

Review

Keyword Analysis and Systematic Review of China's Sponge City Policy and Flood Management Research

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Abstract

With the acceleration of climate change and urbanisation, Chinese cities are facing increasingly severe flood risks. To address this challenge, China began implementing its sponge city policy in 2013, leveraging low-impact development, green infrastructure construction, and integrated water resource management to enhance urban resilience to floods and improve water security. This study utilises the Web of Science database as a reference, retrieving 201 relevant literature sources. From these, 61 studies closely related to China's sponge city policy and urban flood management were selected. CiteSpace was employed to conduct keyword co-occurrence and temporal evolution analyses, comprehensively outlining the research hotspots and developmental trajectory of this field. The results indicate that research content has gradually shifted from early engineering-based flood control models to multi-objective, interdisciplinary comprehensive management, encompassing flood risk assessment, policy implementation mechanisms, integration of green infrastructure, and economic feasibility analysis. Based on this, this paper constructs an analytical framework incorporating technical, environmental, institutional, and social dimensions to integrate existing research findings, while identifying gaps in cross-scale coordination, smart management, and public participation. The research conclusions can provide valuable references for future policy optimisation and urban sustainable development.

Keywords: sponge city; urban flood management; low-impact development; green infrastructure; urban resilience



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1. Introduction

In the practical implementation of international urban flood management, a variety of alternative approaches have been adopted. Traditional grey infrastructure mainly relies on enlarging the capacity of drainage networks, constructing pumping stations, and building levees. The purpose of these measures is to achieve rapid drainage. However, such approaches usually require high levels of investment and impose significant maintenance costs during long-term operation. At the same time, they lack ecological benefits and do not contribute to environmental improvement [1]. In the United States, low-impact development (LID) and Best Management Practices (BMPs) have been proposed. These approaches focus on controlling flooding at the source and adopt decentralised measures to reduce runoff. Common techniques include green roofs, permeable pavements, and rain gardens [2]. In the United Kingdom, the Sustainable Urban Drainage Systems (SuDS) framework emphasises the coordination of overall drainage management and highlights

the importance of enhancing urban resilience. In Australia, Water Sensitive Urban Design (WSUD) has been developed. This approach integrates urban drainage with water resource management and also links water with landscape design and spatial planning [3]. On the international stage, green infrastructure (GI) and Nature-based Solutions (NbSs) have also been widely applied. These measures place ecological restoration at their core and stress the role of multifunctional landscape construction. They not only reduce flood risks but also generate multiple benefits in terms of ecosystem recovery and the utilisation of public spaces [4]. Compared with these alternatives, China's "Sponge City" model demonstrates a high degree of integration at the technical level. It incorporates the experiences and methods of LID, SuDS, WSUD, and GI. Moreover, sponge city construction in China has gone beyond technical application and has been institutionalised at the level of national strategy. Since the proposal of the policy in 2013, the first batch of pilot projects was launched in 30 cities in 2015. Through the combination of institutional support and practical implementation, the sponge city has gradually become a key measure for addressing urban flooding and enhancing urban resilience [5]. Against this background, the present study examines the sponge city approach in China, with particular attention to its distinctive policy implications and the practical outcomes observed in local implementation.

As global climate change continues and urbanisation accelerates, the pressure on urban flood management has become increasingly severe. Traditional drainage systems centred on "rapid drainage" are no longer effective in addressing heavy rainfall and changes in surface runoff, leading to urban flooding characterised by frequent occurrences, high impact, and significant losses [6]. The concept of the "sponge city" in China arose as urbanisation and climate change together increased flood risks. Studies report that in cities such as Beijing the continued spread of impervious surfaces has raised runoff coefficients, and urban flood management has become more difficult as a result [7]. China launched a national sponge city construction programme in 2013. The policy brought low-impact development principles into the urban water management system and treated them as part of one framework. To deliver this, it promoted a coordinated set of measures—detention, storage, infiltration, purification, reuse, and drainage—so that cities could strengthen flood prevention, improve drainage, and make better use of water resources [7]. Since 2015, implementation has expanded across many localities; sponge parks, in particular, have become visible testbeds of the approach [4]. In the international literature, related terms often frame discussions of sponge cities. Low-impact development (LID) developed in the United States focuses on infiltration, storage, and source control. It is often treated as a core strategy in sponge city practice [2]. Green infrastructure (GI) emphasises natural processes and ecological networks. It is used for flood prevention and cost assessment and is frequently studied with sponge parks. Best Management Practices (BMPs) are applied with LID in design guidance. They help optimise facility configurations and are widely recognised in stormwater management [8]. Nature-based Solutions (NbSs) are promoted by the European Union and other organisations. Sponge cities are often discussed within this framework as systemic responses to urban stormwater [9]. The sponge city is a policy tool that combines natural processes and engineered systems. It enhances stormwater storage and water purification, promotes green infrastructure, and reshapes urban form [10]. Pilot programmes in Wuhan and Shenzhen show stronger resilience and climate adaptation capacity and also bring benefits to regional socio-economic systems [11]. Shenzhen sponge parks show these outcomes. Field studies found that peak rainfall runoff falls by 19.2–24.5% and stormwater storage reaches 32.6%. This lowers flood risk during extreme rainfall [4]. The same research measures financial performance and reports a net present value rate of return of 12.3%, showing both economic feasibility and long-term sustainability. The

results confirm that sponge city pilots reduce flood risk in measurable ways and also deliver economic benefits, providing clear evidence of policy effectiveness.

Although sponge city construction has achieved certain results in terms of policy and practice, the academic community still lacks a systematic review and comprehensive assessment of its policy impact. Current research mostly focuses on technical performance or case studies of individual cities, such as quantitative assessments of runoff reduction rates [8] or studies on resilience enhancement in specific contexts [12]; cross-regional comparisons of policy performance and analyses of its changes over time are also rare [9]. A quantitative research framework based on multidimensional indicators has yet to be established [13]. Rainwater and flood risk assessment based on the sponge city concept was carried out in hilly urban areas. Remote sensing and GIS technologies improved the precision of risk identification. Cross-regional comparisons and long-term dynamic analyses are still lacking. Xie and Peng examined governance systems and pointed out weaknesses in current policies in cross-departmental coordination and emergency disaster response [14]. Single case studies cannot provide sufficient support for systematic policy evaluations. proposed an economic performance evaluation method for Shenzhen's sponge parks that measured economic returns and ecological benefits in the same framework. This method moved beyond technical performance metrics and offered a basis for multidimensional quantitative analysis. The findings are still limited to single-site cases without cross-regional or time-series comparisons [4]. Research from 2022 to 2025 broadened both methods and governance approaches. Gaps remain in multidimensional policy evaluation and systemic analysis. A review is needed to bring fragmented studies together and build a unified analytical framework.

This fragmented research landscape has, to some extent, limited the theoretical support for policy implementation pathways, funding mechanisms, and public participation models, and has also hindered the identification of replicable governance experiences [15]. It is necessary to conduct a systematic review to integrate dispersed research findings and establish a unified analytical framework, thereby driving related research from scattered discussions toward systematic synthesis. This review examines physical and environmental outcomes after policy implementation, including runoff reduction, water quality improvement, and the performance of green infrastructure [7]. It also considers the role of institutional arrangements, governance structures, and public perception in shaping policy results [16]. A study in Wuhan showed that public awareness of sponge cities and willingness to pay have a direct impact on policy implementation and social acceptance [5]. Interdepartmental collaboration and funding mechanisms such as PPP models are decisive for long-term project sustainability. The contribution of this review lies in combining technical performance with socio-economic feedback, filling earlier gaps where research focused mainly on engineering measures while neglecting governance and public participation. At the international level, the analytical framework offers a policy evaluation tool for countries facing urbanisation and climate pressures, especially in integrating Nature-based Solutions into resilience planning, such as ecological revetment and rainwater reuse systems [7]. Multi-benefit assessments provide further evidence. In Wuhan, sponge city projects were linked to higher property values [5], while in Yanjin, flood control and groundwater recharge created reinforcing effects [7]. These cases show that sponge city practices can support sustainable stormwater management, strengthen public policies, and enhance urban resilience.

Given the aforementioned background, this study aims to systematically review existing research on the impact of sponge city policies both domestically and internationally, integrate different research perspectives, and construct a multidimensional analytical framework to clearly elucidate the mechanisms through which this policy influences flood

management, ecological restoration, climate adaptation, and socio-economic benefits [14]. In terms of research content, this review focuses on the physical and environmental outcomes following policy implementation, while also emphasising the influence of “soft” factors such as institutional arrangements, governance structures, and public perception on policy performance [16]. By incorporating case comparisons and time-series analysis, this study addresses the limitations of existing evaluation research in terms of multi-scale, multi-stakeholder, and multi-objective interactions, providing theoretical foundations and empirical references for future policy optimisation and cross-regional promotion [17]. Within this framework, this paper serves as an integration and reflection of existing research, as well as a guide for future research directions and policy implementation pathways, establishing its academic contribution.

The contributions of this study are focused on four key points. First, it establishes a comprehensive assessment framework that integrates technical, environmental, institutional, and social dimensions, breaking free from the limitations of relying solely on technical or environmental indicators. Second, by systematically reviewing 57 highly relevant literature sources, it constructs a knowledge map of the policy impacts of sponge cities, revealing research hotspots and evolutionary trends. Third, at the methodological level, it combines bibliometric analysis with qualitative induction, balancing the objectivity of quantitative analysis with the depth of case analysis. Fourth, from a policy implementation perspective, it summarises the experiences and challenges of different cities in areas such as funding, governance coordination, and public participation, providing actionable improvement recommendations for policymakers and urban managers [18]. This study focuses on three main questions: What are the outcomes and mechanisms of China’s sponge city policy in improving urban flood resilience? What structural barriers and governance challenges appear during implementation? How can a multidimensional and multi-scale evaluation framework be built to optimise the policy’s effectiveness in flood management? These findings offer systematic references for academic research on sponge city policies and provide globally applicable insights with Chinese characteristics for cities addressing climate change and enhancing resilience.

2. Materials and Methods

2.1. Materials

To systematically review the literature on China’s sponge city policies and flood management research, this paper standardised the entire process of literature retrieval, screening, inclusion, and reporting in accordance with the PRISMA 2020 statement guidelines. This study used the Web of Science Core Collection, Scopus, and Google Scholar as the main data sources. The searches were conducted in July 2025 with keywords including “sponge city” policies, “urban flood management”, “climate”, and “urban”, and 278 publications from 2017 to 2025 were found (Figure 1). To focus on China’s sponge city policies and urban flood management, manual screening and thematic categorisation were carried out using titles, abstracts, and keywords. Studies with a strong technical focus but no policy context and those not based on Chinese cases were removed. After screening, 61 papers were selected. These included empirical studies from pilot cities such as Wuhan, Shenzhen, and Zhengzhou, and studies on policy effectiveness, public perception, and social acceptance (Figure 2). This formed the data basis for co-occurrence and temporal evolution analyses of keywords.

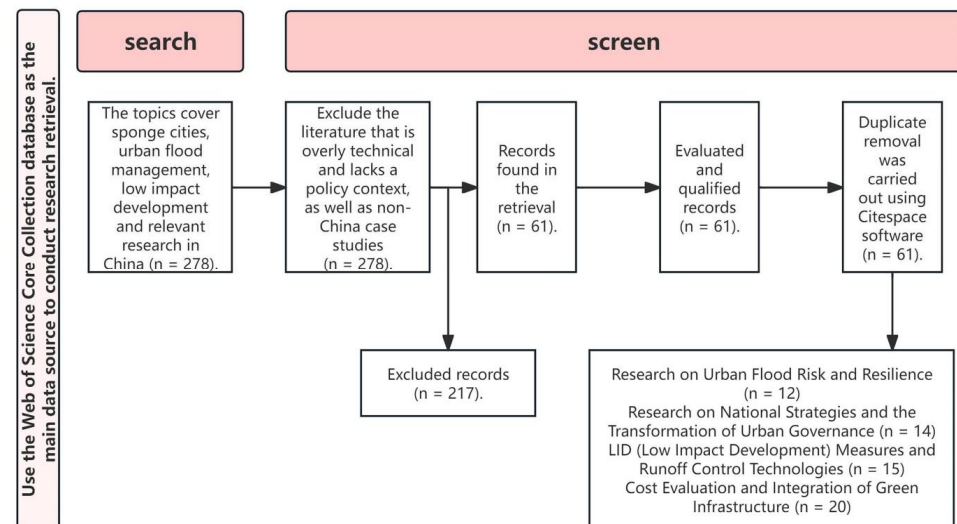


Figure 1. PRISMA diagram for literature search and screening.

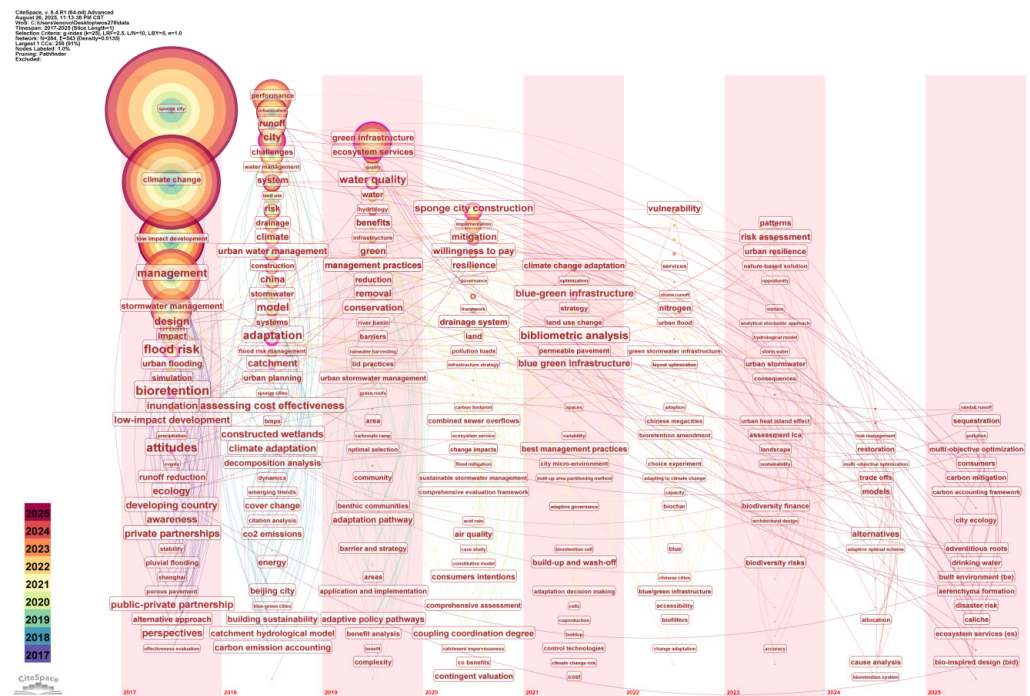


Figure 2. Keyword co-occurrence analysis for “sponge city”.

Co-occurrence analysis and time slice processing of keywords from 61 literature sources were conducted using CiteSpace, and core cluster themes were identified (Figure 2). Nodes such as “sponge city”, “climate change”, and “low impact development” show high centrality and act as hubs that link different research areas. Based on clustering outcomes, research themes can be divided into four dimensions. The technical dimension includes “stormwater modelling”, “pluvial flooding”, and “urban rainfall runoff”, which address flood simulation and engineering interventions. The environmental dimension includes “green infrastructure”, “permeable pavement”, and “rainwater garden”, which describe ecological facilities and runoff control. The institutional dimension includes “policy implementation”, “governance”, and “PPP”, which highlight policy drivers and funding mechanisms. The social dimension includes “public perception”, “willingness to pay”, and “community resilience”, which show the role of public awareness and engagement. These clusters support the dimensional classification of the framework and give it scientific

rigour and representativeness. To test the validity of the framework, the 61 literature entries were grouped into the four dimensions and supplemented with case study evidence. In the technical dimension, studies using the SWMM model quantified the runoff reduction in Wuhan's sponge city measures [5], which corresponds to the keyword "stormwater modelling." In the environmental dimension, practices in Yanjin City showed that ecological revetments and permeable paving improve water quality [7], which validates the role of "green infrastructure." In the institutional dimension, funding gaps were found to be a major obstacle, and the keywords "PPP" and "funding gap" confirm the generality of this challenge [14]. In the social dimension, surveys revealed that residents have limited willingness to pay, and the keyword "public perception" points to the importance of societal factors [5]. The combination of keyword clustering and the literature content shows that the framework captures the full research scope and reveals interactions across dimensions. Technologies depend on institutional support, and public perceptions affect policy effectiveness.

The application of this framework appears in three main aspects. The first is that it gives clear guidance for systematic reviews and reduces the fragmentation found in traditional reviews. For example, in analysing the impact of sponge cities on property values, different perspectives can be considered, such as disaster mitigation benefits, green space appreciation, and resident perceptions. The second is that it helps to identify research gaps by showing where current studies are weak. For example, the low co-occurrence of keywords across basin, city, and community scales (Figure 2) points to under-researched areas, and the limited presence of keywords such as "smart water" shows that smart management needs more attention. The third is that it provides policy and practice references by offering decision-makers multidimensional intervention strategies. For example, sponge city development requires both stronger financing systems and greater public acceptance, which relates to the societal dimension. This framework is built through scientific induction based on bibliometric results and confirmed by empirical studies. It creates a systematic structure for organising knowledge on sponge city research and builds a foundation for practical guidance.

2.2. Methods

To clearly reveal the research hotspots and evolutionary trends in China's sponge city policy and urban flood management field, this paper employs the CiteSpace 6.4.R1 tool for visualisation analysis. The core approach involves dividing the research timeline into multiple distinct time slices (Time Slicing), constructing keyword co-occurrence networks within each time slice, and identifying high-frequency or high-importance nodes. This study utilises the bibliometric analysis software CiteSpace to identify and evaluate the significance of keywords. The significance of keywords is calculated using the term frequency-inverse document frequency (TF-IDF), with the specific formula shown in the following equation.

$$TF-IDF(k, s) = \frac{f_{k,s}}{\sum f_{k',s}} \cdot \log \frac{N}{n_k} \quad (1)$$

In Formula (1), $f_{k,s}$ represents the keyword k in time slot s , which is the number of occurrences, N is the total number of time slots, and n_k is the number of time slots containing the keyword.

The specific calculation formula for the time position of the keyword is as shown in Formula (2):

$$X_k = X_0 + (FirstYear_k - StartYear) \cdot \Delta x \quad (2)$$

In Formula (2), Δx is the time slot interval.

The bridge role of keywords in the network is measured by betweenness centrality (BC), and the calculation formula is as shown in Formula (3):

$$C_B(k) = \sum_{s \neq k \neq t} \frac{\sigma_{st}(k)}{\sigma_{st}} \quad (3)$$

In Formula (3), σ_{st} is the number of shortest paths between nodes s and t , and $\sigma_{st}(i)$ is the number of paths passing through node i . Nodes with high (≥ 0.1) values are considered turning points.

Before formally commencing the analysis, we organised and standardised various types of information, including authors, institutions, and keywords, from the 61 target documents (Figure 3). This was conducted to reduce analysis bias caused by differences in keyword variations or abbreviations. Subsequently, using CiteSpace's "keyword co-occurrence" and "time slice" functions, we generated a keyword temporal association map, extracted high-frequency keywords, and combined them with cluster analysis to obtain corresponding labels, thereby identifying major research hotspots and thematic evolution paths. Based on this, time-feature analysis was employed to visualise the emergence and decline trajectories of different research themes from 2017 to 2024, thereby revealing the temporal shifts in policy priorities and research focuses. This was combined with the indicator systems and methods developed in studies on flood resilience, the benefits of green infrastructure, and economic assessments to further classify and name the hotspot clusters [12,19]. Based on the visualisation analysis results, a qualitative inductive method was employed to analyse the policy and technological contexts of various themes. By comparing research outcomes across different years and regions, the study examined the evolving characteristics of sponge city policies in terms of implementation mechanisms, governance models, and public perception. This approach ensures the quantitative objectivity of the analysis while enhancing the depth of interpretation regarding policy contexts [16].

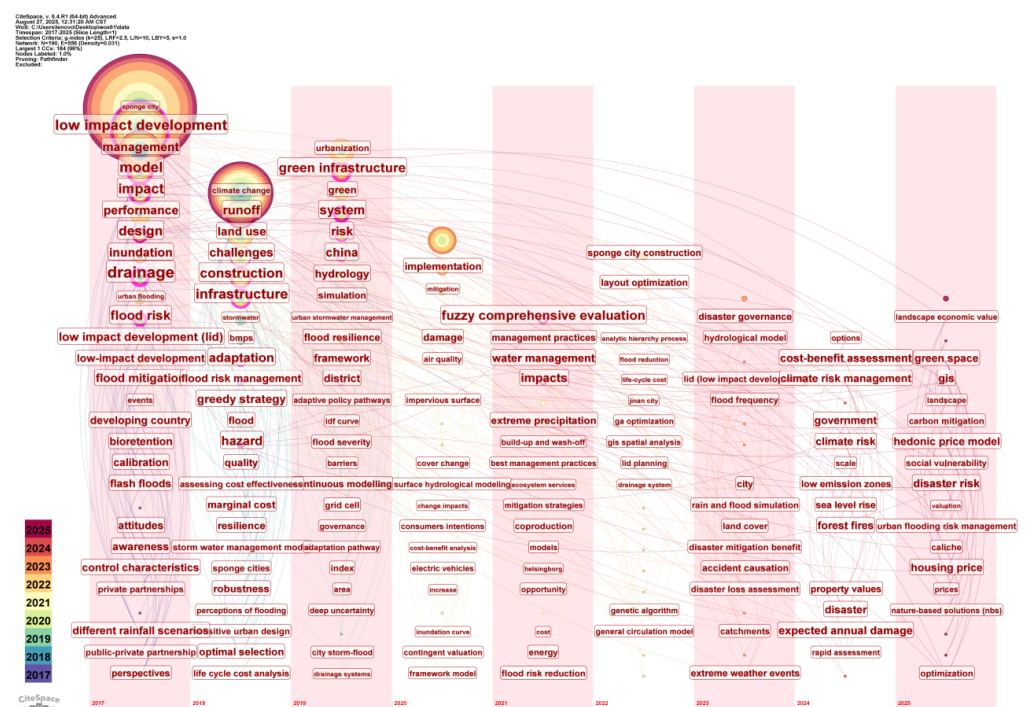


Figure 3. China's sponge city policy and urban flood management themes.

2.3. Research Framework

Based on the visualisation results and thematic cluster analysis of CiteSpace, this paper establishes a comprehensive analytical framework encompassing multiple dimensions such as technology, environment, institutions, and society. The framework aims to systematically present the knowledge structure and evolutionary trajectory of China's sponge city policies and urban flood management research. The study begins with urban flood risk and resilience assessment, employing methods such as model simulation, risk zoning, and indicator system construction to reveal the differences among cities in responding to extreme rainfall events and identify optimisation directions [14]. The integrated analytical framework in this study covers four dimensions: technical, environmental, institutional, and social. It is based on the inductive analysis of co-occurrence clustering results for key terms in the literature (Figure 2). The analysis of 61 selected papers with CiteSpace shows that high-frequency keywords form four clusters. The technical dimension includes terms such as "stormwater modelling" and "pluvial flooding", which point to flood simulation and engineering measures. The environmental dimension focuses on "green infrastructure" and "permeable pavement", which relate to ecological facilities and runoff control. The institutional dimension covers "policy implementation", "governance", and "PPP", which reflect policy drivers and funding mechanisms. The social dimension includes "public perception" and "willingness to pay", which highlight awareness and engagement. This clustering is data-driven, so the classification of dimensions is not set in advance but reflects the actual knowledge structure of the field.

This four-dimensional framework fits the research goals and shows the many impact mechanisms and implementation paths of sponge city policies (Figure 4). The technical dimension focuses on model simulation and engineering effects, which help assess physical outcomes and improve engineering practices. The environmental dimension highlights the ecological benefits of green infrastructure and relates to the main policy goal of improving urban water environments and resilience. The institutional dimension focuses on policy implementation and governance models to show the driving forces and barriers during rollout. The social dimension looks at public acceptance and willingness to pay, which gives insight into social approval and the basis for long-term operation. These four dimensions together form a systemic view that links nature, technology, management, and people. This matches the main goal of the study, which is to map policy impacts in a structured way, go beyond limits of single technical or environmental indicators, and give a basis for improving policy. Based on this, the study analyses the transformation of urban governance under national strategic guidance, examines the mechanisms by which policy drivers, financial investments and multi-stakeholder collaboration influence construction outcomes [15], and explores the interactive relationship between institutional evolution and public participation. The research focuses on the empirical effectiveness of low-impact development measures in reducing runoff and improving water quality [8]. Combining multi-objective optimisation methods, the comprehensive performance and applicability of different technical solutions are evaluated. Additionally, green infrastructure integration and cost-benefit analysis are incorporated into the framework to analyse the synergistic mechanisms of engineering economics, ecological functions, and social benefits from a life-cycle perspective [13]. This framework illustrates the transformation of sponge city research from single-engineering flood control towards comprehensive governance, smart management, and sustainable development, and lays the analytical foundation for subsequent results and discussions, achieving effective integration from fragmented outcomes to systemic understanding [5,7,11].

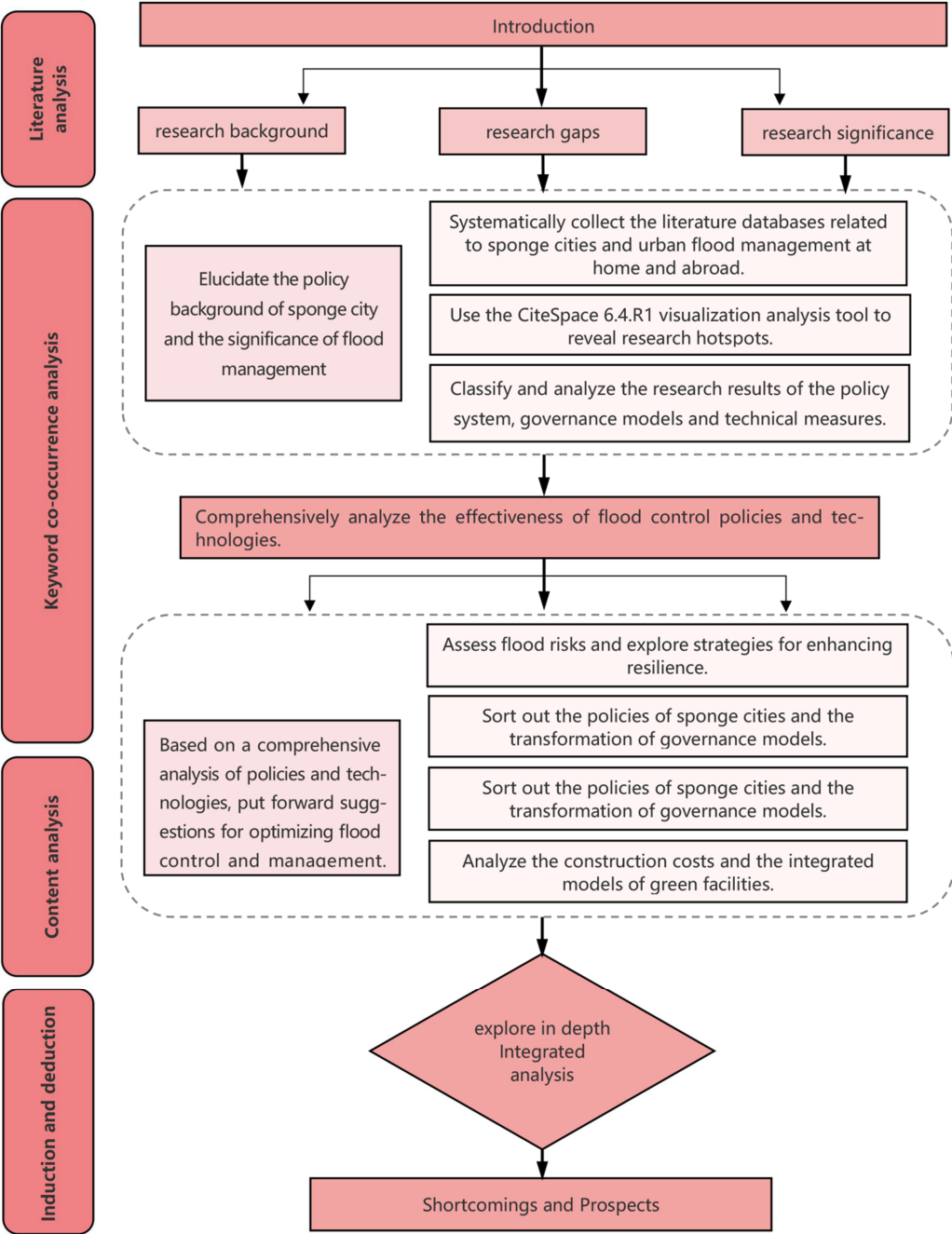


Figure 4. Article framework.

3. Results

Among the 61 literature sources reviewed, there are 38 journal papers, 9 conference papers, 5 monograph chapters, and 5 policy reports and technical papers, which were published in the time period from 2017 to 2024. With the deepening of the concept of sustainable urban development and the continuous promotion of climate resilience policies, sponge cities are gradually becoming a key direction for urban flood management and green infrastructure construction in China. Starting from 2019, the relevant research shows a gradual growth trend and reaches a peak in 2021 and 2023, with literature topics including urban flood management, low-impact development (LID) technology, policy evolution and cost assessment and other areas, and research methods such as model simulation, scenario analysis, case study, and policy assessment, geographically, China is the core of the research. In terms of geographical distribution, China is the core of the research, with 21 papers

focusing on pilot cities such as Beijing, Shenzhen, and Wuhan, which reflects the role of national strategies in guiding research topics.

Combined with CiteSpace keyword clustering analysis and literature classification, the current hotspots of sponge city research can be summarised into four categories: Firstly, urban flood risk and resilience assessment, with the help of model simulation and an indicator system to identify the flood-prone areas, in order to put forward the ways to improve the resilience. Secondly, the national strategy and urban governance transformation, focusing on the policy-driven change in governance system, and analysing the interaction between the government. The second is national strategy and urban governance transformation, which focuses on policy-driven changes in governance systems and analyses the interactions between government, the market, and the public. The third is LID measures and runoff control, which evaluates the effectiveness of green infrastructures in reducing runoff and improving water quality, and introduces multi-objective optimisation and modelling methods. The final one is cost assessment and the integration of green infrastructures, which explores the economics of system integration, life-cycle costs, and multifunctional synergy benefits. Together, these four directions constitute the core framework of current sponge city research.

In the process of literature screening and thematic categorisation, we aimed for comprehensiveness and objectivity, but some bias may still exist. During screening, we removed highly technical studies without policy context and literature not based on Chinese cases. This kept the focus on sponge cities and flood management in the Chinese policy setting. Manual screening gives flexibility, but subjective judgement is hard to avoid. Standards may differ when judging policy relevance. Co-occurrence keyword clustering was carried out with Cite Space, and the results gave four dimensions: technical, environmental, institutional, and social. We classified the literature under these dimensions. The framework is data-driven and has objectivity, but the naming of clusters and the division of dimensions depend on how researchers interpret keywords. This is influenced by disciplinary background and knowledge. This study did not include systematic searches of grey literature or Chinese databases. Some practice-oriented or policy evaluation work may therefore be missing, which limits the scope of coverage. Future research can improve retrieval strategies by using independent screening by multiple people and by expanding data sources to strengthen both coverage and reliability.

From the perspective of time evolution (Figure 5), the research hotspot gradually changed from “flood risk” to “integrated risk management” and “resilient city construction”. Between 2017 and 2019, the research focuses on “flood risk” and “impact”, which mainly focuses on the causes of flooding, the scope of impact, and measures for management; from 2020 onwards, “sponge city” becomes the key term for “resilient city”. From 2020 onwards, “sponge city” becomes the central theme, and the research horizon is extended to include the process of urbanisation, comprehensive risk assessment, and mitigation strategies. From 2021 to 2022, water management and climate change will be the focus, with an emphasis on extreme precipitation events, infrastructure development, and integration with smart cities. In 2023–2024, the focus shifts to “urban resilience” and “disaster governance”, highlighting resilience capacity building and risk management optimisation. This reflects the trend of moving away from a single flood prevention goal towards integrated governance and intelligence.

Echoing the evolutionary trend in Figure 5, Figure 6 shows that research themes have gradually evolved from the core of “sponge city” and “climate change” into a diversified pattern, with the focus on “urbanisation” and “climate change” during the period from 2017 to 2019. In the period from 2017 to 2019, the focus is on “urbanisation” and “precipitation”, exploring the impact of urbanisation on extreme rainfall, while after 2020, “low

impact development” and “stormwater management” become the main themes. After 2020, “Low Impact Development” and “Stormwater Management” become central points, highlighting the significance of low-impact development techniques and stormwater system management. Then, 2021–2022 sees a shift in focus to “Extreme Precipitation” and “Risk Assessment”. In 2023–2024, keywords such as “community resilience” and “nature-based solutions” appear, and the research is expanding from engineering to social resilience and nature-based integrated governance.

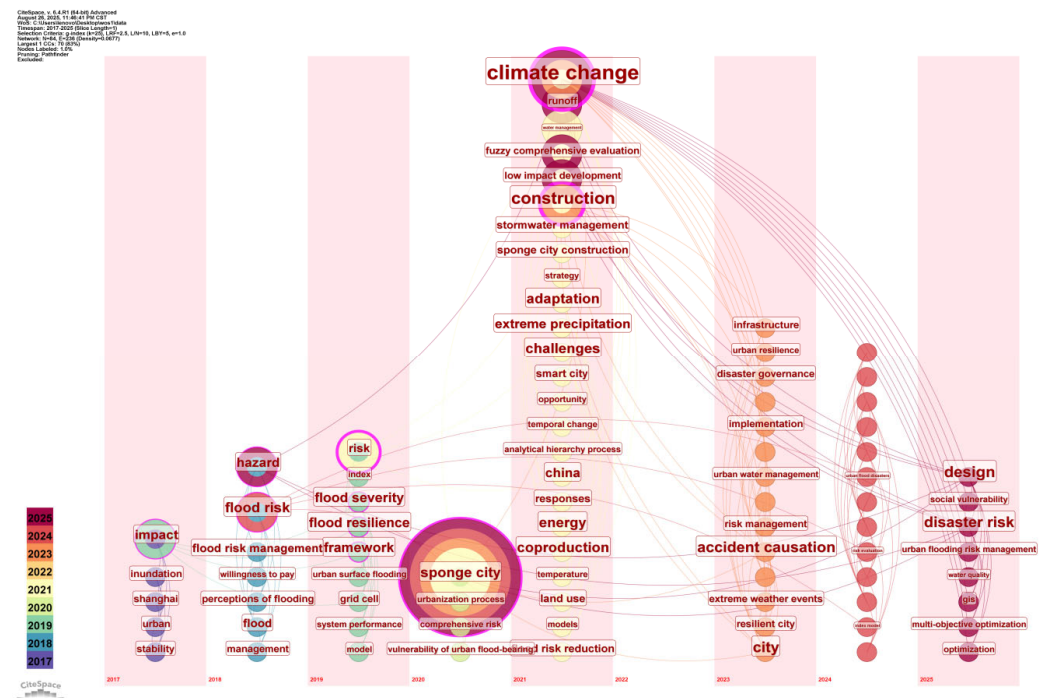


Figure 5. Urban flood risk and resilience research.

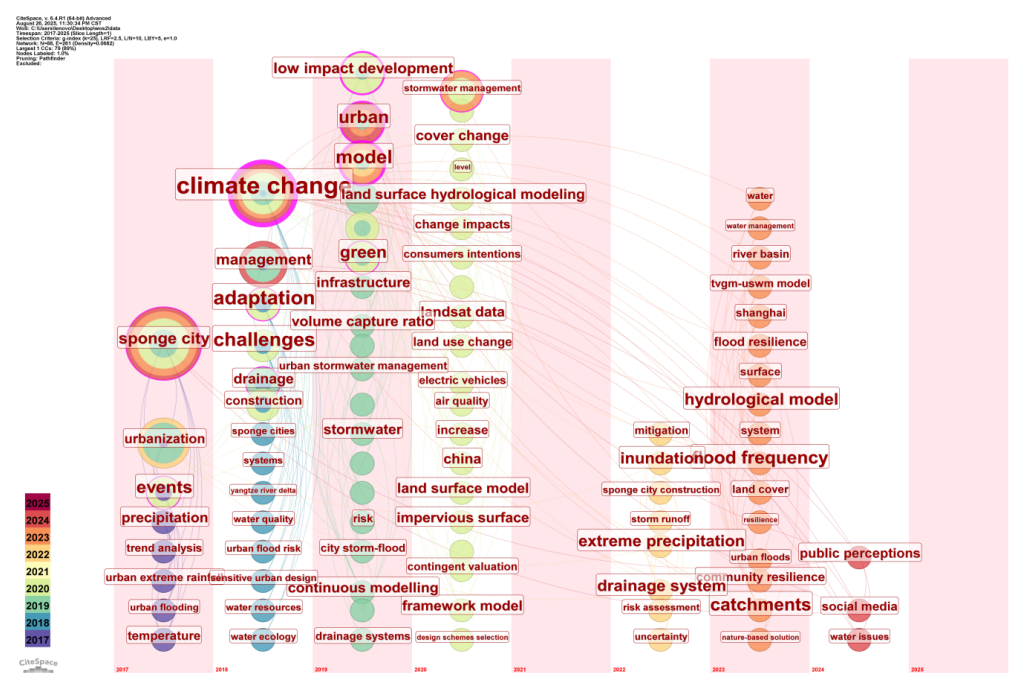


Figure 6. National strategy and urban governance transformation.

In-depth analysis shows that the research hotspots in the field of low-impact development and runoff control are expanding from “low-impact development” to “sponge city”, “stormwater management”, and other core areas. Between 2017 and 2019, research focused on the “performance”, “design”, and “runoff reduction” aspects of low-impact development. From 2020 onwards, “sponge cities” and “climate change” are at the centre of research on adaptation measures such as rainwater harvesting, permeable paving, watershed management, etc. From 2021 to 2022, “optimisation”, “cost-effectiveness” are at the centre of research. In 2021 to 2022, themes such as “optimisation”, “cost-benefit analysis”, and “resilient communities” emerge, focusing on system optimisation, economics, and community resilience enhancement. By 2023 and 2024, “mitigation benefits” and “flood risk” have been added, reflecting the fact that LID and runoff control techniques are being closely integrated with risk management and mitigation benefits assessment (Figure 7).

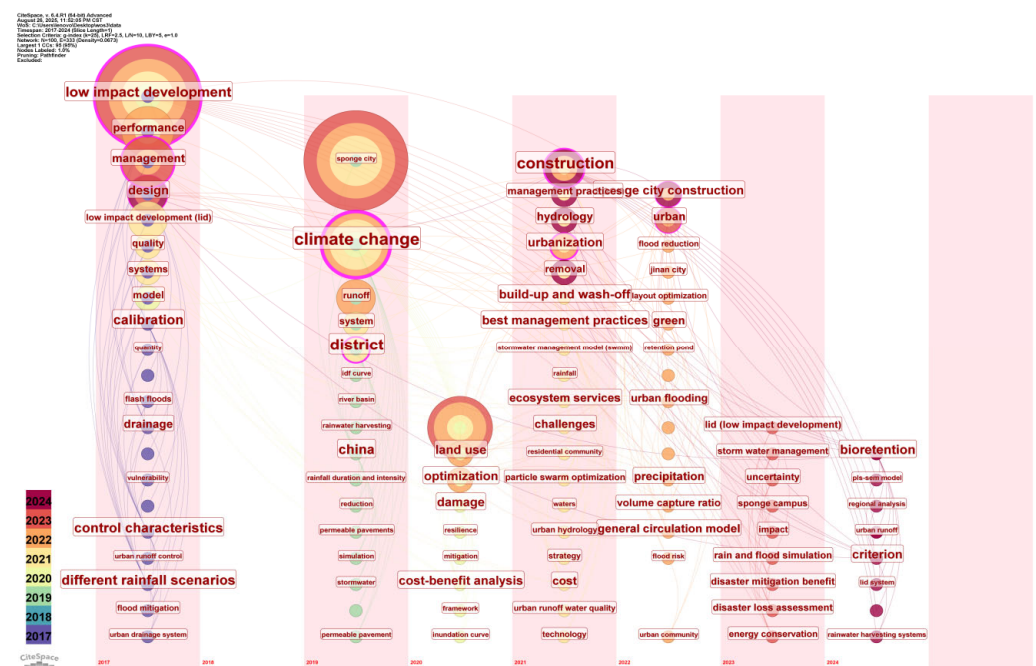


Figure 7. LID measures and runoff control techniques.

Finally, it shows that the research theme has been extended from “sponge city” and “low impact development” to “green infrastructure” and “cost-benefit assessment” (Figure 7). Between 2017 and 2019, the research is mainly centred on “urban flooding” and its “impact assessment”. Between 2017 and 2019, research will focus on “urban flooding” and its “management”, and after 2020, the focus will shift to “green infrastructure”, “performance evaluation”, and “flood risk management”, with an emphasis on performance evaluation of green infrastructure and policy pathways. From 2021 to 2022, the focus will be on “implementation” and “urban resilience” in 2021–2022, and “cost-benefit assessment” and “multi-objective optimisation” in 2023–2024, with an emphasis on “green infrastructure”, “performance evaluation”, and “flood risk management” (Figure 8), indicating that the research has moved from engineering practice and policy discussion to economic analysis and assessment and comprehensive system optimisation, and promoted the integration of green infrastructure and sponge city concepts.

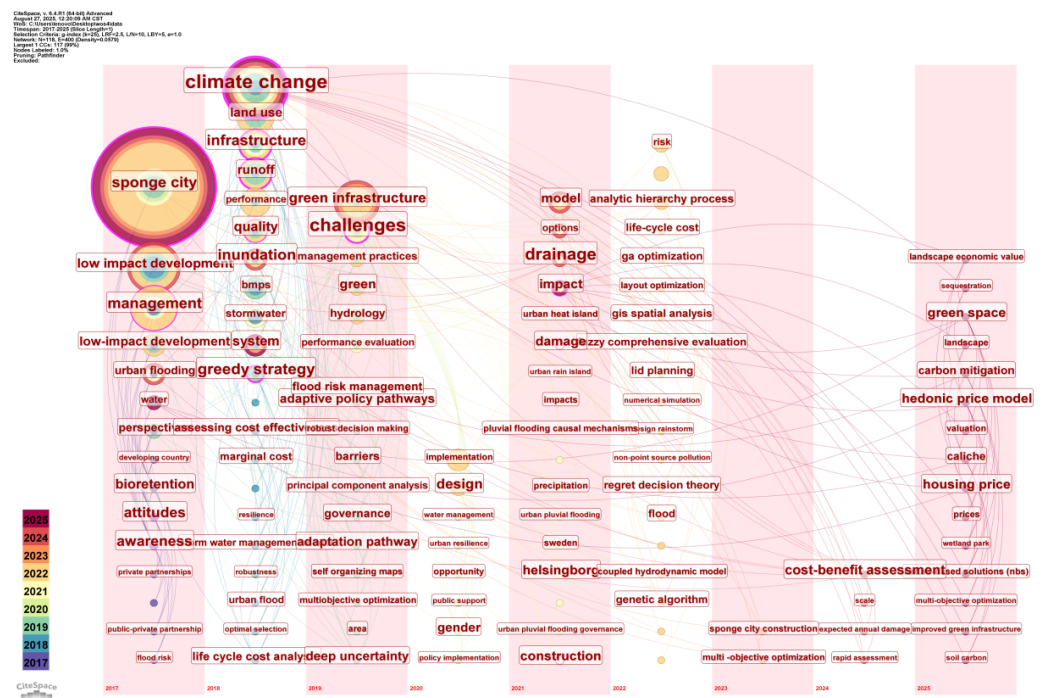


Figure 8. Cost evaluation and green infrastructure integration.

The four CiteSpace keyword clustering diagrams systematically present the evolution of sponge city research. In the early stage, the research focuses on flood risk control and engineering technical means and gradually evolves into a multidimensional system that integrates policy governance, low-impact development, green infrastructure integration, and economic assessment over time. In 2019, research focuses on risk identification and technology application. After 2020, the research scope expands to comprehensive governance and intelligent management, and by 2023 and 2024, a synergistic development of engineering, ecology, and society is presented. The thematic evolution indicates that the research is shifting from a single flood control objective towards multi-objective synergy, interdisciplinary integration, and sustainable development, and that sponge city research has moved from the conceptual exploratory stage to a new stage of system integration and practice deepening. Sponge city research has evolved from a single technical path to a systemic governance issue that intersects policy, ecology, engineering, and social dimensions. Future research needs to explore cross-scale synergistic mechanisms, carry out comparative analysis of regional adaptations, and develop and apply intelligent management tools to provide a more solid theoretical and practical foundation for improving urban water safety and achieving sustainable development.

The third part of this study reviews four core research directions on sponge city policies and flood management and builds a multi-layered framework. The framework covers technical implementation, systemic governance, local measures, and integrated solutions. Research on urban flood risk and resilience assesses flood hazards and response strategies under climate change and rapid urbanisation. It shows how sponge cities improve water absorption, lower flood risks, and strengthen resilience [5,15]. Research on national strategy and urban governance transformation examines how policy drives multi-level governance, central/local coordination, funding innovation, and public participation. It shows the role of sponge cities as a national strategy that supports urban modernisation and ecological transition [10,16]. Research on low-impact development (LID) and runoff control studies the performance of LID in reducing runoff, improving water quality, and controlling floods. It also shows the limits of these techniques in extreme weather and the need to combine

them with grey infrastructure [20]. Research on cost assessment and green infrastructure integration looks at life-cycle cost, multi-objective optimisation, and sharing experience across regions. The goal is to balance ecological benefits and economic feasibility and to combine green and grey systems more effectively [21,22]. These four directions support one another and show how sponge city research has moved from single flood prevention goals to multi-objective coordination, interdisciplinary integration, and sustainable development.

4. Discussion

4.1. Research on Urban Flood Risk and Resilience

The effect of climate change and rapid urbanisation, both of which are superimposed on each other, has made the problem of urban flooding a key challenge that needs to be confronted globally in general. Shiyong Zhang et al. illustrate in their 2018 study that with the rapid expansion of cities, the lakes and rivers that existed have gradually been replaced by artificial structures, and the natural water absorption capacity of cities has decreased dramatically, leading to a drainage system that is difficult to cope with sudden rainstorms. Take Wuhan as an example, the city is located at the confluence of the Yangtze River and the Han River, and floods have occurred frequently in history; in 2016, Wuhan suffered from exceptionally heavy rainfall, with an economic loss of more than CNY 87 billion [5,15]. Research shows that sponge cities can effectively improve the city's ability to absorb and manage rainfall and reduce the risk of urban flood risk [5,15]. These events highlight the urgent need for innovative solutions to urban water management, and sponge cities are one of the solutions to this challenge. The Chinese government launched a pilot sponge city project in 2013 to improve the city's ability to absorb, store and store water through ecological stormwater management, which can fundamentally mitigate the risk of flooding caused by urbanisation, while at the same time improving water quality and restoring the natural water cycle [7,8,14]. Wuhan, as one of the first pilot cities, has introduced ecological infrastructures, such as green spaces and permeable pavements, so that rainwater can be absorbed and utilised locally to improve the city's ability to withstand torrential rains [6,19].

In recent years, many cities have made use of sponge city construction to enhance urban resilience to flooding by introducing green infrastructure, such as permeable paving, green roofs, and rain gardens, to simulate the natural process of collecting, storing, and purifying rainwater, to reduce surface runoff at source and to reduce the pressure on the drainage system [5,17]. According to Shiyong Zhang et al. (2018), after the implementation of sponge city measures in Wuhan, runoff volume was reduced, the rainwater infiltration rate was enhanced, and flood resilience was improved [5] pointed out in their article that this approach focuses on the reduction in the risk of urban floods while also taking into account water quality improvement and groundwater recharge [11]. The study also found that the benefits of sponge city construction are not only in terms of flood prevention, but also in terms of economic and social development, for example, real estate prices have risen after the implementation of sponge measures in some areas of Wuhan, reflecting the positive effect of flood resilience and livability enhancement on the city's attractiveness [5]. This double benefit of environment and economy adds extra impetus to policy promotion. Even so, sponge cities still face multiple challenges in the implementation process. The first one is the problem of funding: Hong Lv et al. (2020) showed in their study that despite some financial support from the government, in many small- and medium-sized cities, the gap of the construction funding is still large, which leads to the slow progress of the project [13]. Secondly, the implementation of sponge cities requires the renovation of existing urban infrastructure, which is particularly difficult for old urban areas; Zhang Xin et al. (2024) found in their study that the drainage systems in many old urban areas are already have difficulty meeting the new stormwater management demands, and spatial

constraints make it difficult to carry out large-scale green infrastructure construction [14]. Thirdly, insufficient public awareness is also a major challenge in the implementation of sponge cities. According to a survey by Shiyang Zhang [5], many residents have low awareness of sponge cities and limited willingness to pay for them, which increases the difficulty of policy implementation [5].

In response to the situation mentioned above, some cities have tried to explore innovative ways of technology and management, for example, Shenzhen has been able to conduct real-time monitoring of rainwater flow, groundwater level, and other data with the help of smart water management system to support early warning and emergency response [11]. In addition, the effective promotion of sponge city construction relies on the synergy of multiple parties, which involves the policy support and regulation of the government, the technical and financial investment of enterprises, and the active participation of the public. Zhang Xin et al. (2024) showed in their study that the coordination of all parties not only facilitates the mobilisation of funds, but also improves the public's awareness of flooding risk, which in turn enhances the ability of the whole city to cope with the disaster [14].

In general, the concept of a sponge city has been proven in practice in many pilot cities in China, through the combination of eco-infrastructure and intelligent management, which improves the city's flood prevention capacity and water environment quality; however, to achieve a wider range of promotion and long-term sustainable operation, it is still necessary to deal with the lack of funds, the difficulty of technological modification, the lack of public participation, and other problems, so that in the future, we can innovate the financing mechanism, improve policy incentives, and promote the participation of multiple social actors in order to enhance the comprehensive benefits of sponge cities in coping with flood risks and improving urban resilience [6,11,12,15].

4.2. Research on National Strategy and Urban Governance Transformation

The social, economic, and environmental impacts of urban flooding are increasing as climate change becomes more severe and urbanisation continues. Rapid urbanisation has led to a significant increase in impervious surfaces, which disrupts the hydrological cycle and also increases runoff during heavy rainfalls, which increases the frequency and intensity of flooding [23,24]. To address this challenge, the Chinese government initiated a sponge city construction project in 2014 to improve the resilience of cities against disasters as well as their flood coping capacity with the help of ecological urban water management [1,25]. As pointed out by Jinjin Hou et al., 2022, this concept focuses on the use of permeable infrastructure to mimic natural hydrological processes to absorb, store, infiltrate, and purify rainwater to mitigate the threat of flooding [1,26]. Sponge cities, as a key strategy to address urban flooding and water scarcity at the national level, centred on the need to improve urban resilience, water quality, water recycling, and urban ecology through low-impact development measures [10]. Since 2014, the Chinese government has implemented pilot projects of sponge city construction, selecting 30 cities to carry out demonstration work, exploring different conditions and accumulating relevant experience for national promotion. According to the Technical Guidelines for Sponge City Construction, sponge cities set the goals of controlling rainwater runoff and pollution and improving the utilisation rate of rainwater resources; their supporting measures include rain gardens, permeable paving, green roofs, etc., so as to enhance the natural environment of the city (Xiang et al., 2019). Zhengzhao Li et al. proposed in 2018 that the government encourages localities and enterprises to participate in the construction of sponge cities with the help of financial subsidies, tax incentives, etc [3]. Although sponge city projects have developed to some extent in China, project promotion faces challenges in many aspects, including the huge amount of capital required for sponge city construction, which has led

to a shortage of funds in many local governments, according to Yang Wang et al. (2020), whose public–private partnership (PPP) model was introduced in some areas to attract social capital to alleviate the funding gap [27]. Sponge city construction is technically difficult, in terms of technology, to deal with the integration of ecological measures and traditional infrastructure, and there are differences in climate, topography, and economic conditions in different regions, which requires the development of a programme tailored to the local conditions. In humid areas, the focus is on rainwater infiltration and pollution control, and in arid areas, rainwater harvesting and storage a priority [28,29]. The central and local governments have been strengthening their policy requirements to integrate stormwater management into urban planning and construction norms, just as the government has stipulated that stormwater management should be taken into account in urban planning and construction and incorporated into urban development planning [3]. Public support is crucial for the sustainable implementation of sponge city projects, as sponge city construction involves many public infrastructures, and the awareness and level of participation by residents will have a direct impact on the sustainability of sponge city projects. The awareness and participation of residents will directly affect the effectiveness of the project. For example, according to a study by Guangtao Fu et al. (2022), there is a strong correlation between the public's acceptance of sponge cities and their perception of urban flood risk [16]. In order to enhance public participation, the government should strengthen publicity and education and use community activities and popularisation of science and technology to raise the residents' awareness of environmental protection and disaster prevention and to make the residents understand their own role in improving the urban environment and mitigating disasters [9,27]. In fact, the construction of sponge cities is not only an engineering update, but also involves a change in the mode of urban governance. Traditional urban water management mainly relies on pipeline systems and hardware facilities, but sponge cities advocate the use of natural ecological processes to achieve rainwater storage and utilisation, along with the integration of ecological concepts into urban planning [18,27]. This transformation requires the participation of the government, enterprises, and citizens to form a multi-party collaborative governance model. As the concept of sponge city continues to be promoted, more and more cities are placing ecological protection and environmental construction in the same critical position as economic development. According to Changmei Liang et al. (2020), this governance shift can enhance the sustainability of cities and also improve their resilience in the face of extreme climate events [18].

Sponge cities are a key strategy to cope with urban flooding, environmental pollution, and water shortage, and have achieved initial results in many places. Their value lies in alleviating floods, improving water quality, and promoting the transformation of urban governance to be ecological and sustainable. But in the process of promoting the sponge city, the lack of funds, technology adaptation, and the lack of social participation are still constraints, necessitating future of continuous policy support, innovative financing mechanisms, and promotion of urban resilience in the face of extreme climate events. In the future, on the basis of continuous policy support, we need to innovate financing mechanisms, promote technology integration and localised application, improve public participation, and realise the leap from pilot exploration to national popularisation, so that sponge cities can become a key way to cope with climate change and enhance urban resilience [29,30].

4.3. LID Measures and Runoff Control Technologies

Against the backdrop of increasing global climate change, frequent urban storm events and rapid urbanisation disrupting natural hydrological processes, traditional drainage sys-

tems are increasing difficulty coping with sudden and heavy precipitation. As the hardened areas of cities continue to expand, the permeability of the ground surface decreases, the rate of rainwater catchment increases, and urban flooding and water pollution problems become increasingly prominent [31,32]. To address these challenges, low-impact development, or LID, has been promoted in many cities in recent years. The core concept is to simulate natural hydrological processes and use distributed green infrastructure to collect, detain, infiltrate, and purify rainwater to mitigate flooding, improve the aquatic environment, and enhance the resilience of urban ecosystems [32,33]. Common LID techniques include permeable paving, bioretention ponds, green roofs, vegetated swales, etc., which reduce the total volume and peak flow of runoff and reduce the risk of urban flooding by inducing the infiltration of rainwater [34,35]. LID mitigates urban runoff and controls rainwater, reducing the amount of surface runoff and the peak flow rate, thus preventing urban flooding; LID measures mitigate urban runoff and control rainwater, reducing the volume and peak flow rate of surface runoff and preventing urban flooding. The effectiveness of LID measures has been widely studied in different urban environments. According to a 2017 study by Qinghua Luan et al., LID measures such as permeable paving and planted root basins reduced runoff significantly during small precipitation events in the Xiangshan area of Beijing, China [36]. In a study in Fuzhou City, Fujian Province, Zheng Peng et al. proposed in 2019 that permeable paving and planted swales are viewed as the most effective LID techniques to reduce runoff during short-period precipitation events [37], like bioretention ponds and green roofs, which can effectively manage stormwater runoff and reduce the pressure on municipal drainage systems to a greater extent [38]. However, the effectiveness of these systems is also affected by a variety of factors such as soil permeability, precipitation characteristics, and urban infrastructure. According to a study conducted by Yiming Fei et al. in 2023, there is a synergistic effect between LID and sponge city concepts, which is very prominent in improving stormwater management capacity [35,39], put forward the view that sponge city focuses on enhancing urban rainfall storage capacity with the help of the natural hydrological cycle, while LID can provide a decentralised management approach to effectively reduce the runoff volume and delay the arrival of flood peaks. In the case of Jinan, for example, when LID is combined with a conventional drainage system, peak flows as well as pollutant concentrations can be reduced under a wide range of rainfall conditions [35,39]. Combining LID measures with other sponge city strategies such as drainage upgrades and flood management infrastructure can improve the overall effectiveness of flood mitigation efforts. Tao Cheng et al. 2022 noted that although LID measures alone can be effective in controlling runoff during frequent small precipitation events, their impacts become smaller under extreme precipitation scenarios [20]. This approach emphasises the need for site-specific planning, i.e., the combination of green and grey infrastructure is tailored to specific hydrological conditions. In addition to flood prevention, LID can also enhance urban ecological functions. Hu et al., 2019, pointed out that LID increases urban green space and permeable surfaces, which can be used for groundwater recharge as well as surface runoff reduction, and realises the “source control” and “process control” of stormwater. This ecological benefit is also potentially valuable for improving the urban heat island effect and enhancing biodiversity [40].

Although LID technology shows good potential for runoff control and flood mitigation, there are challenges in its practical application. The effectiveness of LID technology is strongly related to the intensity and frequency of precipitation, as well as geographic conditions [41]. In mountainous areas or low-lying areas, as mentioned in Huiyi Sun et al. in 2022, the effectiveness of LID facilities may be limited by topography and land use, and their implementation may be complicated [39]. Jiansheng Wu et al. in 2020 illustrated that the cost of implementing LID technology and maintenance problems are the obstacles to

its wide diffusion [42]. Although LID facilities can effectively control runoff and improve water quality, their construction is not as effective as they could be in improving water quality and their construction costs are high. In urban areas where land is scarce, Wenyu Yang et al. 2022 suggest that the effectiveness of LID is strongly influenced by climate change, and that extreme precipitation events may significantly reduce the effectiveness of LID in controlling floods [43]. The planning and implementation of LID technology requires a comprehensive consideration of the city's infrastructure, land use, and environmental conditions. For example, Yiming Fei et al. in 2023 pointed out how to allocate the area of green space and permeable facilities to maximise the hydrological and ecological benefits of LID technology when it is implemented on campuses is one of the focuses of the current research [35].

LID measures have certain advantages in runoff control and flood mitigation, especially for low-frequency, small- and medium-sized precipitation events, and can effectively reduce runoff and improve water quality. However, their effectiveness and economic feasibility in dealing with extreme climate and diverse urban environments need to be optimised, so future research needs to focus on the optimisation of the layout of the facilities, the improvement of their adaptability, and the control of their costs, and at the same time strengthen the integration with the overall strategy of sponge cities. Future research should focus on the optimisation of facility layout, adaptation, and cost control, and strengthen the integration with the overall sponge city strategy, so as to realise multi-objective and cross-scale integrated water security [41].

4.4. Cost Assessment and Green Infrastructure Integration

As climate change and urbanisation continue to accelerate, sponge city construction should not only focus on environmental sustainability but also reach more refined optimisation in terms of cost-effectiveness and green infrastructure integration. Green infrastructure, also known as GI, is a key component of sponge cities, which can effectively reduce surface runoff, improve water quality, and reduce the risk of urban flooding; however, in urban planning practice, determining how to scientifically assess its cost and how to integrate it into the sponge city strategy are crucial for successful implementation [44,45].

Green infrastructure, as an efficient hydrological management approach, has shown some advantages in flood mitigation and water quality improvement, but as pointed out by Yichen Yao et al. in 2022, it has relatively high implementation and maintenance costs, which limits its wider dissemination [46]. Therefore, cost assessment becomes a central point for the sustainable development of green infrastructure. Infrastructure sustainability, which can assist decision-makers in weighing the initial investment against the long-term benefits in the face of limited financial resources, is also essential. Life-cycle cost (LCC) analysis is a widely used approach to assess the costs of construction, operation, and maintenance to provide a basis for the economic viability of a project [22,47]. Although LCC analysis can reflect long-term economic benefits, there is still the problem of how to comprehensively reflect the impacts of climate change and urbanisation-induced flooding in practical applications [48]. Moreover, the hydrological effects of green infrastructure vary across rainfall characteristics. Dongqing Zhang et al. (2022) found that the runoff reduction effect of green infrastructure is greater under short-term heavy rainfall conditions, which is significant for mitigating the risk of urban flooding [49]; the design and deployment process should be optimised for different climatic and rainfall characteristics to achieve the best cost-effectiveness.

Integration and optimisation play a key role in improving the overall effectiveness of green infrastructure. Multi-objective optimisation methods, also known as MOOA, are mostly used to comprehensively assess the environmental and economic impacts of

different scenarios in order to find a balance between cost and ecological objectives. Yifei Zhu et al. (2023) state that the spatial layout and type of green infrastructure have a decisive impact on its performance in terms of flood mitigation and water quality improvement [50]. However, the influence of the resolution of spatial discretisation is often neglected in the optimisation of LID facility layout. Zhaoli Wang et al. in 2022 showed that different resolutions can lead to differences in the hydrological effects simulated by the model, and that the SWMM model under high-resolution conditions can more accurately reflect runoff processes and the effects of the facility, providing a more reliable basis for the optimisation of the facility [51]. The optimisation of green infrastructure does not only involve the selection of a single facility, but also has to consider the synergies between different facilities. Bing Li et al. in 2019 noted that the optimisation of facility combinations can reduce costs while enhancing benefits [45]. found that the combination of green roofs and permeable paving tends to outperform single measures, being more advantageous in terms of economics and hydrological performance [52]. With the development of optimisation algorithms, the combination of multi-objective optimisation and simulation optimisation methods, such as NSGA-II, significantly improves the efficiency and accuracy of layout optimisation, especially when funds are limited, and is able to reduce the construction cost while guaranteeing water quality and runoff reduction effects [53]. These methods can reduce the overall construction cost of green infrastructure while guaranteeing water quality and runoff reduction effects, and provide feasible solutions when budgets are limited. Green infrastructure promotion is not just a single city's task: cross-regional cooperation and experience sharing are critical to optimise green infrastructure design and implementation [54,55]. Different regions vary significantly in terms of climate, topography, land use, and level of urbanisation, and appropriate design and implementation strategies vary accordingly. Yutao Wang et al. in 2017 emphasised that by relying on cross-regional cooperation, cities are able to optimise their own construction solutions by learning from the successful experiences of other regions [56]. Public awareness and engagement directly affect the smooth promotion of these collaborations and access to financial support, and China's sponge city pilot projects provide valuable experience in the application of green infrastructure under different climatic conditions [48]. At the international level, there are differences in the paths of sponge city construction between China and Europe and America, with China focusing more on policy-driven and rapid construction, while Europe and America emphasise long-term sustainability and environmental benefits. Relying on strengthening international technical exchanges and cooperation, it can achieve complementary advantages in terms of funding, technology, and management, and promote more efficient and sustainable sponge city construction. Chao Mei et al. pointed out in 2018 that such experience sharing can enhance the applicability and promotion efficiency of green infrastructure in different regions [21].

Green infrastructure plays an irreplaceable role in sponge city construction; however, high cost and implementation complexity are still the main obstacles to its promotion, and the use of scientific life-cycle cost analysis and multi-objective optimisation methodology can ensure economic feasibility while achieving environmental goals [22,47]. The effective integration of green and grey infrastructures is a key way to improve the efficiency of construction. Cross-regional cooperation and international experience can reduce costs, improve efficiency, and respond to the differentiated needs of different regions [57,58]. Green infrastructure will continue to play a key role in water management in the context of climate change and urbanisation, and optimisation and integration strategies will need to take into account future uncertainties to ensure sustainability and affordability [59,60].

5. Conclusions

This study employed the CiteSpace visualisation analysis system to systematically examine the research trajectory, hot topics, and thematic clustering characteristics related to China's sponge city policies and urban flood management. The analysis revealed that research themes from 2017 to 2019 focused on flood risk identification and engineering measures, and gradually expanded to comprehensive management, low-impact development, and the integration of green infrastructure after 2020. By 2023–2024, the research landscape exhibited a trend toward the synergistic development of engineering, ecology, and society [7,8]. Co-occurrence analysis of keywords indicates that the popularity of core concepts such as “sponge city,” “climate change,” and “urban resilience” has continued to rise, reflecting that research has expanded from single flood prevention functions to multi-objective, multi-scale comprehensive resilience construction [15]. Time-series analysis highlights the key roles of policy direction, technological progress, and social attention in driving the evolution of research [13] (Figure 9). In response to the research questions raised earlier, this study addresses them as follows. Firstly, sponge cities, through measures encompassing infiltration, detention, storage, purification, utilisation and drainage, combined with grey and green infrastructure, can reduce runoff volume and flood peaks, improve water quality, enhance urban flood resilience, and deliver ecological and economic benefits. Second, key implementation challenges include insufficient funding, difficulties in retrofitting older areas, limited drainage system capacity, interdepartmental coordination gaps, and low public engagement and willingness to pay. The roles of PPP models and smart water management remain underutilised. Third, evaluation frameworks should encompass technical, environmental, institutional, and social dimensions, applicable at watershed, city, and community scales. Technically, it assesses runoff reduction and facility effectiveness; environmentally, it focuses on water quality and ecological services; institutionally, it examines policy implementation and funding sustainability; and socially, it addresses public awareness and community flood resilience. Methodologically, it combines life-cycle costing with multi-objective optimisation to select appropriate facilities and layouts within constrained budgets. Concurrently, it incorporates long-term monitoring and smart water management data to establish dynamic evaluation and policy adjustment mechanisms [61].

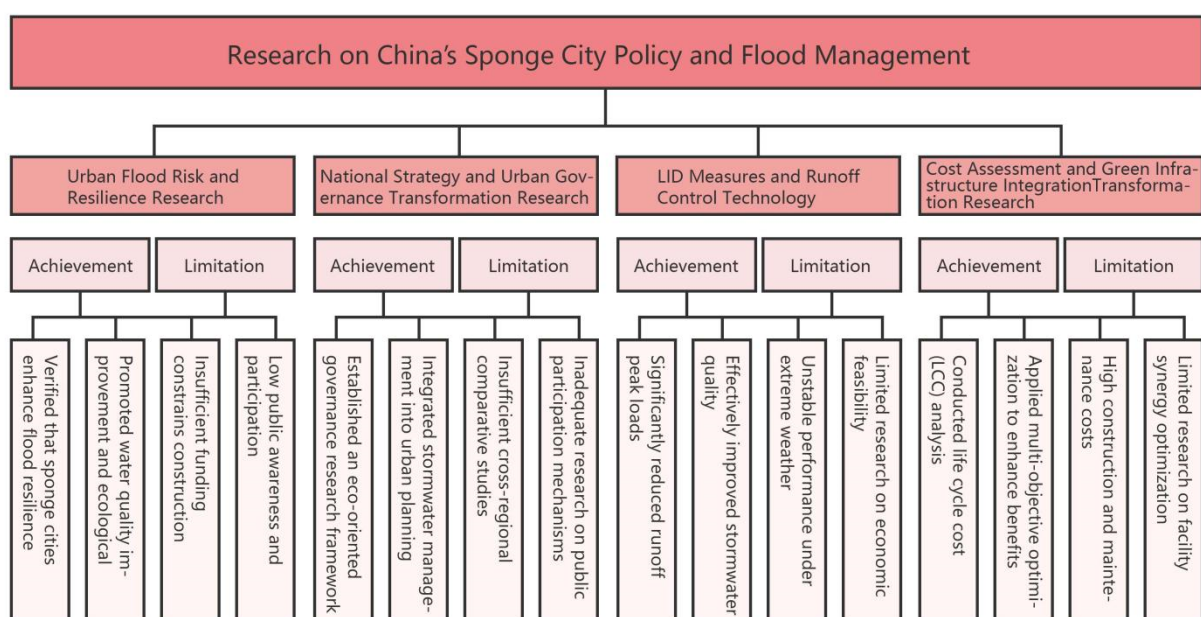


Figure 9. Achievements and deficiencies.

Although certain results have been achieved based on the above visualisation analysis, there are still gaps in the research. On the one hand, the exploration of cross-scale coordination mechanisms is insufficient, with weaknesses in integrated planning and adaptive management across multiple levels such as river basins, cities, and communities. On the other hand, cross-regional comparisons and temporal analyses have limitations, and system assessments under different climatic, topographical, and socio-economic conditions are lacking [14]. Additionally, the application of smart management tools and data-driven decision-making is still in its exploratory phase and urgently needs to be closely integrated with policy evaluation systems [17]. Furthermore, research on public participation and multi-stakeholder collaboration mechanisms is incomplete, particularly in terms of risk communication, behavioural change, and social resilience building. Future research should focus on the following areas: First, strengthen integration across disciplines and scales to bring hydrological modelling, social sciences, and policy analysis closer together, creating a multi-objective optimisation framework. Second, learn from international experience and start adapting local approaches to find solutions that work in different social and climatic contexts. Third, improve long-term monitoring and dynamic simulations under climate change scenarios to better understand how policies perform and how well they adapt to extreme weather events. Fourth, apply smart water management, real-time monitoring, and big data analytics in policy-making to support more precise governance [16]. As data acquisition capabilities, modelling techniques, and policy support continue to improve, sponge city research is expected to transition from conceptual deepening to system integration and refined management. Future outcomes are anticipated to achieve a balance between scientific rigour and practical applicability, driving theoretical innovation in China's urban water security and sustainable development, and providing China-specific solutions and insights for global efforts to address climate change and urban flood risk [12].

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