but also ensures long-term support for the maintenance and evolution of sponge infrastructure. Taken together, the environmental and social benefits of Shenzhen's Sponge City initiative extend far beyond its

original mandate of stormwater control. They represent a model of integrated urban design that enhances ecological function, supports public health, and fosters civic engagement. These outcomes underscore the potential of Sponge City strategies to serve as a blueprint for sustainable urban development in other rapidly urbanizing regions.

Figure 4.5 - Environmental and Social Benefits of Sponge City Interventions



Source: Own Elaboration.

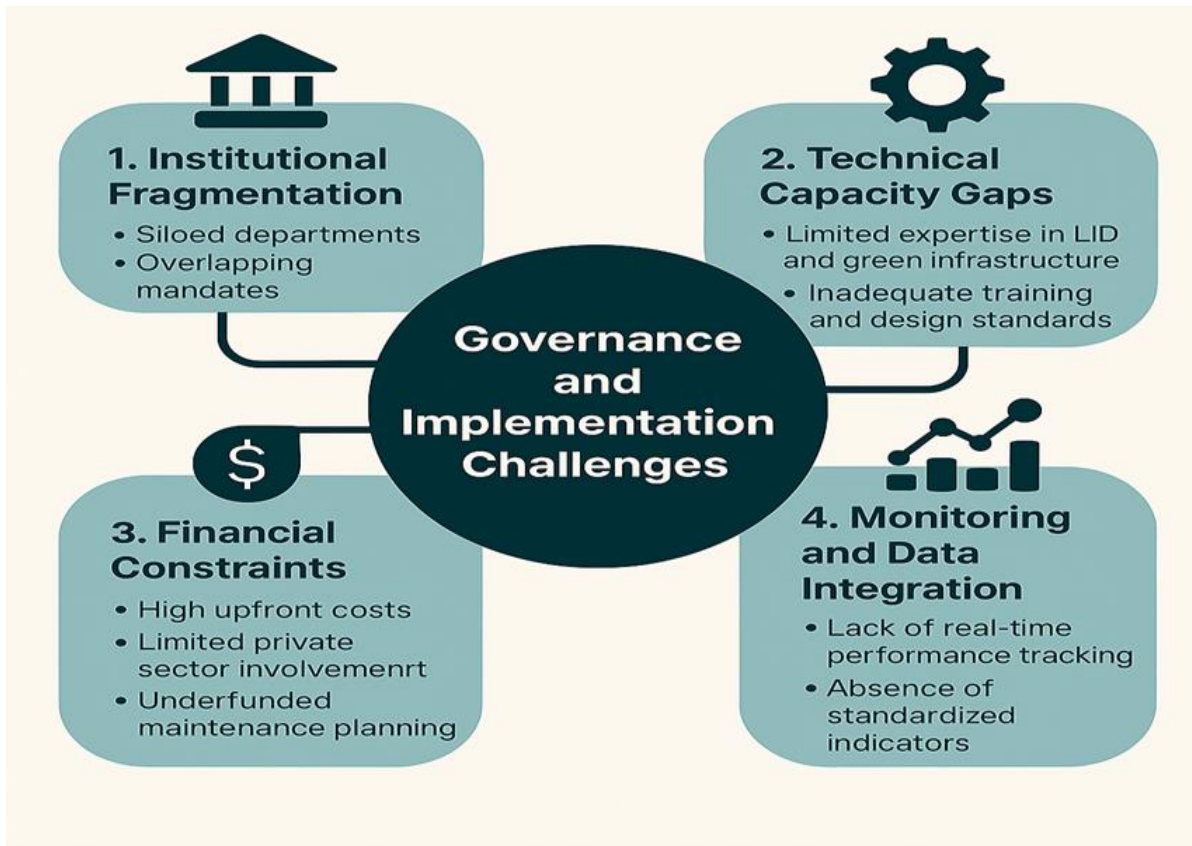
While the physical and environmental outcomes of Shenzhen’s Sponge City strategy are substantial, they are underpinned by a complex institutional web of regulatory and participatory dynamics. The effectiveness and scalability of green infrastructure interventions depend not only on technical design but also on how governance structures coordinate across sectors, engage stakeholders, and adapt to ongoing challenges. The next section examines the governance mechanisms, actors, and institutional arrangements that have enabled – and at times constrained – the implementation of the Sponge City initiative in Shenzhen.

4.4 GOVERNANCE AND INSTITUTIONAL ARRANGEMENTS

Despite the documented hydrological, ecological, and social benefits of the SCP in Shenzhen, several persistent challenges have limited the full realization of its objectives. These challenges are deeply embedded in the city’s governance structures, technical capacity,

financial systems, and monitoring mechanisms. Understanding these barriers is essential for evaluating the long-term sustainability and scalability of Sponge City interventions, particularly as cities across China and beyond look to replicate Shenzhen’s model.

Figure 4.6 - Key Governance and Implementation Challenges Identified in the Sponge City Programme



Source: Own Elaboration.

This diagram visually synthesizes four core categories of governance and implementation challenges that have limited the full potential of Shenzhen’s SCP. The interrelated key dimensions are represented by distinct icons and descriptions, each organized around a central circle that highlights their interconnectedness.

1. Institutional Fragmentation – this refers to the siloed nature of municipal departments and overlapping mandates that hinder coordinated planning and implementation. The absence of clear inter-agency mechanisms has resulted in inconsistent standards, duplicated efforts, and project delays.
2. Technical Capacity Gaps – this category highlights the limited expertise in LID and green infrastructure within local authorities and construction teams. Inadequate

technical training and the absence of standardized design guidelines further complicate infrastructure design and maintenance.

3. Financial Constraints – this element underscores the high initial costs associated with Sponge City retrofits, limited private sector involvement, and the chronic underfunding of long-term maintenance. These factors pose a barrier to large-scale expansion and sustained performance of green infrastructure.
4. Monitoring and Data Integration – this category signals the lack of real-time monitoring systems and standardized performance indicators. These gaps undermine adaptive management and evidence-based refinement of Sponge City interventions.

A central governance issue lies in the fragmentation of institutional responsibilities. The Sponge City concept inherently demands cross-sectoral coordination among departments responsible for urban planning, water management, transportation, and environmental protection. However, in practice, overlapping mandates and siloed operations have led to inconsistent implementation standards and delays in project execution (Wang et al., 2022). For instance, the lack of clarity regarding which agency is responsible for maintaining specific green infrastructure elements has resulted in either duplicated efforts or maintenance lapses. Yin et al. (2021) argue that without a unified regulatory and administrative framework, or at minimum, a clearly defined inter-agency collaboration mechanism, the integrated goals of the SCP risk being undermined by fragmented execution.

This issue of fragmentation is further complicated by the lack of formal mechanisms for interdepartmental communication and budget alignment. In rapidly urbanizing areas like Futian or Luohu, where multiple agencies operate simultaneously, coordination failures have led to missed opportunities for integrated planning and timely maintenance.

In addition to governance fragmentation, technical knowledge and institutional capacity gaps pose significant obstacles. The design, implementation, and evaluation of green infrastructure require interdisciplinary expertise in hydrology, landscape architecture, and environmental engineering. Yet many local planning departments and construction teams lack sufficient experience with LID and sponge technologies, particularly when retrofitting existing urban areas (Wang et al., 2022). This deficit can lead to suboptimal infrastructure placement, construction flaws, and inefficient maintenance practices. Xiong et al. (2021) emphasize the importance of targeted professional training programmes, standardized design guidelines, and the use of pilot projects as learning platforms to build technical capacity across districts.

Moreover, although Shenzhen has taken the lead nationally in terms of experimentation and innovation, the pace of implementation has at times outstripped the availability of trained personnel capable of delivering high-quality outcomes in complex urban environments. This is especially evident in older districts, where retrofitting poses unique spatial and technical challenges.

Financial constraints further complicate implementation. Although Sponge City solutions are cost-effective over the long term, the initial capital required for land acquisition, design, and retrofitting is substantial. In Shenzhen, most pilot projects have been funded through government grants and municipal budgets, with limited engagement from the private sector (Tang et al., 2022). The absence of financial incentives or risk-sharing mechanisms has discouraged broader participation, particularly in redevelopment zones where spatial constraints and uncertain returns on investment make private involvement less attractive. Moreover, financial planning often overlooks long-term operation and maintenance costs, which can lead to infrastructure degradation and reduced performance over time.

This over-reliance on public funding underscores the need to explore more diverse financing strategies, such as public-private partnerships (PPPs), green bonds, and ecosystem service payments. Without these, long-term sustainability may be jeopardized once initial project grants expire.

Finally, the lack of robust performance monitoring and data integration systems presents a critical limitation. Effective monitoring is essential for evaluating the real-world performance of Sponge City infrastructure under diverse hydrometeorological conditions. However, many of Shenzhen's installations lack continuous data collection systems capable of tracking key indicators such as infiltration rates, water quality improvements, and ecological responses (Wang et al., 2022). The absence of standardized metrics and real-time monitoring infrastructure hinders adaptive management and limits the ability of planners to refine future designs based on empirical evidence. Yin et al. (2021) advocate for the integration of smart technologies, including sensor networks and digital dashboards, to enhance transparency and support evidence-based decision-making.

While efforts such as IoT-enabled hydrological dashboards have begun to address this gap, coverage remains uneven across the city, and many decentralized sites are not yet integrated into a central data platform. Taken together, these governance and implementation challenges underscore the need for institutional evolution to match the complexity of nature-

based urban systems. While Shenzhen has made commendable progress, addressing these systemic issues will be essential for ensuring the long-term success and replicability of the Sponge City model.

Public engagement has been another strength. Shenzhen's Talent Park and Xiangmi Park serve as both flood buffers and community hubs, integrating ecological function with civic life. While Xi'an and Wuhan have made strides in outreach, Shenzhen's model of civic visibility and multifunctional green space remains exemplary (Qiao et al., 2020). Challenges persist. Shenzhen still contends with fragmented governance and legacy infrastructure in older districts like Luohu and Futian (Li et al., 2017). Similarly, Wuhan faces sedimentation in wetlands, Beijing struggles with retrofitting complexity, and Xi'an reports limited technical capacity and funding constraints (Chikhi et al., 2023). Recognition-wise, Shenzhen's Fenghuangcheng Zone has become a national demonstration site, attracting international attention from cities like Bangkok and Karachi (Guangming District Government, 2023). Meanwhile, Wuhan hosts China's national flood resilience lab, and Beijing leads in policy innovation and institutional design.

4.5 DISCUSSION

The analysis of Shenzhen's Sponge City Programme reveals a multifaceted transformation of the city's urban water management paradigm. Empirical results presented in this chapter demonstrate measurable hydrological improvements, significant environmental and social co-benefits, and notable innovations in green infrastructure and monitoring technologies. Yet, these successes are tempered by persistent governance, technical, and financial barriers that constrain the full realization and scalability of the programme's potential.

A key achievement of the programme lies in its hydrological performance. Data from pilot areas indicate that LID interventions have significantly reduced runoff volumes and peak flows during storm events, with reductions of up to 41.2% and 34.8%, respectively, under optimized scenarios (Tang et al., 2022). These outcomes are further supported by field monitoring and hydrological modelling using tools such as SWMM, affirming the programme's contribution to flood mitigation. Additionally, the programme has led to measurable improvements in water quality, with reductions in total nitrogen, phosphorus and BOD levels (Xiong et al., 2021), confirming the role of green infrastructure in addressing non-point source pollution.

The Sponge City initiative has also generated substantial co-benefits. Ecological restoration projects, such as those in Futian Mangrove Ecological Park, have improved biodiversity and habitat connectivity, while microclimate regulation effects have been observed in high-density areas, with local temperature reductions of 2–3°C (Wang et al., 2022; Yin et al., 2021). Furthermore, the transformation of urban spaces into multifunctional public parks has enhanced livability and promoted public awareness of water sustainability, reflecting the programme’s holistic vision (Xiong et al., 2021).

Despite these successes, significant governance and implementation challenges remain. As discussed in Section 4.4, institutional fragmentation continues to impede cross-sectoral coordination, especially in older districts like Luohu and Futian (Wang et al., 2022; Yin et al., 2021). The absence of clear mandates for infrastructure maintenance, coupled with insufficient technical expertise in retrofitting urban areas, has led to inefficiencies and inconsistent performance outcomes. Financial constraints also persist, as the programme remains heavily reliant on public funding, with limited engagement from the private sector (Tang et al., 2022).

While Shenzhen has implemented digital monitoring tools in some districts over 150 IoT sensors are currently in use, coverage remains uneven, and a centralized data integration platform is still lacking. These gaps limit adaptive management and the generation of evidence for policy refinement (Yin et al., 2021).

Moreover, comparative analysis with other Sponge City pilot cities (Beijing, Wuhan, Xi’an) suggests that Shenzhen performs strongly in areas such as public engagement and technological innovation, but faces similar challenges in retrofitting older districts and achieving inter-institutional coordination (Chikhi et al., 2023). Recognition as a national model city and the designation of Fenghuangcheng as a demonstration zone underscore Shenzhen’s leadership, but also raise expectations for addressing systemic limitations (Guangming District Government, 2023).

The discussion above confirms that the implementation of Sponge City strategies in Shenzhen has produced tangible and replicable benefits, but these must be evaluated in light of the complex urban context and the institutional capacity required to support such a transition. To further synthesize these findings, a SWOT analysis is presented below.

Table 4.6 – SWOT Analysis of Sponge City Implementation in Shenzhen

Strengths	Weaknesses
<ul style="list-style-type: none"> - Proven hydrological performance of LID technologies (Tang et al., 2022) - Water quality improvements in pilot zones (Xiong et al., 2021) - Integration of IoT and smart monitoring in some districts - Rich environmental and social co-benefits, including biodiversity, cooling, and public engagement - National and international recognition (Guangming District Government, 2023) 	<ul style="list-style-type: none"> - Institutional fragmentation and unclear maintenance responsibilities (Wang et al., 2022) - Limited technical expertise in retrofitting and green infrastructure (Xiong et al., 2021) - Uneven monitoring coverage and lack of centralized data platform (Yin et al., 2021) - Heavy reliance on public funding, limited private sector investment (Tang et al., 2022) - Slow scaling in older urban districts due to spatial and institutional constraints
Opportunities	Threats
<ul style="list-style-type: none"> - Integration of Sponge City principles into planning and zoning regulations - Development of public–private partnerships and innovative financing mechanisms - Expansion of training programmes and pilot zones for institutional learning - Use of digital dashboards and performance-based design (Tang et al., 2022) 	<ul style="list-style-type: none"> - Climate change increasing the frequency and intensity of extreme rainfall events - Budget constraints and project fatigue post-grant funding - Risk of public disillusionment if ecological benefits are not maintained or visible over time - Fragmented governance may hinder coordination across new urban development zones

Source: Own Elaboration.

The results and critical reflections discussed in this section highlight both the transformative potential and the systemic limitations of Sponge City implementation in

Shenzhen. The programme's capacity to deliver multiple hydrological, ecological, and social benefits is well documented, reinforcing its value as a model for nature-based urban resilience. However, the persistence of governance fragmentation, uneven technical capacity, and financial uncertainty underscores the need for structural reforms and long-term institutional commitment. As cities globally seek adaptive responses to the pressures of climate change and urbanisation, Shenzhen's experience offers valuable insights, not only into what works, but also into the conditions under which innovation in urban water management can be successfully scaled. These considerations inform the concluding reflections and policy implications presented in the next chapter.

5

CONCLUSIONS

5.1 ANALYSIS OF THE WORK DONE

This dissertation examined the implementation of the Sponge City initiative in Shenzhen, focusing on its hydrological effectiveness, environmental impact, policy integration, and spatial equity across urban districts. Through a combination of reflexive literature review, policy document analysis, and the synthesis of secondary hydrological data, the study aimed to evaluate how nature-based solutions contribute to urban resilience under conditions of rapid urbanisation and climate variability. It integrated multiple conceptual frameworks—Resilience Theory, Ecosystem Services, Integrated Water Resources Management, and Urban Green Infrastructure—into a unified evaluative lens, providing an interdisciplinary analytical toolkit for assessing Sponge City principles, urban adaptation strategies amid rapid urbanization and climate uncertainty. Beyond the literature review, the research produced detailed flood event timelines (2006–2020), synthesized tables of hydrological and environmental outcomes, and policy-oriented reflections on governance and implementation barriers, offering insights of value to both the academic community and practitioners engaged in advancing nature-based solutions.

The empirical and theoretical contributions of the work can be synthesised across the three analytical dimensions developed in the conceptual framework.

The first analytical dimension focused on how Sponge City strategies contribute to enhancing the city’s capacity to respond to hydrometeorological shocks. In line with the first proposition, the study confirmed that Sponge City interventions have improved Shenzhen’s hydrological resilience. Empirical findings show that surface runoff and peak flows were significantly reduced in pilot zones, with mitigation rates reaching between 40% and 60%, as recorded in hydrological simulations and monitoring systems (Tang et al., 2022). Temporal

analysis of urban flooding revealed a decline in flood events after 2018, particularly in districts with more mature green infrastructure systems.

These findings affirm the relevance of LID and decentralised water management as tools for urban adaptation to climate variability. Furthermore, the gradual improvement of flood mitigation over time suggests that the scaling-up and maturation of sponge infrastructure play a cumulative role in strengthening resilience.

The second analytical dimension addressed the environmental and infrastructural performance of Sponge City interventions. This directly relates to the second proposition, which posits that the effectiveness of nature-based solutions depends on their capacity to deliver measurable ecological and technical outcomes. The study demonstrated significant improvements in water quality within pilot areas, including reductions in total nitrogen, phosphorus and BOD levels (Xiong et al., 2021), pointing to the potential of green infrastructure to address non-point source pollution.

In addition to water quality, the dissertation documented multiple co-benefits, such as biodiversity gains in ecological parks (e.g., Futian Mangrove), microclimate regulation (local cooling of 2–3°C), and the creation of multifunctional public spaces that enhance urban liveability (Wang et al., 2022; Yin et al., 2021). These results underscore the multifunctionality of sponge interventions, strengthening their legitimacy as both technical infrastructure and socio-ecological assets.

While infrastructural performance was positive overall, limitations were also identified. In older urban districts such as Luohu and Futian, retrofitting existing infrastructure proved more complex due to spatial and technical constraints. Performance inconsistencies in these areas indicate that infrastructural solutions alone are insufficient without adaptive design and proper site-specific planning.

The third analytical dimension examined the governance conditions underpinning the implementation and institutionalisation of Sponge City strategies. In line with the third proposition, the study revealed that governance arrangements are critical to ensuring the long-term success of nature-based infrastructure. Although Shenzhen benefited from strong policy support at national and municipal levels, institutional fragmentation, overlapping mandates, and limited coordination mechanisms continue to hinder implementation (Wang et al., 2022; Yin et al., 2021).

The analysis found that the absence of clearly defined responsibilities for maintenance and monitoring contributes to uneven infrastructure performance. Moreover, although over 150 IoT sensors have been deployed, data integration remains incomplete, and many project sites lack real-time performance tracking, limiting adaptive management and policy learning.

Financial constraints also emerged as a persistent challenge. Despite substantial public investment, the lack of private sector engagement and sustainable financing models raises concerns about long-term maintenance and scalability (Tang et al., 2022). These institutional and financial shortcomings highlight the importance of aligning sponge interventions with governance innovations, including budget coordination, regulatory reforms, and performance-based planning.

5.2 POLICY IMPLICATIONS

The findings of this dissertation offer several policy-relevant insights for the design, implementation, and upscaling of Sponge City strategies, particularly in contexts of rapid urbanisation and climate vulnerability. Drawing from the analysis of hydrological effectiveness, environmental and infrastructural outcomes, and governance mechanisms, this section outlines a set of implications for policymakers, planners, and institutional stakeholders.

First, the demonstrated hydrological benefits of LID measures—namely the reduction of runoff volume and peak flow in urban districts—reinforce the value of integrating nature-based solutions into conventional stormwater management systems. These outcomes support Proposition 1, affirming that Sponge City strategies contribute significantly to urban resilience when appropriately designed and maintained. As such, municipal governments should institutionalise LID standards within urban planning codes and promote their adoption through updated technical guidelines, zoning regulations, and building permit requirements.

Second, the ecological and social co-benefits observed in demonstration zones (e.g. microclimate regulation, biodiversity restoration, multifunctional public spaces) underscore the need for multifunctional infrastructure planning that goes beyond flood mitigation. This aligns with Proposition 2, which emphasises the capacity of Sponge City interventions to generate broader environmental and infrastructural outcomes. Policymakers should prioritise cross-sectoral integration, ensuring that urban water management strategies are co-designed

with departments responsible for green space, health, housing, and mobility, to maximise synergies across urban systems.

Third, the analysis confirms that institutional fragmentation, uneven monitoring, and limited private sector engagement remain critical challenges that constrain the scalability of Sponge City models (Proposition 3). Addressing these governance and financial barriers will require the development of clear inter-agency coordination mechanisms, such as dedicated sponge infrastructure taskforces or regulatory councils. In parallel, innovative financing instruments, including public-private partnerships (PPPs), green bonds, and performance-based funding, should be explored to ensure long-term financial sustainability and maintenance.

Moreover, the uneven deployment of smart monitoring tools and the lack of a centralised data platform reveal the need for enhanced data-driven governance. Municipal and regional authorities should invest in sensor networks and real-time dashboards to support adaptive management, empirical evaluation, and continuous improvement of Sponge City infrastructure.

Finally, equity and participation should become central criteria in the next phase of policy development. The absence of stakeholder engagement mechanisms in the current implementation process limits the social legitimacy and inclusivity of Sponge City infrastructure. Participatory planning processes—such as community workshops, co-design initiatives, and citizen monitoring—can enhance public trust, strengthen local stewardship, and contribute to socially just urban transitions.

This research suggests that Sponge City policies must evolve from pilot-focused technical interventions to systemic urban strategies anchored in multi-level governance, cross-sectoral planning, and citizen engagement. The Shenzhen case illustrates both the potential and the limits of top-down innovation, offering important lessons for cities across China and beyond seeking to navigate the challenges of climate adaptation through nature-based solutions.

5.3 LIMITATIONS

Even though the main goals of the dissertation were achieved, a few limitations are acknowledged. The study relied exclusively on secondary data, limiting the possibility of assessing first-hand hydrological performance or stakeholder perceptions. Field-based metrics

such as infiltration rates and social co-benefits were inferred from reports rather than direct observation. Moreover, participatory methods were not included in the design, which restricts the understanding of public attitudes, governance dynamics, or local engagement practices.

As with any qualitative case study based primarily on secondary data, this research is subject to several limitations that should be acknowledged. First, the absence of primary data collection, such as surveys to residents or interviews to strategic stakeholders, constrains the depth of empirical insight into local experiences, implementation processes, and governance dynamics. While official documents and academic sources provide valuable information, they may reflect institutional perspectives or omit informal or critical viewpoints, particularly those of marginalized communities affected by urban flooding or land-use change.

Second, the reliance on published reports and literature may lead to temporal gaps in the data. Some policy documents and technical assessments used in this study may no longer reflect the most recent developments or on-the-ground conditions, especially in a rapidly evolving urban environment like Shenzhen. This temporal limitation affects the ability to capture dynamic changes in infrastructure performance or institutional adaptation.

Third, although spatial analysis tools such as spatial analysis and GIS (Fotheringham & Rogerson, 1994) were initially considered as part of the methodology, access to relevant geospatial data was not granted, limiting the ability to conduct original spatial modelling or empirical testing of relationships between green infrastructure and flood mitigation outcomes. Consequently, the analysis of spatial patterns and resilience remains largely interpretive and dependent on previously published studies.

Fourth, the specificity of the case study design means that the findings cannot be readily generalized to other cities or national contexts. Shenzhen has unique political, economic, and environmental characteristics that shape the design and implementation of Sponge City measures. While the case offers valuable insights into how nature-based solutions are institutionalized in China, caution must be exercised when drawing broader conclusions or transferring recommendations to other urban settings.

Finally, language and accessibility barriers posed additional challenges. Some technical or governmental documents are available only in Chinese, which may have constrained full engagement with locally relevant sources. Although English-language literature was prioritized for consistency and accessibility, this may have introduced a bias in source selection and analytical interpretation.

Despite these issues, the dissertation provides a grounded and critical evaluation of the Sponge City Programme in Shenzhen, affirming the relevance of nature-based solutions while also identifying the structural, technical and governance conditions that mediate their performance. The articulation of results through the three analytical dimensions allowed for a nuanced understanding of the programme's impact and challenges. Ultimately, the study reinforces the idea that building urban resilience is as much a question of institutional design and political will as it is of engineering innovation.

The findings contribute to broader debates on sustainable urban water management and climate adaptation, particularly in rapidly urbanizing contexts. Nonetheless, future research would benefit from incorporating mixed methods approaches, including stakeholder engagement and real-time data collection, to enhance empirical depth and analytical triangulation.

5.4 FUTURE WORK

While this dissertation successfully achieved its primary objectives and offered a comprehensive assessment of the Sponge City initiative in Shenzhen, several important paths for future development and research remain open. These lines of inquiry respond both to the empirical limitations identified and to the need for advancing the analytical dimensions of urban resilience, environmental performance, and governance integration.

A first key path concerns the enhancement of spatial analytical depth. Although the current study included a descriptive spatial and temporal analysis of flooding patterns and green infrastructure coverage, more advanced modelling—particularly spatial autocorrelation and regression analysis—was not implemented due to the unavailability of high-resolution geospatial datasets. Future studies should prioritise access to granular data at the district or sub-district level, enabling the application of tools such as Moran's I, LISA, and spatial regression models. This would allow a more rigorous assessment of spatial clustering and disparities in Sponge City performance, particularly in relation to the second analytical dimension (Environmental and Infrastructural Outcomes) and the spatial equity of nature-based solutions.

A second line of future research should focus on the collection of primary empirical data to complement and validate simulation-based assessments. Field-based measurements of key hydrological indicators—such as infiltration rates, stormwater retention, and pollutant removal—would enhance the robustness and credibility of infrastructure performance

evaluation. Deploying IoT-enabled environmental sensors in selected districts could enable real-time performance tracking, supporting adaptive management and increasing institutional responsiveness. These developments would reinforce the first two analytical dimensions, particularly the evidence base for urban flood mitigation and ecological enhancement.

A third path involves the inclusion of stakeholder engagement and participatory methodologies. The current research did not incorporate primary data from citizens, urban planners, or maintenance personnel, thus limiting insights into how the public perceives, uses, and supports Sponge City infrastructures. Future research should adopt qualitative and participatory methods—such as interviews, community surveys, and participatory mapping—to uncover the social dimensions of resilience, including community trust, acceptance, and co-management practices. This would enrich the third analytical dimension (Governance and Policy Integration) by adding depth to the understanding of implementation processes and civic involvement.

Moreover, comparative case studies across other Chinese Sponge City pilots—such as Wuhan, Xi’an, or Xiamen—offer a promising line of research. By analysing how similar policies unfold across different environmental, institutional, and geographic contexts, future studies can help identify enabling factors and transferability challenges. This would further clarify which elements of the Shenzhen model are generalisable and which depend on localised conditions, contributing to both policy design and theoretical development.

Finally, further research should explore policy instruments and regulatory integration. While this dissertation has offered recommendations, future work could investigate how planning laws, building codes, and fiscal tools are being revised to accommodate nature-based solutions. Special attention should be given to financing mechanisms such as public–private partnerships, ecological tax incentives, and green municipal bonds, which could support the long-term sustainability of Sponge City infrastructures and reduce reliance on government subsidies.

Taking this into consideration, future research should follow four main paths: (1) deepening analysis through advanced geospatial methods; (2) collecting primary data to enhance environmental performance assessment; (3) embedding participatory and stakeholder perspectives; and (4) refining comparative and policy-oriented approaches. Together, these lines of inquiry will contribute to the consolidation of nature-based infrastructure as a robust strategy for building resilient, equitable, and sustainable urban futures.

This dissertation makes academic, methodological, and practical contributions to sustainable urban development, resilience, and nature-based infrastructure planning, while laying the foundation for future dissemination. Planned outputs include a peer-reviewed article on the spatial and governance dimensions of Sponge City implementation in Shenzhen, a policy brief translating key findings into actionable recommendations for urban planning and environmental authorities, and a conference presentation targeting urban sustainability and climate adaptation. Together, these initiatives aim to extend the dissertation's impact beyond academia, informing policy and practice on resilient, ecologically grounded approaches to urban flood management.

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