

Article

From Concept to Practice: Evidence and Lessons from Sponge City Implementation in Shenzhen, China

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Abstract

Urban flooding represents an increasingly critical challenge in rapidly urbanizing cities, where high-density development and climate variability intensify hydrological vulnerability. This article presents an analytically focused case study of Shenzhen, a national Sponge City pilot, to examine not only whether nature-based interventions are associated with flood-resilience gains but also under what spatial, institutional, and governance conditions such gains emerge. The study adopts a qualitative mixed-methods case-study design based on secondary sources, integrating observed flood-event records, reported hydrological and water-quality indicators, model-based projections, and systematic policy analysis. Drawing on data from 2006–2020, the analysis explicitly distinguishes observed outcomes, reported performance indicators, and inferred effects, addressing a key methodological limitation in existing Sponge City assessments. Results indicate that, within designated pilot zones, Sponge City interventions are associated with reduced surface runoff, attenuated peak flows, and reported improvements in pollutant filtration, particularly where green infrastructure density and monitoring capacity are high. However, these performance patterns are spatially uneven and mediated by governance constraints, including institutional fragmentation and maintenance capacity. The principal contribution of the study lies in identifying governance–infrastructure mechanisms that condition Sponge City performance and scalability. By treating Shenzhen as a critical rather than representative case, the article offers analytically transferable insights into the effectiveness, durability, and limits of nature-based flood-management strategies in high-capacity urban contexts.

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



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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 [1].

To address these shortcomings, the Sponge City concept has gained traction as an innovative and ecologically sensitive urban water management strategy [2]. 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 [3].

The Sponge City initiative draws on several complementary theoretical frameworks. Urban Resilience Theory emphasizes cities' capacity to absorb and adapt to disruptions such as flooding while maintaining essential functions [4]. Ecosystem services theory highlights the climatic and hydrological benefits of natural systems, informing the use of wetlands, permeable surfaces, and green spaces as active infrastructure [5]. Integrated Water Resources Management (IWRM) introduces a coordinated water–land–environment perspective that treats stormwater as a resource and promotes decentralized water systems [1,6]. Urban Green Infrastructure further supports vegetation-based systems such as bioswales and rain gardens to enhance stormwater management, climate resilience, and public health while cautioning against superficial greening in the absence of broader governance integration [7,8]. Conceptually, Sponge City development aligns with international paradigms such as Water Sensitive Urban Design, Sustainable Urban Drainage Systems, and Low-Impact Development (LID) and can be understood as a domain-specific application of the broader Nature-based Solutions (NbS) framework in urban water management and climate adaptation.

At the forefront of Sponge City implementation is Shenzhen, a rapidly urbanizing metropolitan region in southern China. With high population density, a monsoon-influenced climate, and increasing exposure to pluvial flooding, Shenzhen constitutes a particularly critical and policy-relevant context for examining how Sponge City principles are operationalized in practice. Its designation as a national demonstration city underscores its relevance to contemporary debates on climate adaptation and sustainable urban planning [9].

In this study, resilience is understood not merely as the capacity to cope with current hydrological variability but more specifically as adaptive capacity to climate change-induced stressors, including increasing precipitation intensity, greater frequency of extreme rainfall events, and heightened uncertainty in urban water regimes [4,10]. Accordingly, the Sponge City programme is examined as a form of climate adaptation infrastructure, designed to reduce flood risk, enhance system flexibility, and mitigate exposure to hydro-climatic extremes through decentralized, nature-based water retention strategies [3,9].

Despite the growing body of literature on Sponge Cities and related nature-based solutions, a persistent gap remains in empirically grounded evaluations of their real-world performance, particularly regarding how and under what conditions such interventions enhance urban flood resilience and sustainable water management. While existing studies have contributed valuable conceptual insights and modelling-based assessments, many remain normatively oriented or technically abstract, offering limited understanding of the mechanisms through which implementation dynamics, governance constraints, and institutional arrangements shape observed outcomes in complex urban environments [10,11]. As a result, questions concerning scalability, durability, and institutional embedding remain insufficiently addressed in empirical research.

In contrast to studies that focus primarily on design principles or modelled performance, this study explicitly examines how implementation dynamics and governance arrangements condition observed Sponge City outcomes in a megacity context. Shenzhen offers a strategic empirical lens through which to address these limitations. Rather than focusing on technical design features alone, this study leverages the Shenzhen case to examine the interaction between infrastructure performance, governance arrangements, and institutional capacity and how these interactions shape urban resilience outcomes in a rapidly urbanizing and climate-vulnerable setting.

Against this background, the study adopts an explicitly analytical focus on how and under what conditions Sponge City interventions shape urban flood resilience and sustainable water management in practice. Guided by this focus, the analysis is structured around the following research questions: (RQ1) How are Sponge City interventions in Shenzhen associated with observed changes in urban flood regulation and water-related environmental performance in designated pilot areas? (RQ2) How do governance arrangements, institutional coordination, and monitoring practices mediate both implementation processes and reported performance outcomes of Sponge City interventions? (RQ3) What constraints, trade-offs, and scaling challenges emerge from Shenzhen's Sponge City experience, and what do these reveal about the conditional relevance and limits of the model for other cities? Together, these questions frame the empirical analysis as an examination of mechanisms, conditions, and limitations, rather than a descriptive evaluation of policy outcomes.

To address these questions and respond to the lack of empirically grounded implementation-focused evaluations, the study adopts a case-based, mixed qualitative–quantitative analytical framework. A reflexive literature review provides the conceptual backbone of the analysis, complemented by an in-depth case study of Shenzhen's Sponge City Programme drawing on planning documents, policy reports, and technical evaluations [3,12]. Descriptive quantitative analysis of selected hydrological and environmental indicators is used to contextualize reported performance outcomes. The analysis focuses on NbS functions related to flood regulation, runoff control, stormwater retention and infiltration, and urban water quality, rather than the full spectrum of ecosystem services potentially associated with Nature-based Solutions. This multi-method approach enables a context-sensitive and empirically grounded examination of how Sponge City principles translate from policy ambition into urban practice.

This article is organized into five integrated sections that collectively explore the principles of Sponge City development, their application in Shenzhen, and broader implications for sustainable urban water management. Through this lens, the study contributes to the broader discourse on adaptive urban design by clarifying the conditions under which nature-based solutions can enhance urban water resilience while also identifying the governance and institutional challenges that shape their effectiveness.

2. Literature Review

2.1. *The Rise in the Sponge City Concept*

Urban water management has become a central concern of contemporary urban planning, as cities face escalating pressures from rapid urbanization, climate change, and hydrological uncertainty [13,14]. Recent syntheses of Sponge City and urban flood management research further highlight that these pressures are not isolated drivers but interact across spatial scales, amplifying runoff generation, flood exposure, and environmental degradation in densely urbanized areas [15,16]. By the late twentieth century, the limitations of conventional, drainage-centric water management systems became increasingly evident, particularly in relation to their inability to cope with intensified rainfall, surface

sealing, and cumulative ecological degradation. Empirical reviews of Sponge City implementation in China confirm that reliance on grey infrastructure alone has repeatedly failed to deliver adequate flood mitigation under extreme precipitation events [17,18].

In response, urban planners and policymakers began to move away from purely engineered drainage solutions towards more integrated and adaptive water management paradigms. One of the most influential of these paradigms is IWRM, which promotes a holistic approach to water governance by explicitly recognizing the interdependencies between water systems, land use, and ecosystem health [1]. Within the Sponge City literature, IWRM is increasingly recognized as a foundational framework that supports cross-sectoral coordination, multi-level governance, and the alignment of hydrological performance with broader sustainability objectives [19,20]. Rather than treating stormwater solely as a hazard to be evacuated, IWRM re-frames it as a resource to be managed across spatial and institutional scales. This conceptual shift provided a critical foundation for later urban water strategies that prioritize decentralization, multifunctionality, and ecological integration. Beyond technical and governance dimensions, Sponge City development has also been framed within broader ecological and economic sustainability paradigms, emphasizing its role in advancing ecological civilization and urban sustainable development [20].

In parallel, the emergence of climate adaptation planning further reinforced the need for resilient urban water infrastructures capable of responding to increasing rainfall variability, extreme precipitation events, and climate-induced uncertainty [3]. Traditional grey infrastructure, designed under assumptions of hydrological stationarity, proved ill-suited to these evolving conditions. Meta-analytical and review-based evidence demonstrates that hydrological performance of Sponge City interventions varies substantially across climatic, geomorphological, and urban contexts, underscoring the limits of standardized engineering solutions [16,21]. As a result, cities increasingly turned to LID and NbS, which aim to restore or mimic natural hydrological processes within the urban fabric [9]. These approaches are now widely understood as central mechanisms for enhancing infiltration, retention, evapotranspiration, and pollutant attenuation within urban catchments [22,23].

Within this evolving policy and planning landscape, the Sponge City concept emerged as a distinct urban water management approach that synthesizes principles from IWRM, climate adaptation, and LID. Rather than prioritizing rapid stormwater conveyance, Sponge City strategies emphasize stormwater retention, infiltration, purification, and reuse, thereby enhancing urban flood resilience while simultaneously delivering ecological and social co-benefits [3]. Systematic reviews of Sponge City practices indicate that this integrative logic represents a qualitative shift from earlier urban drainage paradigms, particularly in its emphasis on multifunctionality and policy-driven performance targets [15,18]. In conceptual terms, Sponge City development can be understood as a domain-specific application of the broader NbS framework in the field of urban stormwater management and climate adaptation. However, unlike many internationally documented NbS initiatives, Sponge City programmes are characterized by their scale, formalized governance structures, and explicit integration into national and municipal planning frameworks [17,19]. These principles are operationalized through a range of blue-green infrastructure components designed to perform specific hydrological and ecological functions, as summarized in Table 1.

Green roofs, which feature vegetated surfaces on buildings, facilitate stormwater absorption and regulate the microclimate [10]. Permeable pavements replace traditional concrete roads and sidewalks, allowing water to infiltrate the ground and reduce runoff accumulation [11]. Rain gardens and bio-retention systems provide stormwater storage and pollutant filtration, creating multifunctional urban green spaces that contribute to both hydrological regulation and biodiversity enhancement [14]. Constructed wetlands

mimic natural wetland processes to treat stormwater and improve water quality [24], while rainwater harvesting systems collect water from rooftops and drainage points for non-potable urban reuse [25]. Lastly, stormwater detention basins and floodable parks slow down stormwater movement, reducing peak flows and reinforcing urban flood resilience [1]. Recent evaluation studies further suggest that the effectiveness of these components depends not only on design specifications but also on spatial configuration, maintenance regimes, and institutional coordination [21,26].

Table 1. Key Infrastructure Components of Sponge Cities and Their Functions.

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

Source: Own Elaboration.

Taken together, these components reflect a broader shift in urban water management from single-purpose drainage infrastructure towards integrated, multifunctional systems that align hydrological performance with ecological sustainability and climate adaptation goals. This conceptual evolution underpins the rapid expansion of Sponge City programmes in China while simultaneously raising questions regarding their real-world performance, governance capacity, and long-term resilience under heterogeneous urban conditions, thereby motivating further empirical investigation [27].

2.2. 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 [28], 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 [29,30]. Beyond its conceptual foundations, the SCP represents one of the most ambitious large-scale applications of nature-based urban water management globally, characterized by explicit performance targets, strong central policy steering, and extensive intergovernmental coordination [18,19].

The initiative, launched collaboratively by the Ministries of Finance, Water Resources, and Housing and Urban–Rural Development, began with 16 pilot cities in the first batch and 14 in the second. In October 2015, the government issued guidelines [31] requiring that a minimum proportion of urban areas progressively integrate sponge features, with targets rising to 70% by 2020 and 80% by 2030. These quantitative targets marked a departure from earlier, more exploratory urban water policies, signalling a transition towards results-oriented implementation and large-scale retrofitting of existing urban areas, alongside the integration of Sponge City principles into new developments [17]. These efforts were supported by national policy instruments and financial mechanisms, including public–private partnership (PPP) models [29]. However, recent reviews suggest that the effectiveness of PPP arrangements has varied considerably across cities, depending on local institutional capacity, risk-sharing arrangements, and long-term maintenance responsibilities [17,19].

Within this national policy framework, Shenzhen has emerged as one of the most prominent and analytically relevant Sponge City pilot cities. As one of China’s fastest-

growing metropolitan regions, Shenzhen faces acute challenges associated with high population density, rapid land-use change, and complex hydrological conditions. These pressures are compounded by high exposure to pluvial flooding and limited natural drainage capacity, making the city a critical test case for Sponge City performance under intense urbanization [16,27]. In response, the city has adopted a data-driven and spatially targeted approach to Sponge City planning, combining spatial analysis and hydrological assessment with the strategic deployment of blue-green infrastructure [30]. The use of high-resolution spatial data and analytical tools has enabled planners to identify flood-prone zones, prioritize intervention areas, and align Sponge City investments with observed risk patterns [15].

These tools have supported the targeted implementation of measures such as vegetated swales, constructed wetlands, permeable pavements, and multifunctional public spaces. Empirical evaluations of Sponge City projects indicate that while such interventions can improve runoff control and water quality, their performance is highly sensitive to local climatic conditions, spatial configuration, and maintenance regimes [21,26]. The Futian Mangrove Ecological Park serves as a flagship example of this approach, integrating ecological restoration with flood mitigation in a densely urbanized context. This project illustrates how Sponge City interventions can simultaneously address hydrological regulation, ecosystem restoration, and urban amenity provision while also revealing the governance and coordination efforts required to sustain multifunctional outcomes over time [18].

Shenzhen's emphasis on spatial planning, technological tools, and large-scale retrofitting distinguishes it from many other pilot cities and underpins its selection as the primary case study for this research [29]. Compared with cities where Sponge City implementation has been more fragmented or confined to isolated demonstration zones, Shenzhen exhibits a higher degree of integration across planning scales and policy domains [17].

China's Sponge City initiative has also been implemented in other major urban centres, providing useful comparative reference points rather than parallel case studies. Cities such as Wuhan and Xiamen illustrate how Sponge City principles are adapted to distinct geographical and urban conditions. Wuhan, located along the Yangtze River, has prioritized large-scale ecological interventions, including wetland restoration and floodplain management, reflecting its exposure to riverine flooding and extensive low-lying terrain [24]. Xiamen, by contrast, has focused on compact, small-scale retrofitting strategies suited to a dense coastal urban fabric, emphasizing rainwater harvesting, bio-retention systems, and permeable surfaces within constrained residential environments [24]. These contrasting approaches highlight both the contextual flexibility of Sponge City strategies and the limits of direct policy transfer across heterogeneous urban settings [16,23].

Rather than offering a broad comparative evaluation of multiple pilot cities, this study uses Wuhan and Xiamen selectively and analytically, as contextual benchmarks that help clarify the specific characteristics and ambitions of Shenzhen's Sponge City model. This positioning allows the analysis to focus on mechanisms and conditions of implementation, rather than on outcome comparison alone, thereby strengthening the analytical contribution of the case study.

Despite the promise demonstrated by Shenzhen and other pilot cities, the broader implementation of Sponge City strategies continues to face significant challenges, including institutional fragmentation, uneven technical capacity, and long-term maintenance constraints [24,29,30]. Recent reviews further point to coordination gaps between planning, construction, and operation phases, as well as limited post-implementation monitoring, as persistent barriers to sustained performance [15,17]. At the same time, these experiences reveal important opportunities for policy learning, governance innovation, and the

refinement of nature-based urban water management strategies, themes that are examined empirically in the subsequent sections of this article.

2.3. 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 promise for sustainable urban water management, empirical studies consistently highlight a set of recurring technical, institutional, and governance constraints that shape how Sponge City strategies perform in practice [24,29]. Recent systematic reviews and comparative assessments confirm that these constraints are not isolated implementation failures but structural features of large-scale Sponge City deployment, particularly during the transition from pilot projects to city-wide roll-out [15,17]. Rather than being evenly distributed, these challenges tend to be most pronounced in dense, rapidly urbanizing metropolitan contexts, where legacy infrastructure, complex administrative arrangements, and high exposure to hydrological risk intersect [32].

One of the most persistent challenges concerns the technical and spatial complexity of retrofitting existing urban areas. Sponge City interventions are highly context-dependent, requiring site-specific hydrological modelling and careful integration with pre-existing drainage and transport infrastructure. In older urban districts, limited space, sealed surfaces, and ageing underground networks can constrain the effectiveness of water-focused nature-based solutions, leading to uneven performance across neighbourhoods [29,30]. Meta-analytical evidence indicates that performance outcomes, such as runoff control and pollutant reduction, vary significantly according to local climatic conditions, soil characteristics, and urban morphology, even when similar intervention types are applied [21]. These findings challenge assumptions of technical transferability and underscore the need for context-sensitive design and evaluation frameworks [24]. These limitations are particularly relevant for cities such as Shenzhen, where large portions of the urban fabric were developed prior to the adoption of Sponge City principles.

Institutional and governance challenges constitute a second, and often more decisive, barrier. The Sponge City approach presupposes coordination across multiple policy domains, including water management, urban planning, environmental protection, and public works. In practice, however, fragmented governance structures and overlapping administrative mandates frequently undermine integrated implementation [1,24]. Reviews of Sponge City policy implementation highlight that misalignment between planning, construction, and operational responsibilities remains a persistent weakness, often resulting in inconsistent standards, delayed project delivery, and unclear accountability for long-term performance [17,19]. Responsibilities for design, construction, and long-term maintenance are often dispersed across agencies, resulting in inconsistencies in standards, delays in project delivery, and uncertainty regarding accountability. These governance dynamics are particularly pronounced in large metropolitan systems, where coordination costs increase with administrative scale [16]. These governance dynamics are directly examined in the Shenzhen case, where institutional fragmentation emerges as a key factor shaping implementation outcomes.

Financial constraints further complicate Sponge City implementation, particularly with respect to long-term operation and maintenance. While Sponge City infrastructure can deliver cost savings over time, initial investment requirements and uncertain maintenance responsibilities often favour conventional grey infrastructure solutions [25,29]. Empirical evaluations indicate that while capital funding for pilot construction phases is relatively well established, stable financing mechanisms for post-construction monitoring, operation, and maintenance remain underdeveloped in many pilot cities [15,19]. The absence of stable

financing mechanisms for post-construction monitoring and upkeep has been identified as a recurring weakness in pilot cities, affecting the durability and performance of installed infrastructure [30].

Beyond these constraints, the literature also identifies select opportunities that are empirically grounded rather than aspirational. One such opportunity lies in the potential for institutional learning and governance refinement within pilot cities. Evaluations of Sponge City implementation indicate that iterative experimentation, supported by pilot zones and phased roll-out strategies, can improve coordination mechanisms, technical standards, and evaluation practices over time [9,24]. In this sense, Sponge Cities function not only as infrastructure programmes but also as policy laboratories, where governance arrangements, performance indicators, and implementation routines evolve through experience rather than static design [15,18].

A second opportunity relates to the integration of Sponge City principles into broader urban planning and redevelopment processes. Where sponge interventions are embedded within large-scale urban renewal or redevelopment projects, rather than treated as stand-alone technical fixes, their hydrological and ecological performance tends to be more robust [29]. Evidence from highly urbanized contexts suggests that alignment with land-use planning, zoning decisions, and long-term development trajectories enhances both the effectiveness and durability of Sponge City outcomes [16,23]. This reinforces the importance of aligning Sponge City strategies with land-use planning, zoning decisions, and long-term urban development trajectories, an issue explored empirically in the Shenzhen case.

Taken together, the literature suggests that the effectiveness of Sponge City strategies depends less on the availability of individual technologies than on institutional capacity, governance coherence, and context-sensitive implementation. This shift in emphasis, from technological potential to implementation conditions, defines the analytical gap addressed in this article, which examines how such challenges and opportunities materialize in Shenzhen and how they shape the city's Sponge City outcomes.

3. Materials and Methods

3.1. Research Design and Case-Study Logic

This study employs a qualitative case-based research design to examine the implementation of the SCP in Shenzhen and to assess its reported effects on urban resilience and sustainable water management under conditions of rapid urbanization and climate change. The methodological approach is designed to support an in-depth, context-sensitive analysis of policy implementation, infrastructure deployment, and governance dynamics within a single urban system. The case-study logic follows established qualitative research design principles [33].

Shenzhen was selected as a critical and theoretically revealing case, rather than as a statistically representative city. Following established case-study methodology [34,35], the study pursues analytical generalization by examining governance–infrastructure mechanisms in a leading Sponge City context. Shenzhen combines rapid urban growth, high exposure to pluvial flooding, strong state-led planning capacity, and sustained financial and policy support for Sponge City experimentation, making it particularly suitable for examining how nature-based solutions perform under enabling institutional conditions and the implementation frictions that remain visible even in high-capacity settings.

3.2. Case Study Selection and Scope

The empirical focus of the case study is Shenzhen's designation and development as a national Sponge City pilot. The analytical scope covers the period 2006–2020, enabling comparison between pre- and post-Sponge City implementation phases using secondary

hydrological records, flood-event data, policy documentation, planning materials, and technical evaluation reports.

At this stage, the purpose of introducing the case study is to define its selection rationale, temporal scope, and analytical boundaries, rather than to provide a full empirical description of the city. A detailed description of Shenzhen's urban, climatic, and hydrological context is therefore presented at the beginning of the Results section (Section 4), where it serves as the empirical analytical baseline for interpreting subsequent findings.

3.3. Data Sources and Analytical Framework

The empirical analysis relies exclusively on secondary data sources. These include peer-reviewed academic literature, official policy and planning documents, technical and hydrological reports, and evaluation materials produced by municipal and national authorities. Academic sources were identified through targeted searches of Web of Science, ScienceDirect, Google Scholar, and CNKI, with selection guided by thematic relevance to Sponge City development, nature-based solutions, urban flood management, and climate adaptation. Policy and technical documentation include municipal master plans, Sponge City pilot evaluations, flood-risk mapping reports, and annual bulletins issued by the Shenzhen Water Resources Bureau. Where necessary, Chinese-language materials were consulted to ensure completeness and contextual accuracy. Source selection prioritized documents with explicit methodological reporting (e.g., monitoring protocols, modelling assumptions, evaluation indicators) and traceable institutional provenance.

Official policy and planning documents are recognized as potentially subject to success bias, as they tend to emphasize intended outcomes and exemplary projects while underreporting implementation difficulties, contestation, or underperformance. To mitigate this limitation, the analysis systematically triangulates policy narratives with technical assessments, hydrological evaluations, and independent academic studies. Discrepancies across document types are treated as analytically informative signals of implementation tensions, coordination gaps, and institutional incentives, rather than as noise to be removed.

A reflexive literature review informed the conceptual framing of the study and the identification of analytical dimensions, drawing on established approaches to structured qualitative review [34,36,37]. Rather than serving as a methodological object in its own right, the literature review functions as an interpretive resource that supports the development of analytical propositions and guides the reading of documentary evidence. Concepts from urban resilience, nature-based solutions, and socio-ecological systems scholarship were used to define the analytical categories applied in the content analysis and to specify the governance–infrastructure mechanisms examined in the Shenzhen case.

The analytical strategy follows a qualitative content analysis approach, structured around four interrelated analytical dimensions: (1) theoretical and conceptual foundations of Sponge City development; (2) reported environmental and infrastructural outcomes of blue-green infrastructure interventions; (3) institutional and governance arrangements shaping implementation; and (4) strategic coherence between policy objectives, instruments, and reported outcomes. These analytical dimensions and their corresponding data sources are summarized in Table 2. Together, they provide a consistent analytical lens through which heterogeneous documentary sources are systematically examined and interpreted.

Table 2 operationalizes the study's analytical framework by linking each dimension to specific evidence types and interpretive tasks. In practical terms, it functions as the coding and synthesis structure for the documentary material: performance claims (e.g., runoff regulation, pollutant reductions) are evaluated against the technical basis provided in hydrological reports and project evaluations; governance claims (e.g., coordination, maintenance responsibilities, financing arrangements) are examined through municipal plans,

administrative guidance, and institutional bulletins; and coherence is assessed by comparing stated policy targets with reported implementation instruments and documented constraints. This structure supports systematic comparison across sources and reduces the risk that empirical material is presented as narrative description rather than analytically interpreted evidence.

Table 2. Analytical Framework and Data Sources.

Analytical Dimension	Research Focus	Data Sources
Theoretical foundations	Explore the normative and conceptual basis of Sponge City development.	Peer-reviewed literature on urban resilience, blue-green 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	Analyze alignment between goals, instruments, and observed outcomes.	Integrated policy reviews, climate plans, and national Sponge City strategy documents.

Source: Own Elaboration.

The analytical strategy and data triangulation are explicitly aligned with the study’s research questions: hydrological and environmental indicators inform RQ1, governance and institutional materials inform RQ2, and cross-cutting limitations, trade-offs, and pilot-zone dynamics inform RQ3. The study does not attempt formal causal attribution or counterfactual analysis. Instead, it employs descriptive indicators and qualitative triangulation to assess observed performance patterns that are plausibly associated with Sponge City interventions while recognizing the influence of concurrent climatic variability and parallel infrastructure development.

Figure 1 illustrates a schematic workflow of the methodological process, indicating the sequence from case selection and source identification to analytical coding (Table 2), triangulation across document types, and synthesis of findings in relation to the research questions.

The case study analysis is guided by a set of substantive propositions derived from literature rather than formal hypotheses. These propositions posit that Sponge City interventions are intended to contribute to urban resilience through flood-risk mitigation and ecological enhancement; that blue-green infrastructure influences urban water management outcomes in rapidly urbanizing contexts; and that governance capacity, institutional coordination, and policy coherence mediate implementation performance. The linkage between these propositions and the empirical material is established through triangulation across academic studies, policy documents, and technical assessments, allowing convergences and discrepancies to be identified and critically assessed.

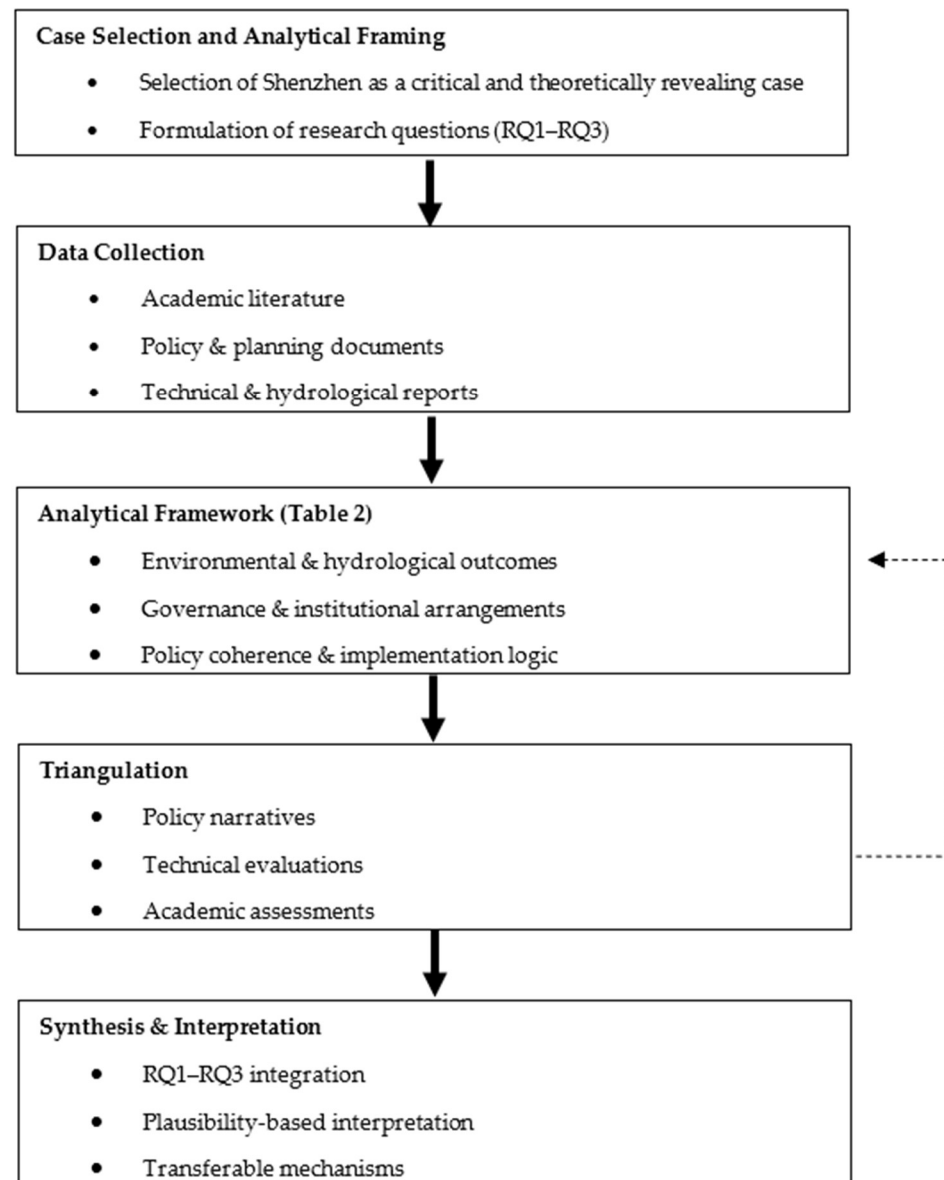


Figure 1. Methodological workflow of the study. Source: Own Elaboration.

3.4. Methodological Limitations

Several limitations are acknowledged. The reliance on secondary data restricts the ability to independently verify reported performance outcomes or capture stakeholder perspectives beyond those represented in official and academic sources. In addition, observed changes in flooding and runoff cannot be fully disentangled from natural climate variability, concurrent grey infrastructure investments, or broader urban redevelopment processes occurring over the same period. Policy and planning documents may privilege normative success narratives and underreport implementation failures or local contestation. Finally, the single-case focus limits statistical generalization. The study therefore does not claim direct transferability to cities lacking comparable institutional capacity, financial resources, or policy commitment. Instead, the findings support analytical generalization by identifying governance–infrastructure interactions and implementation mechanisms that may be relevant to other rapidly urbanizing cities facing similar hydrological pressures under sufficiently enabling institutional conditions.

Overall, this methodological approach provides a transparent and analytically replicable framework for examining Sponge City implementation as a form of nature-based urban

water governance, balancing analytical depth with empirical feasibility in the context of complex urban systems.

4. Results

The Results section examines Shenzhen's Sponge City implementation through an explicitly analytical lens, drawing on the empirical baseline established in Section 4.1 and linking observed patterns to the study's research questions and analytical framework. Sections 4.2–4.4 then analyze environmental and infrastructural performance patterns, governance arrangements, and implementation constraints, respectively.

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. Since the late twentieth century, the city has transitioned from a small coastal settlement into a major global innovation and manufacturing hub, with a population exceeding 17 million [38]. 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. This accelerated growth trajectory is analytically significant, as it has intensified land-use pressures and reshaped hydrological risk exposure, creating structural conditions under which Sponge City interventions have been deployed. Figure 2 situates Shenzhen spatially and illustrates key dimensions of urban flood exposure, combining geographic location with municipal flood-risk modelling and transport infrastructure overlays that provide essential contextual grounding for the subsequent analysis.

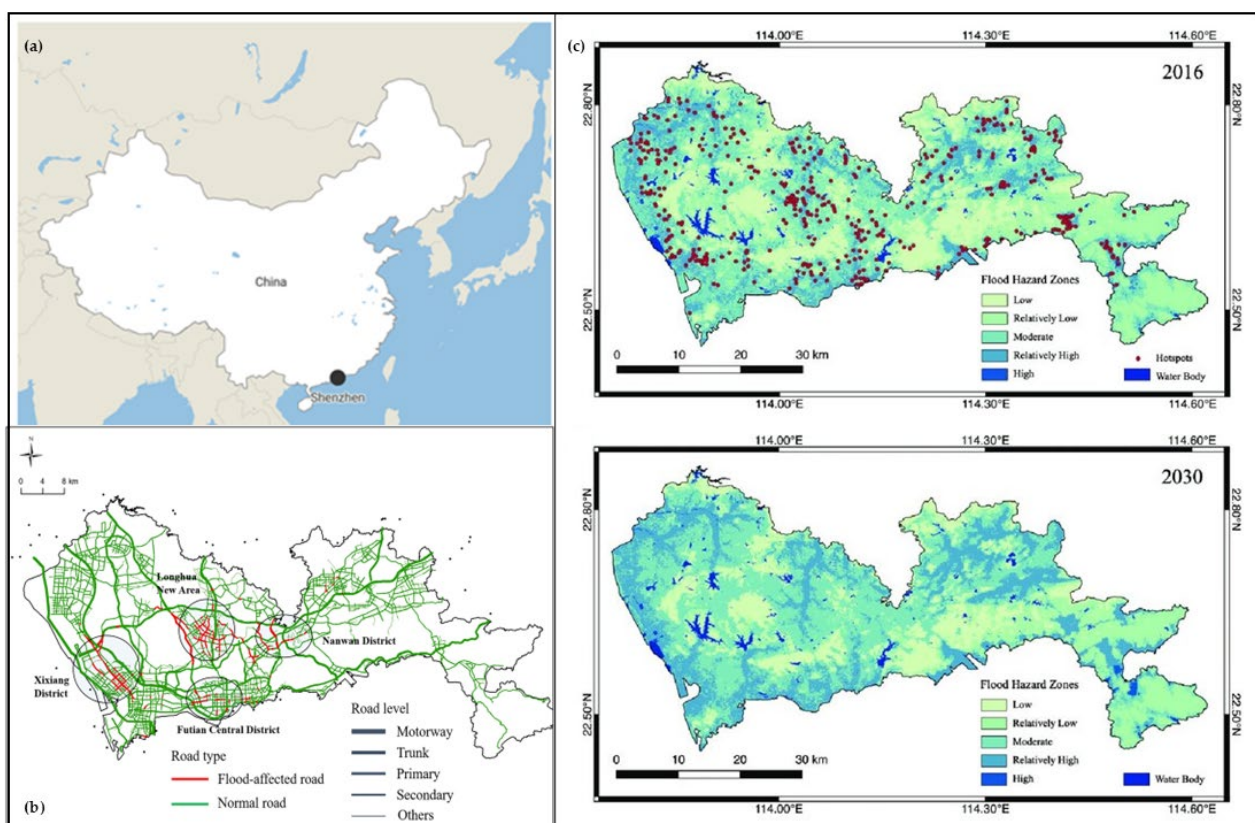


Figure 2. Spatial and hydrological context of Shenzhen. **Source:** (a) Geographic location of Shenzhen within China, Own elaboration created with Datawrapper [39]. (b) Flood-prone road segments and transport infrastructure exposure in Shenzhen, reproduced from [40]. (c) Modelled flood hazard zones under baseline (2016) and projected (2030) conditions, reproduced from [41].

This intense urbanization has significantly altered the city's natural hydrological systems [9]. Originally composed of estuarine wetlands, rivers, and lowland floodplains, Shenzhen's landscape has been profoundly reshaped through large-scale construction and infrastructure expansion. The progressive encroachment on natural waterways and the widespread sealing of soil surfaces through impervious materials have increased surface runoff, heightened flood risk, and disrupted local ecological processes. These changes constitute observed physical conditions that shape baseline flood vulnerability, rather than outcomes attributable to Sponge City interventions.

These hydrological systems are now frequently overwhelmed during storm events, particularly in densely populated districts such as Luohu, Futian, and Bao'an, where impervious surface coverage exceeds 60% [39]. Groundwater conditions further illustrate the environmental strain facing the city. Although Shenzhen's groundwater accounts for only around 12% of annual precipitation discharge, it remains a critical component of stream baseflow and a supplementary source of water in peri-urban areas. Despite this role, groundwater resources remain underutilized and poorly protected, with surface and subsurface pollution limiting their suitability for direct use [42]. Reported groundwater withdrawals remain low, at approximately 5.9 million cubic metres per year, reflecting both institutional management practices and water-quality constraints rather than hydrological availability alone [42].

Shenzhen experiences a subtropical monsoon climate characterized by high annual precipitation, concentrated during the summer months. This climatic pattern, when combined with high urban density, extensive impervious coverage, and legacy drainage infrastructure in older districts, renders the city particularly vulnerable to pluvial flooding. The city's mountainous topography further constrains natural infiltration and accelerates surface runoff. In recent decades, Shenzhen has experienced recurrent flood events during the monsoon season, with evidence pointing to an increasing frequency and intensity of extreme rainfall episodes linked to climate variability and change [43–45]. These climatic trends are treated in this study as exogenous stressors shaping urban flood risk, rather than as effects of Sponge City implementation. Average annual precipitation is approximately 1935 mm, with the majority occurring between May and September. Together, these interacting climatic and urban factors have resulted in a growing number of reported flood-prone locations across the city, summarized in Table 3.

Table 3. Indicators of Urban Flood Risk and Water Stress in Shenzhen.

Indicator	Value/Trend	Source
Annual average precipitation	~1935 mm	[44]
Trend in extreme rainfall events	Increasing frequency and intensity	[44]
Groundwater use	5.9 million m ³	[43]
Flood-prone locations	Over 200 identified sites	[43]

Source: Own Elaboration.

In response to these converging hydrological and urban pressures, Shenzhen was designated as one of China's national pilot cities under the Sponge City Programme. This designation reflects not only the severity of the city's water-related risks but also its institutional capacity for policy experimentation and implementation at scale. The SCP promotes an integrated urban water management model grounded in ecological principles, with the explicit objectives of flood risk reduction, water quality improvement, and enhanced urban resilience.

In addition to its environmental exposure, Shenzhen exhibits a complex urban governance environment characterized by overlapping administrative responsibilities,

strong state-led planning frameworks, and extensive involvement of private developers. These governance conditions are analytically relevant, as they influence the spatial selection of pilot zones, the allocation of financial resources, and the coordination of Sponge City interventions across districts, thereby shaping both performance patterns and implementation outcomes.

Overall, this urban and hydrological context underscores Shenzhen's relevance as a critical case for examining the operationalization of Sponge City principles in practice. Rather than serving as descriptive background alone, this section establishes the baseline environmental conditions, reported risk indicators, and governance constraints against which Sponge City performance and implementation dynamics are evaluated. The following sections therefore examine Shenzhen's Sponge City implementation through the analytical dimensions outlined in Section 3, focusing on (1) environmental and infrastructural performance patterns, (2) institutional and governance arrangements, and (3) constraints, trade-offs, and scaling challenges, in order to assess the city's evolving approach to urban water resilience.

4.2. Urban Resilience

Urban flooding represents a critical and persistent challenge in Shenzhen, driven by rapid urbanization, increasing impervious surface coverage, and intensifying climatic variability. Within this context, the Sponge City initiative, implemented from 2016 onward, constitutes a strategic policy response aimed at enhancing urban flood resilience through the integration of green infrastructure and LID principles. This section examines how observed flood patterns, reported performance indicators, and projected risks intersect with Sponge City implementation, rather than treating flood reduction as a direct or isolated outcome of policy intervention.

The frequency of flood events in Shenzhen exhibits marked interannual variability over the past two decades, with clear distinctions between events occurring during tropical cyclone (TC) periods and those recorded outside TC influence, based on a national flood event dataset compiled from historical records [46]. Between 2005 and 2015, flood events were relatively sporadic, averaging approximately one event per year, with a balanced distribution between TC and non-TC periods. These patterns reflect baseline climatic exposure and urban hydrological vulnerability prior to Sponge City implementation. Following the launch of the Sponge City initiative in 2016, flood occurrences initially increased, peaking at two to three events per year between 2016 and 2018, predominantly during TC periods. This short-term increase coincides with intensified extreme rainfall rather than indicating policy underperformance, highlighting the importance of situating flood outcomes within broader climatic dynamics. From 2019 onward, flood frequency stabilized at lower levels relative to the peak years, suggesting an emerging capacity for improved stormwater regulation and adaptive response, although not a definitive reduction in flood occurrence. The temporal distribution of TC versus non-TC floods (Figure 3) thus illustrates both Shenzhen's climatic exposure and a gradual shift from reactive flood management toward more anticipatory, infrastructure-supported resilience.

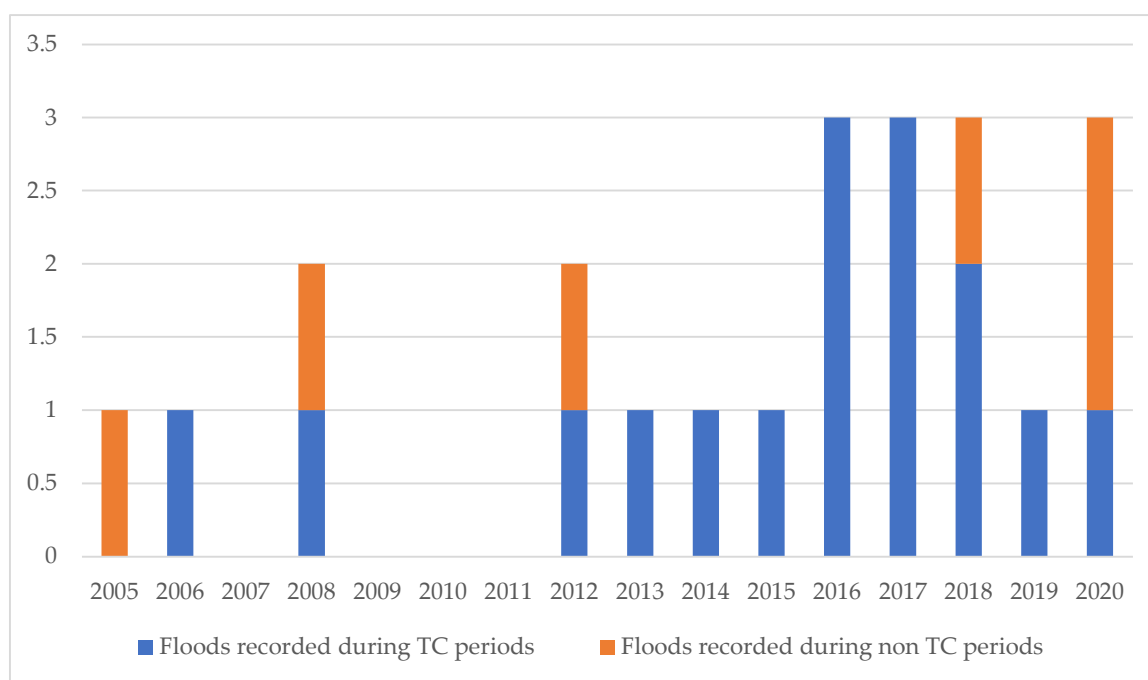


Figure 3. Flood events by year in Shenzhen, 2006–2020. **Source:** Own elaboration based on flood event dataset by Wang [47].

These dynamics are further summarized in Table 4, which contrasts selected indicators before and after the implementation of the Sponge City Programme. Rather than demonstrating a linear decline in flood events, the reported indicators point to structural changes in how flood risks are monitored, managed, and absorbed within the urban system.

Table 4. 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 Guangming District
Infrastructure monitoring	Minimal	Real-time, AI-enabled hydrological dashboards
Runoff control rate	<30% in unprotected zones	72% in sponge districts
Smart monitoring	Fragmented, event-based reporting	Real-time hydrological monitoring with IoT sensors and digital dashboards in sponge districts

Source: Own Elaboration.

Prior to 2016, Shenzhen’s flood management capacity was characterized by limited hydrological monitoring, low runoff control rates, and widespread vulnerability in densely built districts. Following the adoption of Sponge City principles, reported improvements are observed in runoff regulation, monitoring capacity, and targeted remediation of flood-prone areas, particularly in pilot districts such as Guangming, which served as an early demonstration zone for integrated Sponge City planning and implementation [47].

Average runoff control rates increased from below 30% to approximately 72% in designated sponge districts, while real-time hydrological monitoring systems enabled earlier detection and response to storm events. These reported changes are interpreted as evidence of institutional and infrastructural learning associated with Sponge City implementation, enhancing the city’s capacity to cope with extreme rainfall under continued

climatic pressure. At the same time, these improvements coincide with broader urban redevelopment processes and advances in digital monitoring capacity, which cannot be analytically disentangled from Sponge City interventions alone.

It is important to emphasize that these performance indicators are derived primarily from designated pilot and demonstration zones, rather than representing average hydrological conditions across the entire metropolitan area. These zones were intentionally selected for early implementation based on flood risk exposure, redevelopment opportunities, and policy experimentation objectives. As such, reported performance gains reflect the logic of targeted policy experimentation rather than citywide outcomes, introducing a pilot-zone bias that must be considered when interpreting resilience gains and scaling potential.

Spatially, flood impacts remain concentrated in central districts such as Luohu, Futian, and Bao'an, areas characterized by high-density development and legacy drainage infrastructure. These districts were prioritized for early Sponge City interventions as part of a risk-based implementation strategy, reinforcing the spatial concentration of reported performance outcomes [41,48].

Model-based projections provide further insight into the future resilience challenge. Projections based on the SLEUTH urban growth model indicate that Shenzhen's built-up area could expand from 858 km² in 2016 to 1166 km² by 2030 [48]. These projections represent inferred future exposure rather than observed outcomes. If unmanaged, this expansion would substantially increase flood exposure, particularly in peri-urban districts where construction outpaces drainage and green infrastructure provision. Model results suggest that areas classified under the two highest flood hazard levels could increase by approximately 88%, affecting an additional 212 km² of land [48]. In response, the Shenzhen Water Resources Bureau has identified high-risk road corridors, particularly in Bao'an, Guangming, Luohu, and Futian, requiring prioritized intervention due to outdated drainage systems and excessive runoff loads [40].

To address these projected risks, Shenzhen's 2025–2030 flood adaptation strategy targets 50% Sponge City coverage across all districts and aims to enhance drainage capacity to withstand rainfall intensities of up to 90 mm h^{−1} or 200 mm within three hours [40]. These targets represent policy aspirations and planned capacity thresholds rather than achieved performance, indicating an ongoing transition from localized pilot projects toward more integrated, citywide resilience planning.

National-scale flood datasets provide a useful contextual benchmark for interpreting Shenzhen's trajectory. Fu et al. [49] document a rising trend in urban flood events across China between 2000 and 2022, driven by urban expansion and climate variability. Situated within this national pattern, Shenzhen's experience appears distinctive not because flood risks have been eliminated but because institutional and technological responses have evolved more rapidly than in many comparable cities. This supports the interpretation of Shenzhen as a proactive Sponge City pilot rather than an outlier in exposure.

Comparative evidence from other pilot cities further contextualizes these findings. While cities such as Wuhan, Beijing, and Xi'an face different hydrological and climatic conditions, Shenzhen stands out for the scale of green infrastructure deployment, advanced monitoring technologies, and integration of flood risk analytics into planning processes [9,50]. By 2022, Shenzhen had sponge-adapted approximately 46% of its urban area, above the national pilot average of 30–35 and implemented over 1000 green infrastructure projects [9]. These comparative indicators are used analytically to situate Shenzhen within the national Sponge City landscape, rather than to imply superior or comprehensive resilience outcomes.

Overall, Shenzhen's Sponge City strategy reflects a multifaceted approach to urban flood resilience, combining ecological infrastructure, real-time monitoring, and strategic policy coordination. While flood risks persist under continued urban growth and climatic

uncertainty, the evidence points to a progressive strengthening of adaptive capacity rather than definitive risk elimination. The following section examines in greater detail the specific green infrastructure components underpinning this transition, focusing on their spatial distribution, ecological functions, and hydrological performance.

4.3. Green Infrastructure for Sustainable Water Management

The implementation of Sponge City infrastructure in Shenzhen has been associated with measurable changes in urban hydrological processes, particularly within designated pilot and demonstration zones. A diverse range of interventions, including permeable pavements, rain gardens, bioretention basins, sunken green spaces, and constructed wetlands, have been strategically deployed to slow, store, and infiltrate stormwater runoff at its source. These interventions are analytically examined here not as isolated technical solutions but as components of an integrated urban water management system whose performance is shaped by spatial configuration, density, and governance context. Performance assessment has relied on a combination of field monitoring and hydrological simulation models applied primarily in pilot areas [39,42]. A key objective has been to reduce runoff volumes and attenuate peak flows during storm events, particularly in high-density urban catchments.

Empirical evidence from pilot areas indicates that LID technologies are associated with reductions in runoff volume and flood peaks under modelled and monitored conditions. Tang et al. [51], for instance, employed a multi-objective optimization algorithm to evaluate alternative spatial configurations of LID measures within a residential catchment in Shenzhen. Their analysis represents model-based inference rather than direct observation and demonstrates that the effectiveness of sponge infrastructure is highly sensitive to both spatial arrangement and infrastructure density, a finding of particular relevance in a city characterized by steep topography and limited natural infiltration capacity.

Their results show that integrated layouts combining green roofs, permeable pavements, and rain gardens reduced total runoff by up to 41% during a two-year design storm and approximately 30% during a ten-year event. Furthermore, modelling using the Storm Water Management Model (SWMM) suggests that optimized LID configurations could attenuate flood peaks by 20% to 35%, depending on catchment slope and infrastructure distribution [51]. These modelled outcomes are consistent with the intended hydrological functions of Sponge City interventions and suggest that, under favourable spatial and design conditions, green infrastructure can plausibly contribute to stormwater regulation at the catchment scale. Table 5 summarizes these modelled performance ranges.

Table 5. Performance of LID Configurations in Flood Mitigation.

LID Scenario Configuration	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. [52].

While evidence from Shenzhen highlights the potential effectiveness of spatially optimized LID configurations in dense urban catchments, comparative studies from contrasting geographical contexts caution against universal design assumptions. For example, Leng et al. [53] demonstrate that sponge-based runoff and pollution control in large-scale mountainous watersheds requires substantially different spatial layouts, hydrological thresholds, and performance expectations than those observed in compact coastal megacities. This

comparison reinforces the interpretation that Shenzhen's reported performance gains are contingent on its specific urban morphology, governance capacity, and infrastructural density, rather than indicative of a transferable or uniform model.

In parallel with physical infrastructure deployment, the integration of digital monitoring technologies has strengthened Shenzhen's capacity to assess and manage hydrological performance in near real time. More than 150 IoT-based sensors have been installed across pilot districts to monitor rainfall intensity, drainage performance, and groundwater dynamics. These monitoring systems provide observed operational data rather than modelled estimates and are embedded within the operational logic of Sponge City management. Their primary contribution lies in enabling adaptive adjustment of infrastructure operation and maintenance, rather than guaranteeing performance outcomes in themselves. As such, digital monitoring functions as a governance and learning tool as much as a technical one.

Beyond runoff control, Sponge City interventions have been associated with reported improvements in urban water quality through reductions in pollutant loads entering receiving waters. Xiong et al. [53] report that pilot sites equipped with LID technologies recorded reductions in total nitrogen (17.4%), total phosphorus (21.1%), and biochemical oxygen demand (23.2%). These figures represent monitored outcomes at selected sites and should not be interpreted as citywide averages. Performance varied across districts depending on land-use intensity, soil conditions, and maintenance practices, with more densely developed districts such as Futian exhibiting stronger runoff retention outcomes, partly due to the integration of underground storage systems and vegetated rooftops.

While technical performance remains central, the hydrological functions of Sponge City infrastructure in Shenzhen are closely intertwined with broader environmental and social co-benefits. These co-benefits are analytically relevant insofar as they influence political support, public acceptance, and long-term maintenance incentives, rather than being treated as ancillary outcomes. In addition to improving stormwater regulation, the SCP has contributed to ecological restoration, microclimate regulation, and enhanced access to green space, reflecting an emphasis on multifunctional infrastructure rather than single-purpose drainage solutions.

One of the most visible environmental effects has been the restoration of urban ecosystems within previously sealed or degraded areas. The integration of green infrastructure into Shenzhen's dense urban fabric has facilitated ecological renewal, particularly in waterfront and redevelopment zones. Notable examples include wetland restoration within the Futian Mangrove Ecological Park and the creation of vegetated corridors in urban renewal areas, which have improved habitat connectivity and supported the re-emergence of native species [52]. Constructed wetlands in Guangming District further illustrate this multifunctionality, simultaneously retaining stormwater and providing habitat for migratory bird species [39].

Sponge City infrastructure has also contributed to localized microclimate regulation. By replacing heat-absorbing surfaces with vegetated and water-retaining elements, such as green roofs, sunken green spaces, and urban tree canopies, ambient temperatures in high-density districts including Futian and Luohu have reportedly been reduced by approximately 2–3 °C relative to adjacent grey infrastructure zones [9,39]. These effects are spatially limited and context-dependent, but they demonstrate the potential for synergistic climate adaptation benefits alongside hydrological regulation.

Social outcomes form an additional, secondary dimension of sustainable water management in Shenzhen. The conversion of flood-prone or underutilized land into multifunctional parks, walkways, and public spaces has enhanced urban livability while maintaining flood storage capacity. These spaces often incorporate educational elements, such as interpretive signage and water-themed installations, promoting public awareness of sustainable

water practices [52]. While such social benefits do not directly influence hydrological performance, they play a role in legitimizing Sponge City interventions and sustaining public and political support.

Taken together, the evidence suggests that green infrastructure under Shenzhen's Sponge City Programme operates as an integrated socio-hydrological system, delivering runoff control, water quality improvement, ecological restoration, and localized climate regulation under specific spatial and institutional conditions. These outcomes extend the role of stormwater infrastructure beyond risk mitigation while remaining contingent on design optimization, maintenance capacity, and governance coordination. Figure 4 provides a conceptual synthesis of the main governance and implementation challenges identified through the empirical analysis, highlighting their interdependence rather than presenting standalone empirical results.

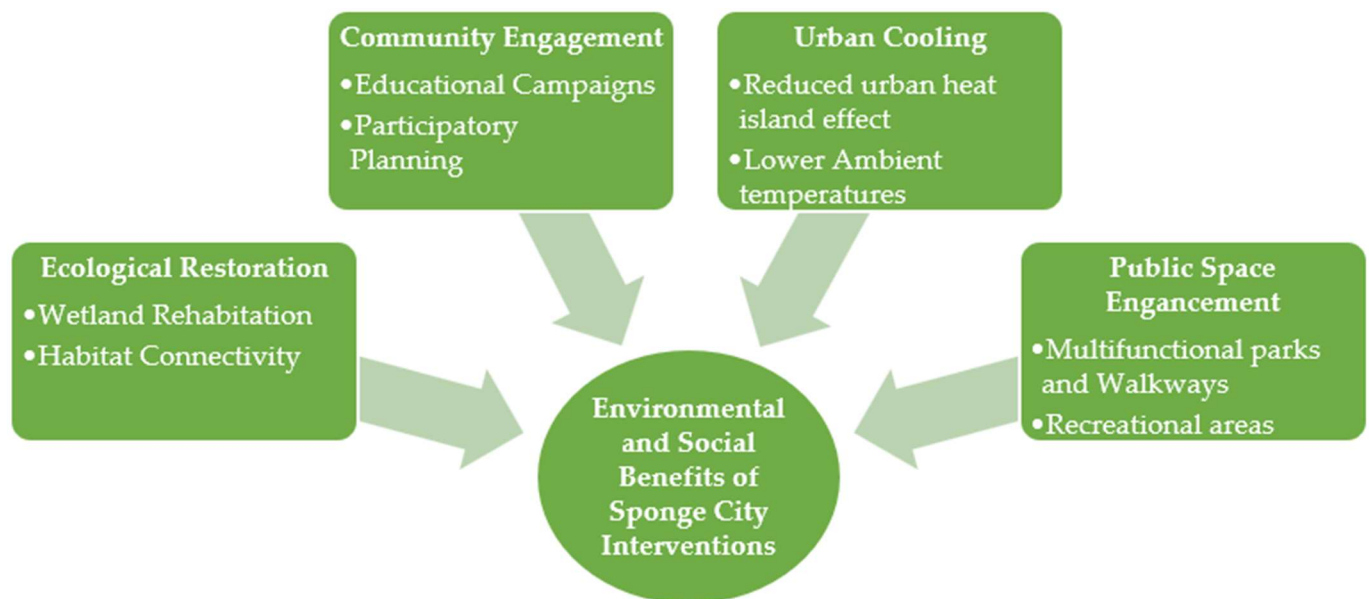


Figure 4. Environmental and Social Benefits of Sponge City Interventions. **Source:** Own Elaboration.

While the environmental and hydrological performance of green infrastructure in Shenzhen is substantial within pilot contexts, its longer-term effectiveness and scalability are shaped by governance arrangements, institutional coordination, and maintenance regimes. The following section therefore examines the governance mechanisms and institutional structures that have enabled, and in some cases constrained, the implementation of Sponge City interventions across the city.

4.4. Governance and Institutional Arrangements

Despite the documented hydrological, ecological, and social benefits associated with the SCP in Shenzhen, its implementation has been shaped, and in some cases constrained, by persistent governance and institutional challenges. These challenges are not merely operational shortcomings but reflect deeper structural conditions that influence how Sponge City principles are translated from policy ambition into practice. Examining these dynamics is essential for assessing not only current performance but also the long-term sustainability, scalability, and institutional durability of Sponge City interventions, particularly as other cities seek to adapt elements of Shenzhen's model.

Figure 5 synthesizes triangulated documentary evidence (municipal plans and bulletins; technical evaluations; academic assessments) and links institutional fragmentation,

capacity constraints, financing design, and monitoring integration to short-run performance variability in pilot contexts and longer-run risks for scaling and durability.

A central governance challenge lies in the fragmentation of institutional responsibilities. The Sponge City concept inherently requires cross-sectoral coordination among departments responsible for urban planning, water management, transportation, and environmental protection. In practice, however, overlapping mandates and siloed administrative structures have resulted in inconsistent implementation standards and delays in project execution [39]. In Shenzhen, the absence of clearly delineated responsibilities for the operation and maintenance of specific sponge assets has been particularly problematic, leading to duplicated efforts in some areas and maintenance gaps in others. These governance frictions reveal a misalignment between the integrative logic of Sponge City design and the compartmentalized structure of urban administration. Yin et al. [9] note that without a unified regulatory framework, or at minimum, stable inter-agency coordination mechanisms, the SCP's integrative ambitions risk being undermined by fragmented execution.

This institutional fragmentation is further compounded by limited mechanisms for interdepartmental communication and budget alignment. In high-density districts such as Futian and Luohu, where multiple agencies operate simultaneously within constrained urban space, coordination failures have reduced opportunities for integrated planning and timely upkeep of green infrastructure. As a result, some sponge installations have reportedly delivered below their intended performance, not due to design limitations but because of organizational and administrative constraints.

In addition to institutional fragmentation, technical capacity gaps constitute a significant constraint on implementation quality. The planning, construction, and evaluation of sponge infrastructure require interdisciplinary expertise spanning hydrology, landscape architecture, and environmental engineering. Yet many local planning authorities and construction teams continue to lack sufficient experience with low-impact development and sponge technologies, particularly in complex retrofitting contexts [39]. These capacity limitations have, in some cases, translated into suboptimal design execution, construction deficiencies, and maintenance challenges, reducing the effectiveness of otherwise well-conceived interventions. Xiong et al. [52] emphasize the importance of targeted training programmes, standardized design guidelines, and pilot projects as institutional learning platforms to address these deficits.

Although Shenzhen has emerged as a national leader in experimentation and technological innovation, the pace and scale of policy rollout have at times exceeded the availability of skilled personnel, especially in older districts where retrofitting must contend with spatial constraints and legacy infrastructure. This imbalance highlights a structural tension between rapid policy ambition and the slower accumulation of institutional and technical expertise, with implications for the consistency and durability of Sponge City outcomes.

Financial arrangements further condition implementation trajectories. While sponge solutions are widely framed as cost-effective over the long term, the upfront capital required for land acquisition, design, and construction remains substantial. In Shenzhen, most pilot projects have relied heavily on public funding through municipal budgets and targeted grants, with relatively limited private-sector involvement [51]. The absence of robust risk-sharing instruments, long-term revenue models, and maintenance financing mechanisms has constrained private participation, particularly in redevelopment zones characterized by high uncertainty and delayed returns. Moreover, financial planning has frequently prioritized initial construction over long-term operation and maintenance, raising concerns about performance degradation as infrastructure ages.

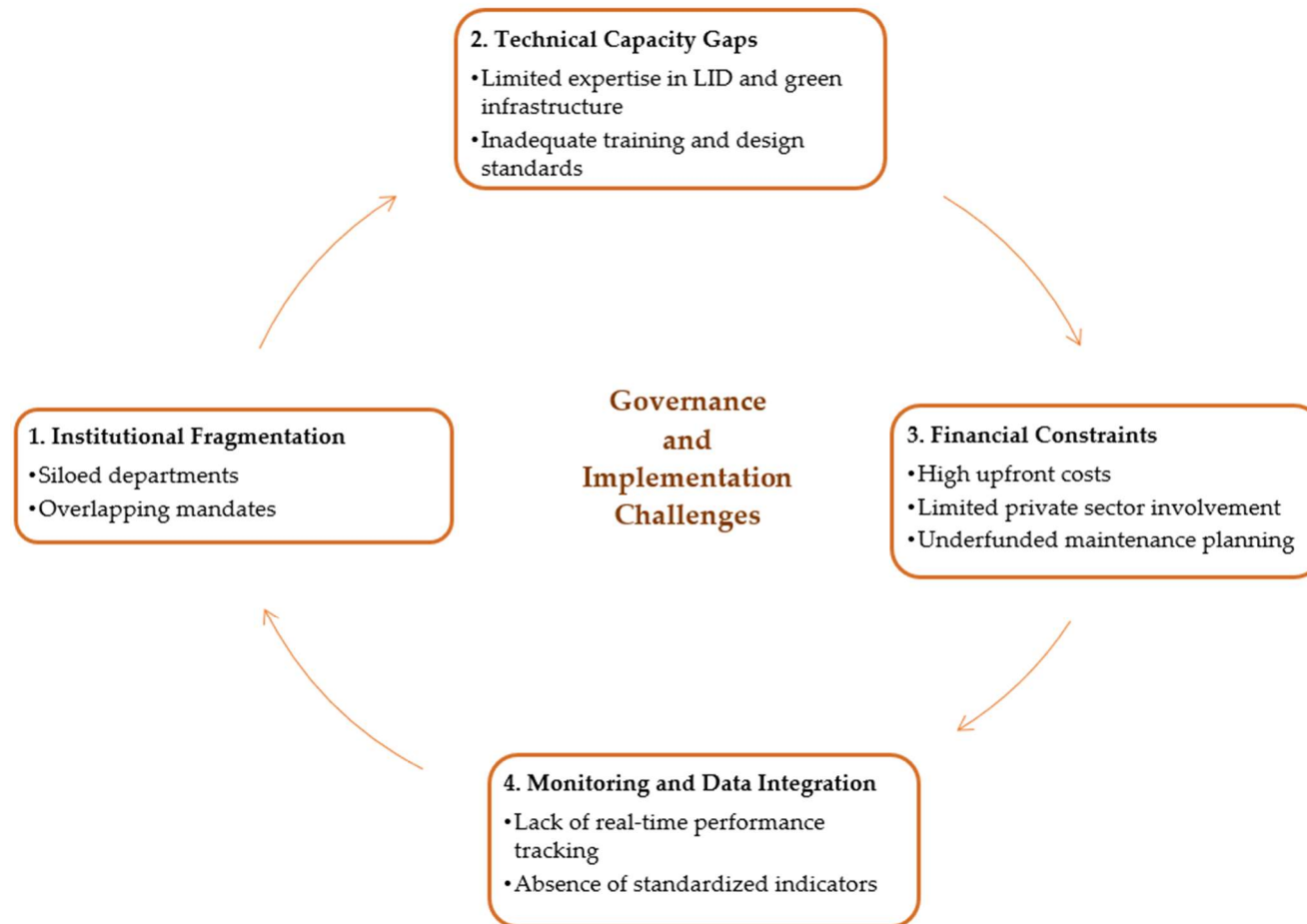


Figure 5. Key Governance and Implementation Challenges Identified in the Sponge City Programme. **Source:** Own Elaboration.

Monitoring and data integration represent a further institutional challenge. Effective governance of sponge infrastructure depends on the ability to track performance under varying hydrometeorological conditions and to adapt management practices accordingly. However, many sponge installations in Shenzhen lack continuous monitoring systems capable of capturing indicators such as infiltration rates, water-quality dynamics, and ecological responses [39]. Inconsistent monitoring coverage, limited standardization of performance metrics, and weak data integration reduce the city's capacity for adaptive management and evidence-based refinement of future projects. Yin et al. [9] therefore argue for the expansion of sensor networks and integrated digital dashboards to enhance transparency and support iterative learning.

This challenge is particularly salient given Shenzhen's prior engagement with international standardization initiatives in water management. Earlier river governance efforts in the city, documented through ISO-led case studies, demonstrate how standardized frameworks can enhance inter-agency coordination, monitoring consistency, and accountability when effectively embedded in institutional practice [54]. The partial disconnection between these standardization experiences and current Sponge City monitoring practices points to an unresolved governance gap between technical ambition and institutional integration.

While initiatives such as IoT-enabled hydrological dashboards have begun to address some of these gaps, coverage remains uneven across districts, and decentralized monitoring installations are not yet fully integrated into a unified, citywide data platform. Taken together, these governance and institutional challenges suggest that the effectiveness of Shenzhen's Sponge City Programme depends as much on administrative coordination, financial design, and institutional learning as on technical performance. Addressing these systemic issues will be critical to sustaining performance gains over time and determining the extent to which the Sponge City model can be credibly scaled or adapted beyond its current pilot contexts.

4.5. Discussion

The analysis of Shenzhen's Sponge City Programme reveals a multifaceted transformation of the city's urban water management paradigm. Rather than representing a purely technical shift, the findings point to a deeper reconfiguration of how urban water risk, ecological infrastructure, and governance capacity are negotiated within a rapidly urbanizing megacity. Synthesizing the empirical results across Sections 4.1–4.4, the discussion highlights how hydrological performance patterns, governance arrangements, and institutional constraints interact to shape Sponge City implementation outcomes. Empirical results presented in this section demonstrate measurable hydrological improvements, significant environmental and social co-benefits, and notable innovations in green infrastructure and monitoring technologies. At the same time, the Shenzhen case exposes structural and institutional tensions that complicate dominant assumptions within Sponge City and nature-based solutions theory.

It is important to emphasize that the hydrological, environmental, and governance outcomes discussed in this section reflect early to mid-stage implementation effects rather than long-term sustainability, lifecycle performance, or institutional stability. The Sponge City Programme in Shenzhen remains in an active implementation and adjustment phase and observed performance patterns should therefore be interpreted as indicative of emerging trajectories rather than consolidated long-term outcomes. As such, claims regarding durability, institutional persistence, or long-term cost-effectiveness remain necessarily provisional.

The extent to which insights from Shenzhen can inform Sponge City implementation elsewhere depends on local institutional, financial, and spatial conditions. Elements that

appear strongly context-dependent include the scale of public investment, the capacity for centralized planning coordination, and access to advanced monitoring technologies. By contrast, several mechanisms identified in this study, such as the coupling of green infrastructure performance with governance coordination, the role of pilot zones as policy laboratories, and the integration of hydrological data into planning decisions, are analytically transferable, even if their practical realization will vary across political and economic contexts.

A central empirical contribution of the study lies in its examination of hydrological performance under real-world urban conditions. Data from pilot areas indicate that LID interventions have been associated with reductions in runoff volumes and peak flows during storm events, reaching up to 41.2% and 34.8%, respectively, under optimized scenarios [51]. These outcomes, supported by field monitoring and hydrological modelling using tools such as SWMM, are consistent with the intended flood-mitigation function of Sponge City interventions and suggest a plausible contribution to improved stormwater regulation, rather than definitive causal attribution. Additionally, reported reductions in total nitrogen, phosphorus, and BOD levels [52] reinforce theoretical claims that blue–green infrastructure can address flood risk and diffuse pollution simultaneously when deployed at sufficient scale and density.

However, the reliance on pilot and demonstration zones has important implications for interpreting performance outcomes and assessing scalability. Pilot zones are intentionally designed to test technical configurations, governance arrangements, and monitoring systems under relatively favourable conditions, often supported by higher levels of investment and administrative attention. While this experimental logic enables learning and innovation, it also introduces spatial bias, as performance observed in pilot areas may not translate directly to districts characterized by denser development, legacy infrastructure, or weaker institutional capacity. Consequently, the findings should be interpreted as evidence of what Sponge City interventions can achieve under enabling conditions, rather than as indicators of uniform citywide performance.

Isolating the causal effects of Sponge City interventions from broader climatic and urban dynamics remains methodologically challenging in real-world urban systems. Shenzhen's hydrological outcomes are shaped simultaneously by climate variability, ongoing grey infrastructure upgrades, land-use change, and evolving monitoring practices. As a result, the analysis does not claim to establish direct cause–effect relationships but instead advances a plausibility-based assessment grounded in observed trends, process tracing, and triangulation across multiple data sources. This approach aligns with qualitative case-study logic while explicitly recognizing the limits of causal inference in complex urban transformations.

From a theoretical perspective, the findings support key propositions in Sponge City and nature-based solutions literature, particularly the argument that decentralized, infiltration-based systems can outperform conventional grey infrastructure in managing pluvial flood risk under climatic variability. At the same time, the Shenzhen case refines these propositions by demonstrating that performance gains are not merely design-dependent but critically shaped by spatial configuration, infrastructure density, governance coordination, and monitoring capacity.

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 [9,27]. Furthermore, the transformation of urban spaces into multifunctional public parks has enhanced livability and promoted public awareness of water sustainability [52]. These co-benefits are

analytically relevant insofar as they contribute to public acceptance and political support, rather than being treated as automatic indicators of long-term sustainability.

Recent research has highlighted that cultural ecosystem services associated with sponge city infrastructure remain underexplored relative to hydrological and governance performance, suggesting an important avenue for future research [55]. At the same time, the Shenzhen case challenges more optimistic or linear interpretations of Sponge City theory, particularly assumptions that institutional adaptation will naturally follow technical innovation. Instead, the findings indicate that institutional change is contingent, uneven, and politically mediated, rather than an automatic consequence of technical success [9,27]. The persistence of siloed mandates, fragmented responsibilities, and uneven maintenance regimes underscores that technical effectiveness alone is insufficient to guarantee governance transformation.

Financial constraints further complicate this picture. While Sponge City interventions are often framed as cost-effective over the long term, Shenzhen's continued reliance on public funding and limited private-sector engagement [51] reveal a structural gap between theoretical models of sustainable financing and the political-economic realities of urban retrofitting. These findings challenge assumptions that market-based instruments or public-private partnerships will readily emerge in high-density, high-risk urban contexts without stronger regulatory frameworks or incentive structures.

Digital monitoring and data integration represent an additional point of tension. While Shenzhen has implemented advanced monitoring tools in selected districts, with over 150 IoT sensors currently in operation, coverage remains uneven and a fully integrated citywide data platform is still lacking [9]. This uneven digitalization complicates narratives of "smart sponge cities," revealing that data-driven governance remains contingent on institutional capacity, interoperability standards, and sustained operational investment.

To synthesize these findings and respond explicitly to the need for an integrated evaluative perspective, Figure 6 presents a SWOT analysis of Shenzhen's Sponge City implementation. The SWOT matrix does not constitute a definitive success-failure assessment; rather, it provides an analytical synthesis of the main strengths, weaknesses, opportunities, and threats emerging from the empirical results discussed above. By juxtaposing demonstrated hydrological performance signals and co-benefits against pilot-zone bias, governance fragmentation, and long-term operational risks, the figure highlights the conditions under which Sponge City interventions appear most effective, as well as the structural constraints that limit their scalability and transferability.

Comparative insights from other Sponge City pilots indicate that Shenzhen performs strongly in technological experimentation and public engagement yet faces challenges common to many Chinese cities in retrofitting legacy infrastructure and achieving durable inter-institutional coordination [56]. Recognition as a national model city and the designation of Fenghuangcheng as a demonstration zone [57] underscore Shenzhen's role as both a leading example and a critical stress-test for Sponge City theory under real-world governance constraints. This demonstrative role is further reinforced through platforms such as Shenzhen Design Week, where Sponge City projects are framed as urban innovation showcases linking ecological infrastructure, design experimentation, and public engagement [58].

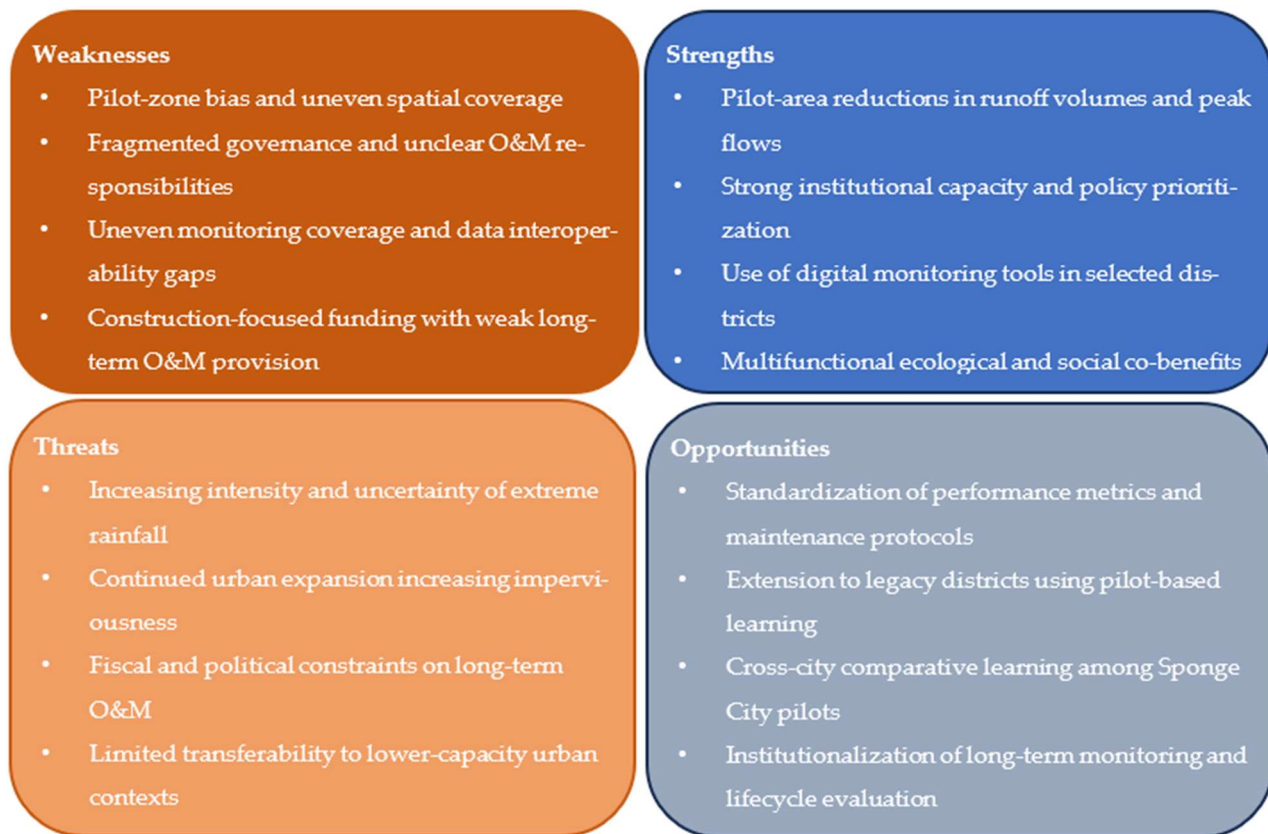


Figure 6. SWOT Analysis Synthesizing the Empirical Findings on Sponge City Implementation in Shenzhen. Source: Own Elaboration.

5. Conclusions

This article examined the implementation of the Sponge City Programme in Shenzhen as an empirical test of nature-based urban water governance under conditions of rapid urbanization and climate variability. Rather than treating Sponge City development as a purely technical intervention, the study analyzed how and under what conditions hydrological performance, ecological outcomes, and governance capacity interact to shape urban resilience in a high-density megacity context. Drawing on a reflexive literature review and systematic analysis of secondary hydrological, policy, and planning data, the research assessed early performance patterns and implementation dynamics associated with Sponge City strategies, rather than definitive long-term outcomes.

The findings generate three central analytical contributions. First, the study provides empirically grounded evidence from pilot contexts supporting the hydrological effectiveness of Low-Impact Development and blue–green infrastructure under dense urban conditions. Evidence from pilot districts demonstrates substantial reductions in runoff volume and peak flows, alongside reported improvements in water quality. These findings are consistent with key propositions in the Sponge City and nature-based solutions literature while also demonstrating that performance gains depend critically on spatial configuration, infrastructure density and monitoring capacity rather than design principles alone.

Second, the Shenzhen case extends socio-ecological systems perspectives by demonstrating that sponge interventions function simultaneously as hydraulic infrastructure, ecological assets, and social space. The documented co-benefits, ranging from biodiversity restoration and microclimate regulation to enhanced public space and civic engagement, illustrate how multifunctional infrastructure can generate environmental and social value alongside hydrological regulation. This reinforces the argument that urban water infras-

structure should be evaluated as a socio-spatial system rather than as a narrowly defined flood-control mechanism.

Third, and most significantly from a governance perspective, the analysis challenges linear assumptions embedded in Sponge City theory that institutional adaptation will naturally follow technical innovation. Despite strong reported hydrological and environmental performance in pilot areas, the Shenzhen case demonstrates that nature-based solutions do not automatically induce institutional convergence. Governance fragmentation, uneven monitoring capacity, and sustained reliance on public funding emerge as structural constraints on scalability and durability. Shenzhen's experience illustrates that urban resilience emerges not from infrastructure alone but from the alignment of technical systems with governance coordination, financial instruments, and institutional learning, with governance adaptation remaining contingent, uneven, and politically mediated rather than a natural consequence of technical success.

Beyond its empirical insights, the study contributes a transferable analytical framework for evaluating Sponge City and nature-based urban water interventions in other contexts. The case-based methodology, combining structured qualitative content analysis, descriptive performance indicators, and systematic triangulation across policy, technical, and academic sources, can be replicated in cities where primary data access is limited but documentary and monitoring materials are available. In this sense, the novelty of the contribution lies not in the Shenzhen case alone but in the methodological approach used to interrogate governance–infrastructure interactions under real-world implementation conditions.

While Shenzhen benefits from exceptional institutional capacity and policy support, the value of this case lies not in its representativeness but in its ability to reveal the enabling conditions, mechanisms, and constraints through which Sponge City strategies operate in practice. Taken together, these contributions position Shenzhen not only as a leading Sponge City pilot but also as a critical stress-test for the limits of nature-based urban water governance under real-world institutional conditions. The case illustrates both what Sponge City strategies can achieve in the early post-implementation phase and the structural factors likely to shape their future durability and transferability.

The temporal scope of this study is constrained by the relatively short post-implementation period of Sponge City interventions in Shenzhen. As a result, the analysis cannot evaluate long-term sustainability, lifecycle performance, or the persistence of institutional arrangements over time. Whether the observed hydrological, environmental, and governance improvements persist, degrade, or adapt under changing climatic, financial, and political conditions requires longitudinal evaluation extending beyond the current assessment horizon.

Future research should therefore prioritize longitudinal and comparative investigation of Sponge City systems across multiple implementation cycles. First, access to high-resolution spatial and hydrological data would enable more rigorous modelling of the relationship between green infrastructure deployment and flood risk reduction across urban districts. Second, mixed-method approaches incorporating interviews, surveys, and participatory mapping would deepen understanding of governance dynamics, public acceptance, and maintenance practices. Third, comparative analyses across multiple Sponge City pilots would help clarify which elements of the Shenzhen model are context-specific and which mechanisms are transferable across different institutional and climatic settings.

Overall, the study reinforces the view that building urban resilience through nature-based solutions is as much a question of institutional design, governance coordination, and political commitment as it is of engineering innovation. Shenzhen's experience offers analytically grounded, but conditional, lessons for cities worldwide seeking

to navigate climate adaptation through integrated, ecologically grounded urban water management strategies.

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