

Dual-Use Stormwater Storage Facilities for Normal and Emergency Situations in Urban Pluvial Flood Control: Advances and Optimization Pathways

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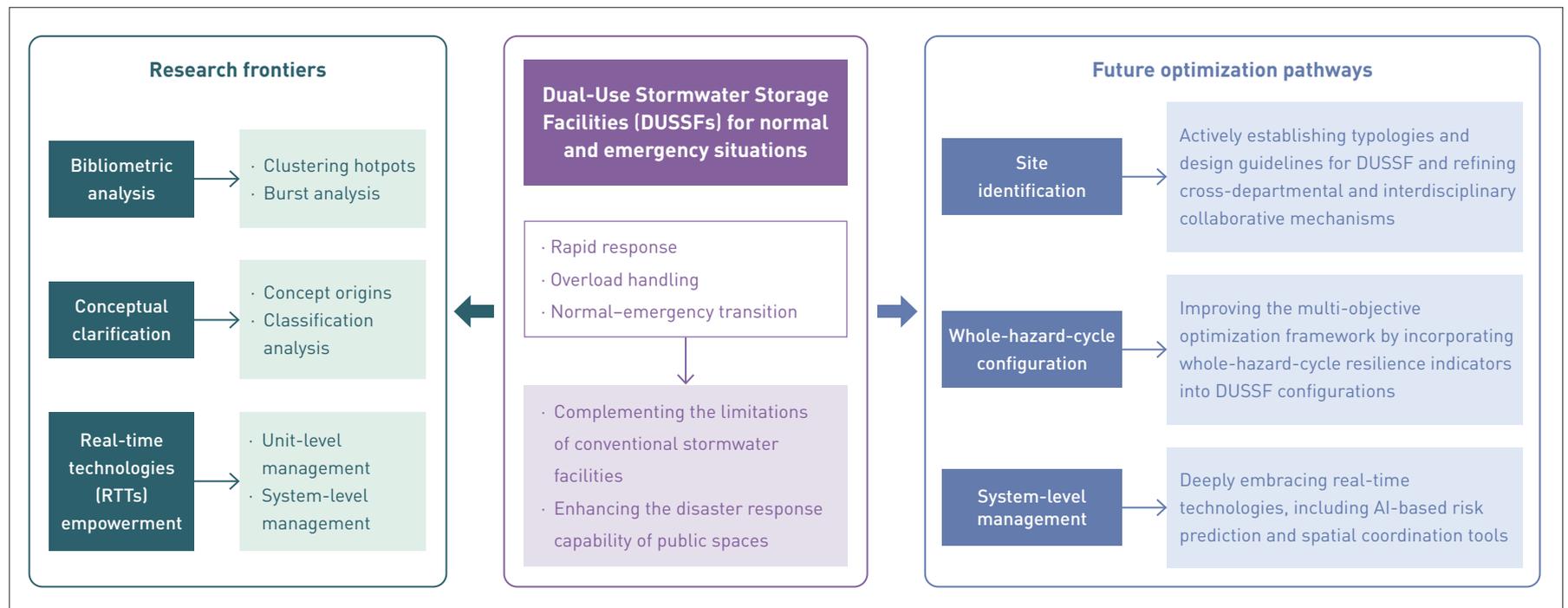
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GRAPHICAL ABSTRACT



ABSTRACT

To alleviate the increasing urban pluvial flood risks, Dual-Use Stormwater Storage Facilities (DUSFs) for normal and emergency situations have emerged as a vital complement to traditional stormwater facilities. DUSFs not only effectively enhance urban capacity to cope with extreme rainfall but also align with the growing demand for multifunctional and intensive utilization of existing spaces. With the continuous empowerment of real-time technologies (RTTs), DUSFs play an increasingly crucial role in strengthening urban resilience, activating public spaces,

and enhancing disaster response capabilities, necessitating a systematic review of its research development and frontiers. Based on bibliometric analysis and CiteSpace visualization methods, this paper systematically analyzes current research hotspots in DUSFs, thoroughly examines its conceptual origins and classification methods, and summarizes cases of both unit- and system-level management enabled by RTTs. Looking toward the construction of future intelligent drainage and flood prevention systems, this paper summarizes spatial optimization pathways for

DUSSF across three dimensions—site identification, whole-hazard-cycle configuration, and system-level management. The pathways require: 1) actively establishing typologies and design guidelines for DUSDF and refining cross-departmental and interdisciplinary collaborative mechanisms; 2) improving the multi-objective optimization framework by incorporating whole-hazard-cycle resilience indicators into DUSDF configurations; and 3) deeply embracing RTTs, particularly artificial intelligence-based risk prediction and spatial coordination tools, to enhance the response capabilities to urban flood disaster. This review aims to provide theoretical references for urban flood management and qualitative spatial optimization, while offering new perspectives in addressing challenges posed by extreme rainfalls for planning and design practice.

KEYWORDS

Blue-Green Infrastructure; Sponge City; Real-Time Control; Flood Resilience; Disaster Prevention Green Space; Dual-Use for Normal and Emergency Situations; Urban Pluvial Flood

HIGHLIGHTS

- Clarifies the conceptual origins, core features, and classification framework of DUSDF
- Summarizes RTT-empowered applications of unit- and system-level management of DUSDF
- Proposes DUSDF optimizations via site identification, whole-hazard-cycle configuration, and system-level management

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1 Research Background

With the accelerating impacts of global climate change and rapid urbanization, urban pluvial flood has become increasingly frequent and is now a critical constraint on sustainable urban development and the improvement of residents' quality of life^[1-2]. Studies show that from 1990 to 2021, the global area prone to flooding in the cities increased by 94%, with low- and middle-income countries experiencing a continuous rise in population exposed to pluvial flood risks. In China, flood-prone built-up urban areas have expanded at an annual rate of 6%, ranking first globally in both newly affected area and overall risk^[3-4]. According to the Ministry of Emergency Management of China, during the 2024 rainy season alone, several cities—including Nanning, Guangxi Province (late May), Yueyang, Hunan Province (early July), Nanyang, Henan Province (mid-July), and Huludao, Liaoning Province (late August)—suffered severe pluvial flood disasters^[5-7]. This underscores the urgent need for effective urban flood risk management.

Within the frameworks of sponge city and resilient city development, stormwater storage facilities (SSFs) serve as fundamental infrastructure for regulating total rainfall-runoff volume, reducing peak flows, and alleviating loads on drainage systems—thus playing a key role in mitigating urban pluvial floods^[8-9]. However, as Chinese cities enter the era of high-quality urban development, single-function SSF planning and construction face multiple challenges: 1) urban land resources are increasingly scarce, making it difficult to allocate sufficient space for large-scale SSFs; 2) upgrading and retrofitting aging drainage networks in built-up areas is costly and technically challenging; 3) regulatory detailed sponge city planning largely focuses on meeting the defined control rate of total annual runoff by cascading it to each parcel, without setting explicit emergency stormwater storage targets; and 4) while blue-green infrastructure (BGI) effectively reduces runoff at the source, its capacity to attenuate peak discharges during heavy storms is limited, and governance often remains fragmented without effective coordination^[10-13].

In July 2023, the State Council of China called for the steady and proactive development of dual-use public infrastructure in mega and large cities^[14-15]. This introduced the concept of Dual-Use Stormwater Storage Facilities (DUSDFs) for normal and emergency situations^{①[16-18]}. The relevant documents have explicitly proposed making full use

① Based on the *Technical Code for Stormwater Storage Works in Towns* (GB 51174-2017) and related literature [source: Refs. [16-18]], this paper adopts “Dual-Use Stormwater Storage Facilities for normal and emergency situations” as the English term.

of public spaces, e.g., parks, plazas, stadiums, and parking lots, to temporarily retain stormwater runoff that exceeds the standards of source-control and drainage pipelines and channels (“excess runoff” hereafter)^[19–20].

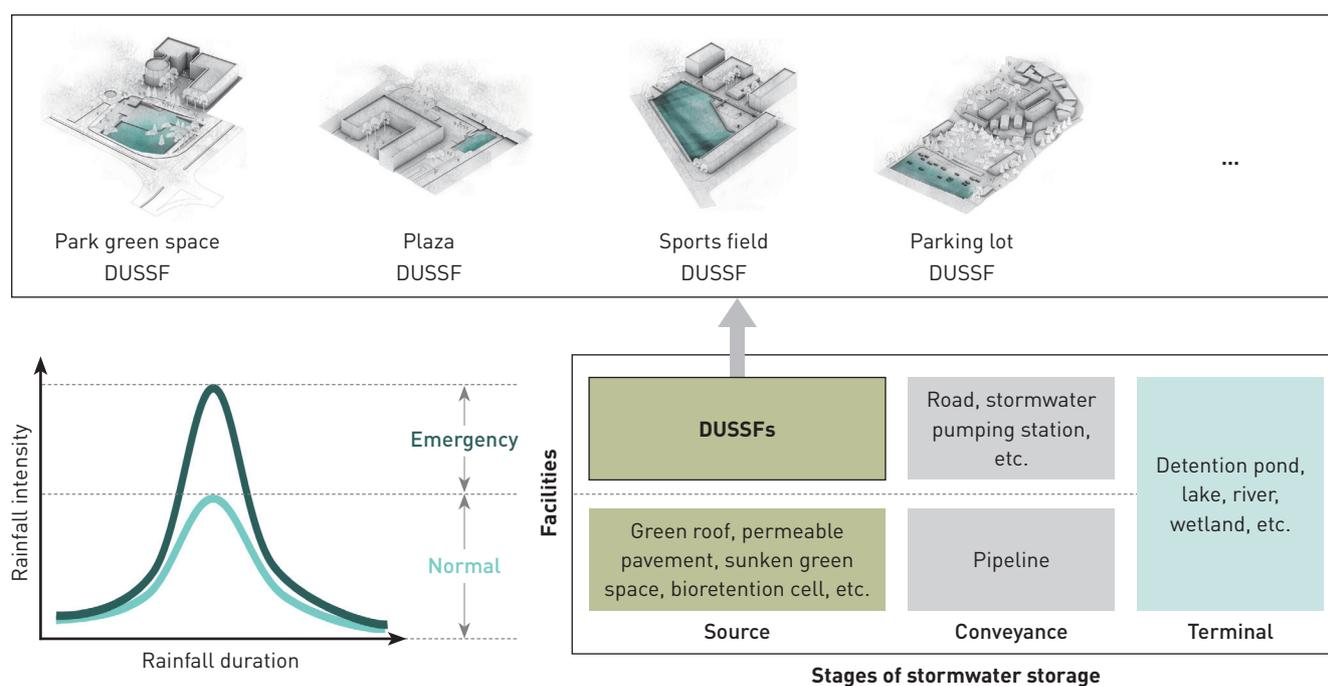
Unlike conventional sponge city facilities (e.g., green roofs, permeable pavements, sunken green spaces, bioretention ponds), DUSSFs overcome the limitations of passive stormwater collection. First, they emphasize active management—under normal conditions, these spaces function as urban public landscapes providing leisure and recreational services, while in emergencies, they can be integrated with the excess runoff system following contingency plans. Second, the features of DUSSF—rapid response, overload handling, and transition between normal and emergency functions—endow the facilities with significant advantages in efficient land use and the integration of multiple benefits, making them particularly suitable for flood management in the complex contexts of built-up areas (Fig. 1). The rapid rise of real-time technologies (RTTs), including rainfall nowcasting^[21–23], Internet of Things (IoT) online monitoring^[24–26], and optimal control^[27–30], has greatly enhanced DUSSF planning and management^[31–33]. By continuously tracking rainfall, water depth, and facility status, DUSSF can be activated based on flood risk forecasts and quickly return to its original functions after events^[34]. Furthermore, systematic configuration of DUSSF using the multi-objective optimization algorithms can enable staggered upstream–downstream discharge at the sub-watershed level, significantly improving operational efficiency.

Driven by supportive policies and technological innovation, DUSSF is increasingly valued for its role in enhancing urban resilience, revitalizing underutilized public spaces, strengthening drainage and flood management systems, and improving disaster response capacity. However, integrated research on the policy, planning, and technological coordination of DUSSF remains at an early stage, highlighting the urgent need for a review of relevant progress from the perspectives of urban planning and landscape design. To address the gap, this research employs a bibliometric analysis and CiteSpace visualization to summarize the development trajectory of DUSSF research, synthesize progress in RTT applications, and explore pathways for spatial optimization. The results aim to provide a theoretical basis for urban pluvial flood mitigation and the optimization of existing public spaces, expand the research scope of planning and design disciplines, and offer new perspectives for design practices in responding to extreme rainfall events.

2 Research Methods and Data Sources

2.1 Literature Retrieval and Screening

To ensure a comprehensive review, this research identified “stormwater storage facilities” (雨水调蓄设施) and “dual-use” (平急两用) as the core search terms, supplemented with semantically related keywords. The search was conducted in August 2024 using the Web of Science (WoS) Core Collection for English literature and China National Knowledge Infrastructure (CNKI) database for

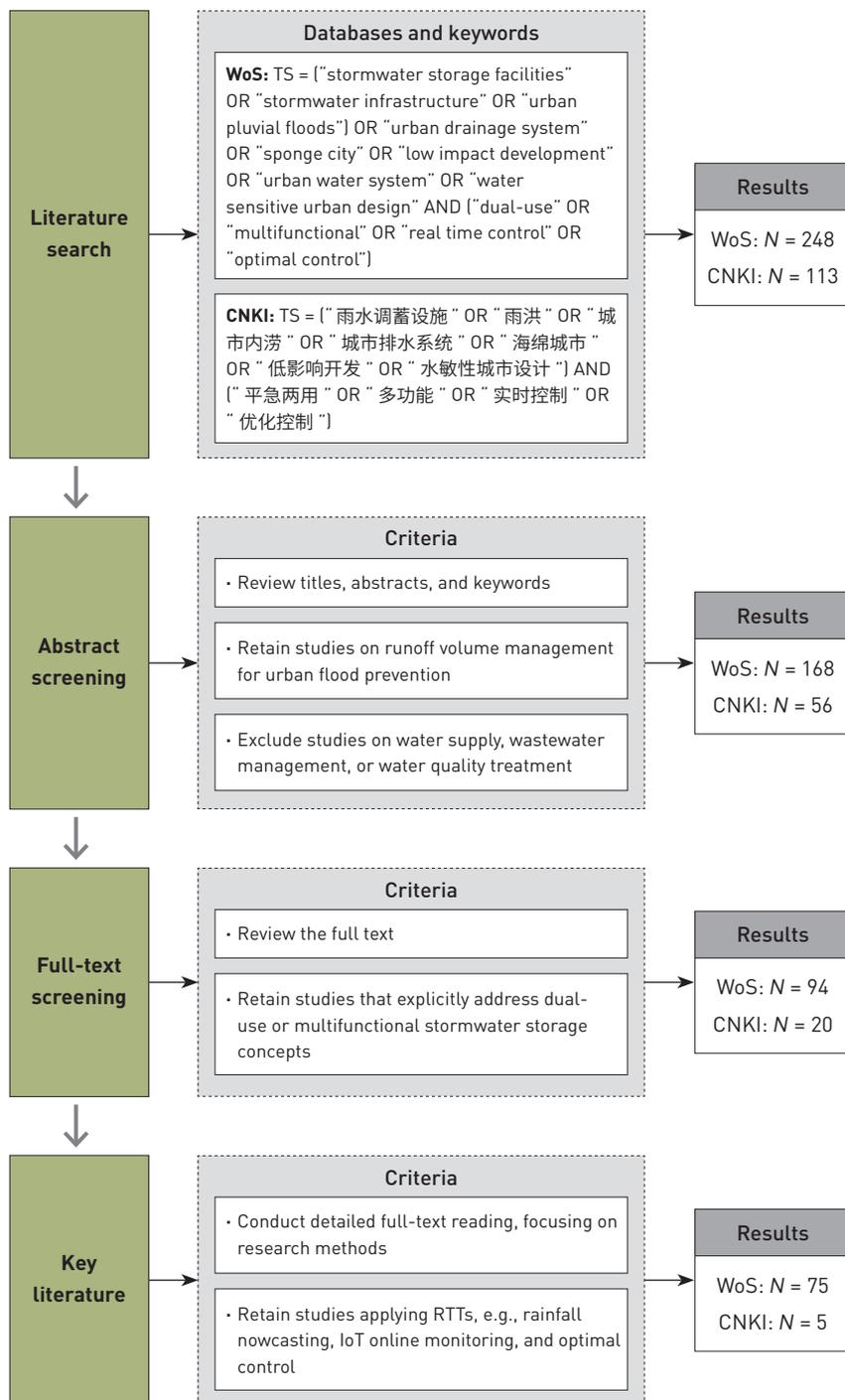


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Fig. 1 Application of DUSSF in urban stormwater storage systems.

Chinese literature, without restriction on publication year (Fig. 2). Titles, abstracts, and keywords were screened to retain studies focusing on runoff volume control in urban pluvial flood mitigation, while excluding research on urban water supply, wastewater management, or water quality improvement. Full-text screening was then performed to identify publications explicitly addressing dual-use strategies rather than single-function facilities; these

Fig.2 Literature screening method.



were included as the sample set for bibliometric analysis to reflect the overall development trend. Subsequently, in-depth reading was performed to select case studies that applied at least one RTT, including rainfall nowcasting, IoT online monitoring, and optimal control.

2.2 Bibliometric and Visualization Analysis

The annual number of publications in Chinese and English was charted to illustrate temporal trends in DUSFF-related research. CiteSpace 6.4.1 was employed to visualize the academic developments in this field. First, keyword clustering analysis was conducted to identify the temporal span of studies, the evolution of research hotspots, and the relationships among them. Next, the burst period and burst strength of keywords were examined to characterize the phases of DUSFF research development.

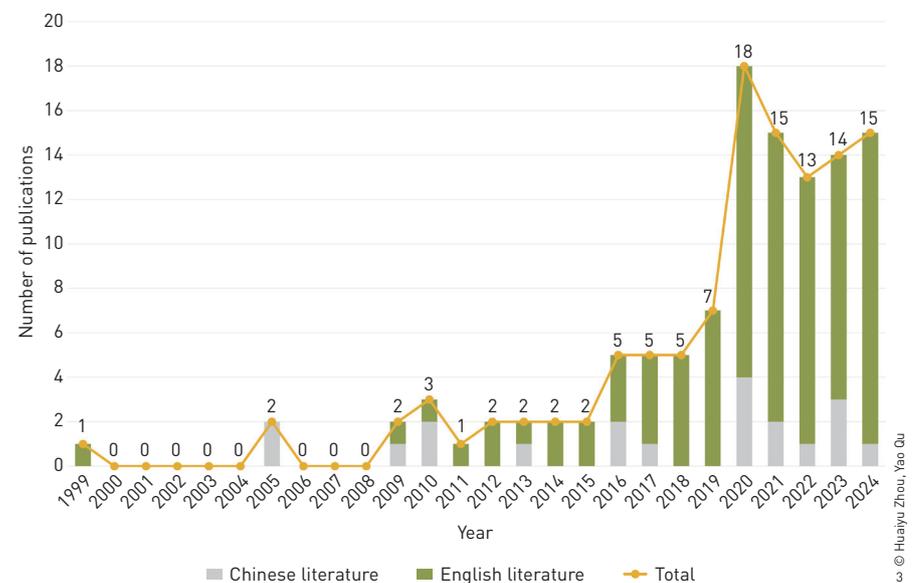
3 Results and Discussion

3.1 Bibliometric and Visualization Analysis Results

After full-text screening, 114 articles were retained for bibliometric analysis. The temporal trend shows that DUSFF-related research was relatively sparse prior to 2019, but experienced a substantial growth thereafter, with publication peaks in 2020 and 2021. In addition, English articles significantly outnumbered Chinese ones (Fig. 3).

Due to the limited number of studies published in Chinese, this research conducted a visualization analysis of the 94 English

Fig. 3 Annual number of screened Chinese and English articles on DUSFF.



papers. The timeline analysis of the clustering hotspots (Fig. 4) show that, between 2016 and 2024, the strongest associations emerged among Cluster #0 “Nature-based Solutions” (NbS), Cluster #1 “BGI”, and Cluster #2 “Model predictive control” (MPC). BGI serves as a spatial carrier to implement NbS; RTTs are commonly employed to regulate the inflow and outflow of stormwater in BGI

to maximize its storage performance^[35]; in addition, MPC algorithms represent one of the most widely applied optimization approaches in RTTs^②.

Analysis of keyword burst period and strength suggests that the development of DUSFF-related research can be divided into three phases (Fig. 5). 1) The concept formation phase (2016–2019):

Fig. 4 The timeline analysis of the clustering hotspots of screened English articles.

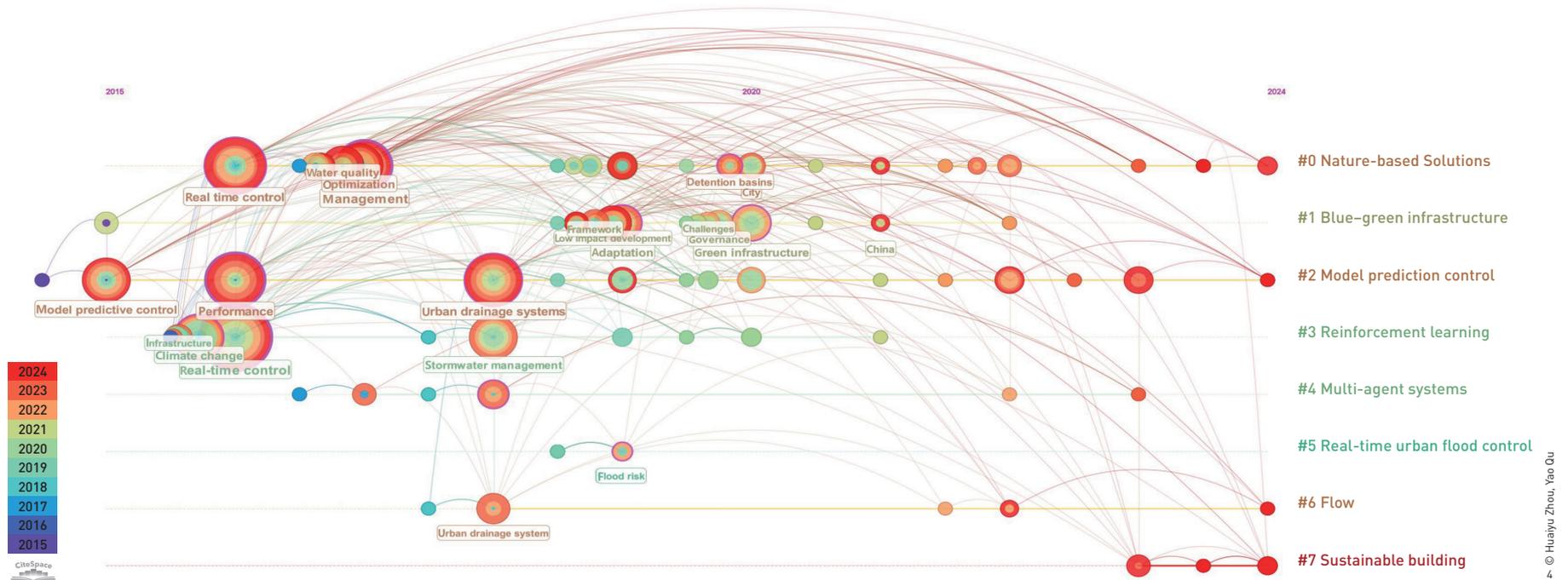
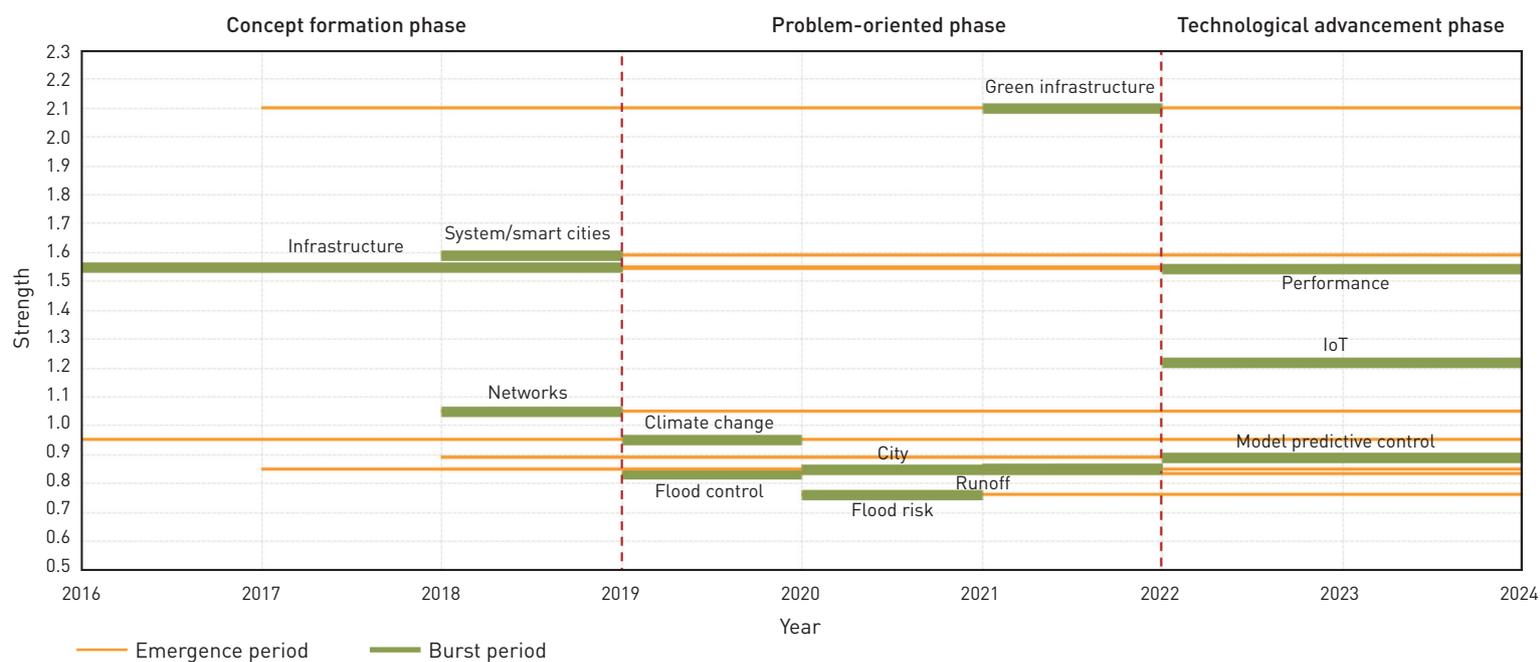


Fig. 5 Keyword burst analysis of screened English articles.



② MPC is an online optimization algorithm that uses predictive models to generate control signals and dynamically recalibrate them in real time, enabling continuous interaction between the physical space and the simulation model.

keywords such as “infrastructure” and “system/smart cities” indicate that DUSFF was initially conceptualized as a novel infrastructure in smart city. 2) The problem-oriented phase (2019–2022): the burst of keywords like “green infrastructure,” “climate change,” and “flood risk” reflects increasing attention to extreme rainfall, flood risk reduction, and issues related to NbS. 3) The technological advancement phase (2022–2024): with the iterative upgrading of RTTs, keywords such as “IoT” and “MPC” have emerged, and the performance of DUSFF in regulating urban pluvial flooding has received growing attention.

3.2 Research Development of DUSFF

3.2.1 Concept Origins of DUSFF

As a term that emerged under the public infrastructure agenda of China, DUSFF has yet to become a widely recognized academic concept globally. However, the core idea underlying DUSFF—the functional transition between normal and emergency use—has long been present in earlier research and practice. At the end of the 20th century, countries such as Japan and the USA had implemented DUSFFs. In Japan, urban planning projects in Chikuma, Utsunomiya, Okazaki, Neyagawa, and Himeji integrated school playgrounds, green spaces, and parking lots with runoff conveyance corridors, which substantially enhanced flood resilience and were promoted nationwide^[36]. In the USA, the Low Impact Development framework promotes multifunctional SSFs, emphasizing landscape-based solutions to increase practical utility^[37–39]. For example, the Washington Park, Downers Grove, Illinois, used soccer fields as emergency detention basins during heavy rainfall, actively diverting runoff and saving USD 5 million in pipeline repair costs^[40].

In 2005, Wu Che et al. proposed design concepts for multifunctional SSFs adapted to Chinese urban contexts, classifying them into depressed landforms, ponds, wetlands, public facilities associated with daily life, and large-diameter storage conduits^[41–42]. Junqi Li et al. further developed corresponding volume calculation methods to address differing functional requirements^[43]. Between 2006 and 2010, the Dutch design firm De Urbanisten introduced the Watersquare concept—public squares that double as temporary SSF^[44–45]. Relevant projects in Rotterdam, Tiel, and Amsterdam gained broad public recognition. Around the same period, Norwegian scholar Oddvar Lindholm proposed a three-stage stormwater management framework based on rainfall intensity: natural infiltration under normal conditions, detention to delay peak flow during moderate storms, and ensuring unobstructed conveyance pathways during extreme events^[46].

Since China promotes sponge city construction across the nation

in 2021, developing urban open space systems with stormwater regulation and storage functions has become a prominent focus in urban design. For instance, Guanglong Wei et al. advocated a seasonal composite model to integrate underground functional spaces and water retention areas^[47]; while Qiao Wang et al. emphasized increasing the proportion of “floodable” open space across multiple urban scales to enhance flood resilience^[48–49]. Globally, numerous examples have emerged. In Kuala Lumpur, Malaysia, SMART Tunnel serves as a traffic tunnel under normal conditions, but diverts stormwater to adjacent low-speed lanes during moderate rainfall, and is fully dedicated to runoff conveyance during extreme storms^[50]; in Auckland, New Zealand, the revitalization of Sannynook Park connects a rugby field with a runoff conveyance channel, allowing the field to serve as short-term detention during heavy rainfall^[51]; in Hamburg, Germany, community sports fields and playgrounds are promoted as emergency SSFs^[52]; in Shenyang, China, the Xiannyu Lake Community Park can channel floodwater from a nearby river through sluice gates and discharge them after the storm peak has passed^[53].

Building on the global theoretical and practical evolution of DUSFF, and drawing on the latest design guidelines as well as studies by Xiaolu Gong et al.^[54] and Xinnan Zhang et al.^[18], DUSFF can be defined as urban public spaces that are adapted or co-constructed, without compromising their normal functions, to temporarily store stormwater. Such spaces constitute a critical component of sponge city for managing excess runoff.

3.2.2 Classification of DUSFF

Current scholarship primarily classifies DUSFF based on its management mode, elevation, and land-use type. Based on management mode—specifically, whether human intervention is required for the functional transition between normal and emergency use—DUSFF can be categorized as actively managed and passively operated types^[55–56]. Actively managed DUSFF functions as micro-scale detention zones within the city. The temporary storage function is activated under certain hazard conditions, diverting runoff via surface channels, pipelines, or pumps. Passively operated DUSFF mainly relies on topography and gravity. Once the water depth exceeds a threshold, runoff automatically flows into the storage facility.

By elevation, DUSFF can be classified as aboveground, underground, and lake types^[54]. By land-use type, DUSFF can be classified as park green space, protective greenbelt, plaza, parking lot, sports field, and municipal land. Land-use type has a significant influence on both spatial design strategies and functional transition

mechanism. Park green space DUSFF performs basic detention functions under normal conditions and can be converted to concentrated flood storage during storm events. Hard-surfaced DUSFFs (e.g., plazas, sports fields, parking lots) require structural measures such as inlets, temporary barriers, and sluice gates, to embed emergency detention capacity within existing facilities. Under regular rainfall, they maintain smooth drainage; during extreme storm events, they are operated following contingency plans to form temporary detention areas, which are then rapidly drained to restore normal use.

3.3 RTT-Empowered DUSFF

When responding to sudden urban flooding events, although the concept of functional dual-use has notable advantages, there is still a lack of systematic solutions to the challenge of “how to activate and how to restore” DUSFF. On the one hand, if DUSFF is activated too early or too late, its peak flow reduction effect would be greatly diminished; on the other hand, if floodwater is not drained in time, it would pose certain safety risks. For instance, pedestrians may accidentally fall into the water; the pathogenic bacteria in the floodwater may cause public health issues^[57]; and prolonged inundation may kill flood-intolerant plants and thus increase maintenance costs. Since 2019, a growing body of research has emerged applying RTTs such as rainfall nowcasting, IoT online monitoring, and optimization control to manage DUSFF. It should be emphasized that RTT-based DUSFF is categorized as actively managed DUSFF. According to the *Technical Standard for Real-Time Control of Urban Drainage Systems (Draft for Comments)*, such facilities can be further classified by control level into unit-level (localized autonomous decision-making) and system-level (distributed collaborative decision-making) DUSFFs.

In the bibliometric review, 80 key publications involving RTTs were identified (75 in English, 5 in Chinese). From a global perspective, the USA ranks first with 27.27% of the literature, followed by China (20.45%) and Australia (9.09%), with the UK, Canada, Estonia, and other countries/regions also contributing to this field. Table 1 lists recent unit- and system-level DUSFF management case studies published in high-impact international journals, and compares their site areas, applied RTTs, and performance^[58-71].

3.3.1 Unit-Level Management

Unit-level management refers to the optimized control of individual DUSFF units. It primarily relies on real-time monitoring of rainfall and water depth to dynamically regulate facility outflows,

thereby regulating the peak discharge of each catchment area during storm events and alleviating downstream drainage pressure.

For aboveground DUSFF, the research teams from Vrije Universiteit Amsterdam in the Netherlands^[58] and the University of Cagliari in Italy^[59] have independently proposed smart blue-green roof schemes. The principle is to add rooftop water storage layers and smart valves, which use 6-hour rainfall forecasts to dynamically regulate roof water storage and utilization, thereby reducing roof outflow under extreme storms by 70% ~ 97%. Researchers at Tennessee State University, USA proposed applying RTT to optimize rain garden design, increasing its storage capacity by about 11% compared with conventional bioretention systems^[60]. The research team from Institut National de la Recherche Scientifique in Quebec, Canada, has in recent years focused on the real-time control of stormwater retention ponds and peak outflow reduction. The concept was first introduced by Karine Bilodeau et al. in 2018: adding a retention pond and automatic valves at the site outlet, with multiple valve openings set according to water depth and 6-hour rainfall forecasts, achieving a 46% reduction in peak outflows^[61]. Subsequently, Shadab Shishegar and colleagues further improved the optimization algorithm, adjusting valve states every 30 minutes and reducing peak outflow by 73% ~ 95%^[62]. In addition, Nils Kändler et al. implemented floodable parking lots around buildings, reducing peak outflows from individual urban catchments by more than 50%^[63]. Addressing the issue that the storage capacity of small urban water bodies often cannot be released before storms, Huaiyu Zhou et al. developed a predictive algorithm with a 5-minute interval to pre-drain and activate landscape retention ponds, reducing catchment peak flows by up to 45%^[64].

For underground DUSFF, Lanxin Sun et al. used a predictive algorithm (5-minute cycle) to optimize underground storage modules in Shenzhen's sponge communities, reducing peak runoff by 23% ~ 58%^[65]. Mingkun Xie et al. developed an IoT-based monitoring and control system for green infrastructure, enabling real-time performance assessment and synchronized adjustment of stormwater storage modules, achieving a site water capture rate of 75%^[66]. Ye Zhong et al. employed rule-based control to regulate the open/close status of outlets in storage modules, significantly improving operational efficiency during storms^[67].

3.3.2 System-Level Management

System-level management refers to the real-time coordinated control of multiple unit-level DUSFFs across interconnected discharge areas, determining priority- and staggered-discharge zones to relieve drainage pressure in high flood-risk areas^[72-73]. The

Table 1: Case studies of RTT-empowered DUSFF

Type	Research object	Area (hm ²)	RTT			Performance	Source
			Rainfall nowcasting	IoT online monitoring	Optimal control		
Unit-level management	Multi-layer blue-green roof	—	√	—	√	Absorbed 70% ~ 97% of storm outflow	Refs. [58–59]
	Rain garden	—	√	√	—	Increased storage capacity by 11%	Ref. [60]
	Stormwater retention pond	142.00	√	—	√	Reduced peak outflow by an average of 46%	Ref. [61]
	Stormwater retention pond	311.00	√	√	√	Reduced peak outflow by 73% ~ 95%	Ref. [62]
	Floodable parking lot	12.00	—	√	√	Reduced peak outflow by over 50%	Ref. [63]
	Stormwater retention pond	0.85	√	√	√	Reduced peak outflow from drainage areas up to 45%	Ref. [64]
	Sponge community underground storage module	1.14	√	—	√	Reduced peak runoff by 23% ~ 58%	Ref. [65]
	Stormwater detention pond	1.25	—	√	√	Achieved 75% rainwater capture rate	Ref. [66]
	Stormwater detention pond	215.00	—	√	√	Increased treatment capacity by 5% ~ 30%	Ref. [67]
System-level management	Road conveyance channels and temporary storage landscapes	150.00	—	√	√	Reduced CSO volume by an average of 12.4%	Ref. [68]
	Road detention units	41.90	√	—	√	Reduced 30% of identified flooding hotspot	Ref. [69]
	Internal-drainage roof system in high-density block	130.00	√	√	√	Reduced flood-prone area by up to 30%	Ref. [70]
	Smart watersquare	450.00	√	√	√	Reduced inundated area by 46% ~ 48%	Ref. [71]

research team from the Technical University of Denmark proposed using roads as temporary conveyance channels to divert excess stormwater runoff in real-time to temporary storage sites such as parks, skateparks, and soccer fields, thereby achieving staggered shifts of discharge^[68,74]. In related case studies, by managing roads that accounted for 7% of the total area, they significantly reduced combined sewer overflow (CSO) volumes during heavy rainfall events in Copenhagen communities. Researchers at Tallinn University of Technology in Estonia developed road detention units, using open spaces covering about 6% of Tallinn's old town area to eliminate 30% of identified flooding hotspots^[69]. Zhou et al. applied a smart internal-drainage roof system to manage rooftops

covering 11% of a high-density block, reducing the flood-prone area by up to 30%, and cutting the duration and depth of flooding at a high-risk underpass by 50% and 28%, respectively^[70]. They also took Wangchengpo, an old residential community in Changsha, as a case study and demonstrated that a smart water square occupying 5% of the community's total area reduced the inundated area by 46% ~ 48% and decreased the maximum water depth by nearly 40%^[71].

3.4 Spatial Optimization Pathways for DUSFF

The literature review shows that, while there is broad international consensus on the potential of DUSFF in urban

drainage, pluvial flood mitigation, and emergency response systems, scholars have also highlighted research and practice bottlenecks in applying DUSF within high-density built environments^[64,70-71]. Building on three dimensions—site identification, whole-hazard-cycle configuration, and system-level management—this review further synthesizes optimization pathways and recommendations from existing research, aiming to inform DUSF planning and design through new theoretical perspectives and practical guidance.

3.4.1 Optimizing Site Identification for DUSF

Within urban drainage and pluvial flood management systems, the operating principles of DUSF are comparable to those of flood detention zones and stormwater parks^[75], emphasizing the conversion of micro-scale public spaces into temporary storage facilities. However, existing research on the disaster-prevention functions of existing open spaces has assessed their accessibility and adequacy, particularly their roles in shelter, evacuation, and quarantine during earthquakes, fires, or public health emergencies—while comparatively less attention has been paid to their capacity to manage short-duration and excess runoff^[76-77]. The key reasons for this research gap include the following aspects. 1) Lack of systematic summary of typologies and design guidelines for DUSF, leading to the absence of robust methods for assessing the retrofit potential of different public spaces. 2) To meet the annual runoff control rate, SSFs in existing areas are often designed based on a fixed return period. However, the absence of a scientific allocation mechanism for storage capacity under non-routine extreme events makes it difficult to balance demands between regular rainfall management and emergency flood control. 3) Insufficient connectivity between public spaces and primary runoff conveyance corridors, resulting in limited coordination of upstream and downstream SSFs^[78-80]. 4) Unclear inter-agency responsibilities across departments such as landscaping, water management, and subdistrict administration, require development of effective coordination mechanisms. To address these issues, developing a systematic DUSF site identification methodology has become a key pathway for advancing its application. For instance, Pengcheng Li et al. proposed a “six-step resilience method” for identifying and allocating DUSF sites in central Shanghai^[81]. Similarly, Zhou et al., in their smart watershed study, suggested using indicators such as slope, enclosure, permeability, and proximity to conveyance corridors and flooding points to identify potential sites^[71].

3.4.2 Optimizing Whole-Hazard-Cycle Configuration for DUSF

Recent studies have applied multi-objective optimization techniques, e.g., genetic algorithms and simulated annealing, to balance water regulation, ecological benefits, and management costs across various types of SSFs^[82-84]. However, these approaches are typically based on fixed storm return periods and target functions, without incorporating the whole hazard cycle of “resistance–response–recovery”^[85-86]. Although resilience assessment methods in urban planning and landscape architecture have advanced significantly, they still fail to capture the complete process by which urban functions degrade and recover during flood events^[87-88], thereby limiting comparative evaluations of DUSF configurations. To address this limitation, scholars have introduced the system performance curve (SPC). Michel Bruneau et al. conceptualized the “resilience triangle” to represent the proportion of normal urban functionality (0 ~ 100%) over disaster timelines^[89]; Seith N. Mugume applied SPC to optimize the storm drain systems^[90]; and Yuntao Wang et al. used SPC to illustrate the recovery procedures of different land use types during floods^[91]. More recently, Jiada Li et al. compared static and real-time management of DUSF in Salt Lake City using SPC, demonstrating that real-time control markedly improves urban recovery speed^[92]. Similarly, Zhou et al. evaluated the impacts of different real-time control intervals on the number of flooding points, confirming the effectiveness of RTTs^[71]. Building on these insights, future research could apply SPC to compare recovery efficiency under varying DUSF configurations and incorporate resilience metrics into target functions to enable more systematic performance assessments.

3.4.3 Optimizing System-Level Management for DUSF

The introduction of RTTs has significantly enhanced the capacity of DUSF to cope with emergent pluvial flooding. At present, unit-level management approaches, typically based on peak outflow or ponding depth, are relatively well established, whereas research on system-level management that emphasizes upstream–downstream coordination remains limited. The main bottlenecks lie in the enormous demand for urban spatial data, the substantial computational resources required for risk prediction at the city scale, and the need for deep integration of hydrological–hydrodynamic mechanism models with city information modelling (CIM). As a result, achieving global optimal solutions at second-level timeframes remains highly challenging^[93]. By contrast, unit-level management primarily addresses overflow or ponding risks of the facilities, requires far fewer computational resources, and can be implemented directly with established hydrodynamic mechanism

models. With the rapid advancement of artificial intelligence, surrogate models based on artificial neural networks can overcome the limitations of mechanism models in terms of computational speed and error tolerance to a certain extent. Trained on large volumes of offline data, surrogate models have been applied to urban flood risk prediction and spatial management^[93-95]. Recent studies by Benjamin D. Bowes et al. and Xinran Luo et al. have employed multi-agent reinforcement learning and long short-term memory, reducing global risk prediction times in system-level management from the minute- to second-level, while maintaining stability under disturbances like monitoring errors^[96-97]. These emerging technologies hold promise for enabling system-level management of upstream and downstream DUSFs, yet current research remains at an exploratory stage and requires further development.

4 Conclusions

Using bibliometric methods, this review visually analyzed research hotspots and trends of DUSF, systematically investigated its conceptual origins and classification framework, and illustrated applications of RTTs in both unit- and system-level management. Building on this basis, this review further identified spatial optimization pathways for DUSF across three dimensions—site identification, whole-hazard-cycle configuration, and system-level management.

Research trends show that since 2019, studies on DUSF have grown significantly, with the focus shifting from early conceptual development to problem-oriented research, and more recently to advanced RTT applications. The USA, China, and Australia have been the leading contributors, driving global adoption and development. This review traces the origins of the DUSF concept to China's "dual-use for normal and emergency solutions" policy and the design practices of multifunctional SSFs. DUSFs can be classified by management mode, elevation, and land-use type. Multiple cases worldwide have demonstrated their effectiveness in mitigating urban pluvial floods. At the research frontier, the integration of RTTs has greatly enhanced the proactivity and precision of DUSF in flood management, leading to unit- and system-level management pathways that leverage rainfall nowcasting, online monitoring, and optimized control to improve operational efficiency.

Overall, DUSF presents an important opportunity for urban planning and landscape architecture disciplines to advance research on urban flood prevention and resilience. First, beyond conventional stormwater detention infrastructure such as pipes, reservoirs, and

pumping stations, DUSF constitutes a critical storage space. This calls for the development of systematic DUSF site identification methods, the establishment of spatial typologies and design guidelines, and the refinement of cross-departmental and cross-disciplinary coordination mechanisms to effectively link existing public spaces with systems managing excess runoff. Second, multi-objective optimization frameworks should be improved by incorporating resilience metrics that capture functional changes across the whole hazard cycle, thereby enabling more comprehensive performance evaluation. In addition, advanced technologies from multiple disciplines, particularly AI-based global risk prediction and spatial coordination methods should be actively integrated to explore coordinated scheduling strategies for SSFs at the city scale, ultimately enhancing the speed and effectiveness of urban flood response and management.

It should be noted that this review primarily focuses on practical DUSF case studies and spatial optimization pathways. It does not provide a systematic comparative analysis of specific algorithmic frameworks or control intervals for methods such as rainfall nowcasting, IoT online monitoring, and optimal control in different urban contexts. Furthermore, the mechanisms by which cross-disciplinary spatial coordination contributes to flood management, as well as the long-term effectiveness of DUSF, require further in-depth research and empirical validation.

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应对城市内涝的“平急两用”雨水调蓄设施： 前沿进展与优化路径

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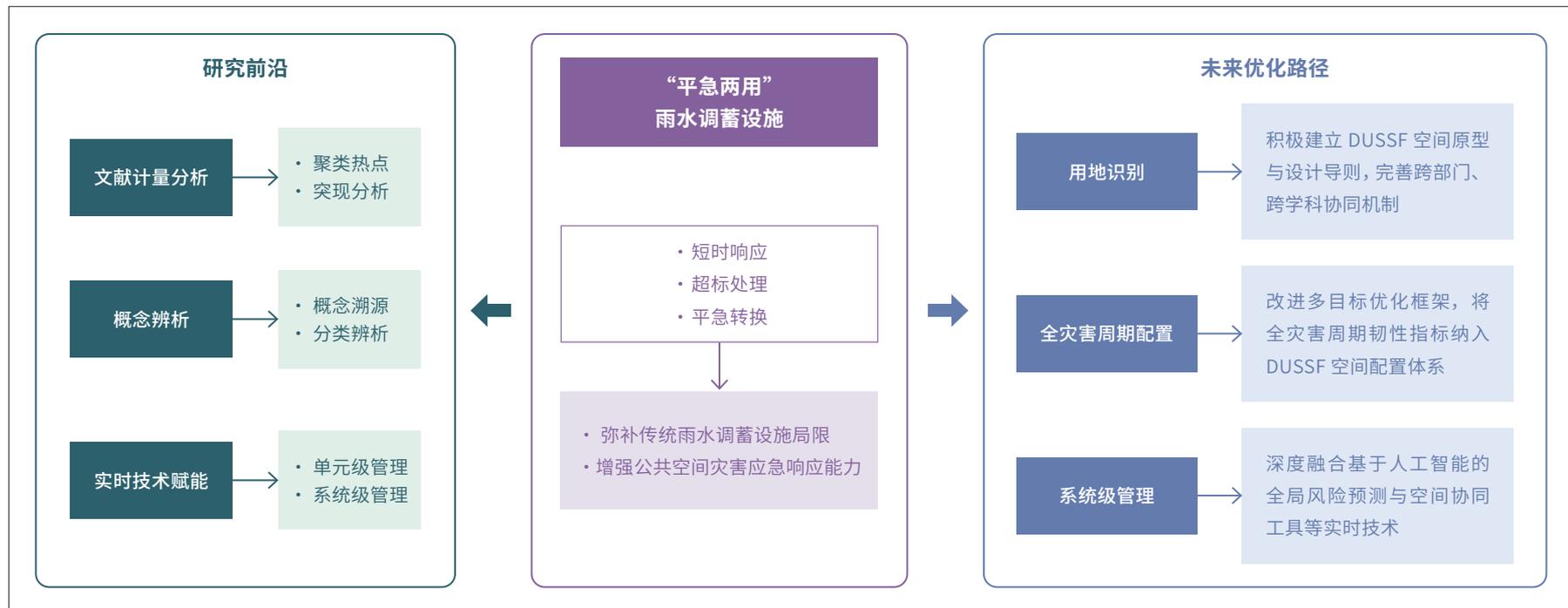
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图文摘要



摘要

为缓解城市中日益严峻的内涝风险,“平急两用”雨水调蓄设施(DUSF)作为传统雨水调蓄设施的重要补充,不仅能够有效提升城市应对极端暴雨的能力,也契合存量空间多功能化与集约利用的需求。伴随实时技术的持续赋能,DUSF在增强城市韧性、激活公共空间和提升灾害应急响应能力等方面的作用愈发凸显,但鲜有对其研究脉络与前沿趋势的系统梳理。本文运用文献计量与CiteSpace可视化方法,揭示了当前DUSF的研究热点,厘清了其概念脉络与分类体系,并归纳了实时技术赋能DUSF的单元级和系统级管理案例。面向未来智慧化的排水防涝体系构建,本文从用地识别、全灾害周期配置和系统级管理3个维度归纳了其空间优化路径:1)积极建立DUSF

空间原型与设计导则,完善跨部门、跨学科协同机制;2)改进多目标优化框架,将全灾害周期韧性指标纳入DUSF空间配置体系;3)深度融合实时技术,特别是基于人工智能的全局风险预测与空间协同工具,从而提升城市内涝应急响应水平。综述成果旨在为城市内涝治理与存量空间优化提供理论参考,并为规划与设计实践中如何应对极端暴雨挑战提供新思路。

关键词

蓝绿基础设施; 海绵城市; 实时控制; 洪涝韧性; 防灾绿地; 平急两用; 城市内涝

文章亮点

- 厘清了DUSSF的概念起源、核心特征与分类体系
- 总结了实时技术赋能的单元级与系统级DUSSF管理应用
- 基于用地识别、全灾害周期配置与系统级管理3个角度提出DUSSF优化路径

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1 研究背景

随着全球气候变化加剧及城市化进程的快速推进,城市内涝现象日趋频繁,且已成为制约城市可持续发展和居民生活质量提升的关键因素^[1-2]。研究显示,自1990年至2021年,全球城市易涝面积增加了94%,低收入和中等收入国家暴露于内涝风险的人口数量持续上升,其中,中国易涝城区面积以每年6%的速度增长,新增面积与综合风险均居全球首位^[3-4]。据中国应急管理部统计,仅2024年雨季,广西南宁(5月下旬)、湖南岳阳(7月初)、河南南阳(7月中旬)和辽宁葫芦岛(8月下旬)等城市相继遭遇特大内涝灾害^[5-7]。因此,内涝治理已刻不容缓。

在海绵城市与韧性城市建设体系中,雨水调蓄设施(stormwater storage facilities, SSFs)作为调节雨水径流总量与峰值、减轻排水系统负荷的基础设施,在应对城市内涝方面发挥着关键作用^[8-9]。然而,随着中国城市发展进入存量时代,单一功能的雨水调蓄设施规划建设面临多重挑战:1)城市空间资源日趋紧张,难以为大型调蓄设施建设提供足够的用地;2)建成区地下管网改造升级难度大、成本高;3)海绵城市控制性详细规划编制主要关注年径流总量控制率,采用“地块达标”模式来逐级分解该指标,而缺乏内涝应急调蓄指标;4)蓝绿基础设施(blue-

green infrastructure, BGI)虽能够发挥重要的源头减排功能,但对暴雨径流峰值削减效果有限,且存在上下游管理“各自为政”、缺乏协同的难题^[10-13]。

2023年7月,中国国务院提出应在超大及大型城市积极稳步推进“平急两用”公共基础设施建设^[14-15]。由此,“平急两用”雨水调蓄设施(Dual-Use Stormwater Storage Facilities for normal and emergency situations, DUSSFs)的概念应运而生^[16-18]。此外,相关文件均明确提出应充分利用公园、广场、体育场、停车场等公共空间来短时承担超出源头减排和传输管渠标准的雨水径流(以下简称“超标雨水径流”)^[19-20]。

相较于传统海绵设施(如绿色屋顶、透水铺装、下凹式绿地、生物滞留池),DUSSF突破了被动雨水收集模式的局限。首先,DUSSF强调主动化管理——在平时可作为城市公共景观发挥休闲娱乐功能,应急时可按照预案与超标雨水径流系统对接。其次,DUSSF“短响应、超标处理、平急转换”的特征赋予了设施集约利用空间、兼顾多重效益的突出优势,使其更适用于建成区复杂环境中的内涝治理(图1)。随着临近降雨预报^[21-23]、物联网在线监测^[24-26]、优化控制^[27-30]等多样化实时技术的快速兴起,DUSSF的规划管理水平已得到显著提升^[31-33]。通过实时监测降雨量、积水深度和调蓄设施状态,DUSSF能够基于内涝风险预测得到及时启用,并于灾后快速恢复原有功能^[34];同时,借助多目标优化算法对DUSSF进行系统化配置,可在小流域尺度实现上下游错峰排放并显著提升设施运行效率。

在政策扶持与技术迭代的驱动下,DUSSF在增强城市韧性、盘活存量公共空间、完善排水防涝体系及提升防灾应急能力等方面的价值日益凸显。然而,关于其政策、规划设计与技术应用系统如何衔接的研究尚处于起步阶段,亟需从城市规划和景观设计等学科视角对相关进展进行综述。为弥补这一空白,本研究采用文献计量与CiteSpace可视化方法,系统展示DUSSF研究的发展脉络,梳理实时技术赋能DUSSF管理的进展,并重点探讨其空间优化路径。本研究旨在为城市内涝治理与存量空间优化提供理论参考,拓展规划设计学科的研究方向,并为应对极端暴雨的设计实践提供新的视角与思路。

2 研究方法与数据来源

2.1 文献检索与筛选

为确保综述的全面性,本研究首先将“雨水调蓄设施”(stormwater

① 目前,尚未有官方文件提供“平急两用雨水调蓄设施”的标准翻译。参考《城镇雨水调蓄工程技术规范》(GB51174-2017)与相关文献(来源:参考文献[16-18]),本文将其翻译为“Dual-Use Stormwater Storage Facilities for normal and emergency situations”。

storage facilities) 和“平急两用”(dual-use) 确定为中心检索词, 并将其与概念相近的延伸词一并纳入检索。选取Web of Science (WoS) 核心数据库和中国知网 (CNKI) 作为数据源分别筛选英文、中文文献, 于2024年8月进行检索, 时间范围不作限定 (图2)。通过阅读文章标题、摘要和关键词, 保留以城市内涝防治中的水量控制为主题的文章, 排除城市供水、污水管理或水质净化相关研究; 随后, 通过概览全文, 筛选出明确体现平急两用策略而非关注设施单一功能的研究, 将其作为文献计量研究的样本, 以反映该领域的总体发展趋势; 在此基础上, 通过精读全文, 遴选出应用临近降雨预报、物联网在线监测、优化控制等实时技术 (至少包含1种) 的重点文献作为研究案例。

2.2 文献计量与可视化分析

研究采用逐年变化图呈现DUSFF相关中、英文文献发表数量的变化趋势, 并利用CiteSpace 6.4.1对DUSFF学术动态进行可视化分析。首先, 利用关键词聚类分析展示DUSFF相关研究的时间跨度、聚类热点演变及聚类热点间关系; 随后, 利用关键词的突现时间和突现强度来总结DUSFF相关研究的发展阶段。

3 结果与讨论

3.1 文献计量与可视化分析结果

经全文筛选后, 共有114篇文献被纳入文献计量分析。文章发表时间趋势显示, DUSFF相关研究在2019年之前偏少, 2019年后文献数量显著增长, 2020年和2021年出现发文高峰, 且英文文献显著多于中文文献 (图3)。

由于中文研究数量不足, 研究对94篇英文文献进行了可视化分析。聚类时间线分析结果 (图4) 显示, 2016—2024年, 聚类#0“基于自然的解决方案”(Nature-based Solutions, NbS)、聚类#1“蓝绿基础设施”(BGI) 和聚类#2“模型预测控制”(Model Predictive Control, MPC) 之间的关联性最强。BGI是一种实施NbS的空间载体; 实时技术通常用于管理BGI的径流流入与流出, 使其发挥最佳的调蓄效果^[35]; 同时, MPC算法是目前实时技术中应用最广泛的优化算法之一^②。

根据关键词的突现时间与强度分析结果, 可将DUSFF的发展划分为3个阶段 (图5)。第一阶段为概念构建阶段 (2016—2019), “基础设施”(infrastructure)、“系统性/智慧城市”(system/smart cities) 等关键词突现表明DUSFF的最初定位是智慧城市中的新型基础设施系统; 第二阶段为问题导向阶段 (2019—2022), “绿色基础设施”(green

② MPC 是一种在线优化算法, 利用预测模型生成控制信号并实时校准, 实现真实空间与仿真模型的实时交互。

infrastructure)、“气候变化”(climate change)、“洪涝风险”(flood risk) 等关键词表明极端降雨、洪涝减灾与NBS相关议题逐渐得到关注; 第三阶段为技术深化阶段 (2022—2024), 随着实时技术的升级迭代, “物联网”(IoT)、“模型预测控制”(MPC) 等关键词涌现, 而DUSFF的内涝调节绩效 (performance) 也得到了学界的充分关注。

3.2 DUSFF研究脉络

3.2.1 DUSFF概念溯源

作为中国公共基础设施政策导向下的新术语, DUSFF虽尚未成为在全球范围内被广泛认可的学术概念, 但其背后功能平急转换的核心理念在国内外早期研究与实践中均有迹可循。20世纪末, 日本、美国等国家便已开展了DUSFF相关实践。日本在千曲、宇都宫、冈崎、寝屋川、姬路等地的城市规划中, 有机衔接了学校操场、绿地、停车场与径流行泄通道, 显著提升了城市防涝能力, 并在全国范围内推广^[36]。美国低影响开发理念中的多功能SSF强调使用基于景观的解决方案来提高雨水设施的功能实用性^[37-39]。例如, 美国伊利诺伊州唐纳斯格罗夫华盛顿公园将足球场用作为应急滞涝池, 可在暴雨时主动引流, 此举亦节省了500万美元的管渠修缮投资^[40]。

2005年, 车伍等提出了适合中国城市情况的多功能SSF设计思路, 并将其分为低凹地、池塘、湿地收集设施、市民生活相关公共设施及大口径调蓄管道^[41-42]。李俊奇等则进一步从技术角度出发, 针对SSF的功能需求差异提出了对应的容积计算方法^[43]。荷兰设计事务所De Urbanisten在2006—2010年期间提出兼顾日常活动与蓄水功能的“水广场”(Watersquare) 理念^[44-45], 多个水广场项目陆续在荷兰鹿特丹、蒂尔、阿姆斯特丹等城市落地, 收获了广泛的社会认可; 挪威学者奥德瓦尔·林德霍姆等也在同一时期提出基于降雨强度的三阶段雨水调蓄方法——日常降雨保障自然渗透消纳, 中等降雨滞留延迟洪峰, 极端降雨确保行泄路径畅通^[46]。

自2021年中国全域推进海绵城市建设以来, 建立兼具雨水调蓄功能的城市开放空间系统逐渐成为了城市设计领域的热点。例如, 魏广龙等提出应探索地下功能空间和蓄水空间的季节性复合开发模式^[47]; 王峤等则强调增加各层级“开放空间可浸区”面积比例来增强城市内涝韧性^[48-49]。世界各地也涌现了大量实践案例。马来西亚吉隆坡的“精明隧道”平时作为隧道发挥交通功能, 中等降雨时部分雨水会被引入用作排水通道的低速道路, 暴雨时则全部转换为排洪通道, 用于疏导径流^[50]; 新西兰奥克兰桑尼努克公园更新项目将橄榄球场与径流行泄通道衔接, 使前者在暴雨条件下发挥短时滞涝功能^[51]; 德国汉堡市大力提倡将社区球场和儿童活动场地作为应急性SSF^[52]; 沈阳市仙女湖社区公园可通过闸门短时引入附近河道的洪水, 待暴雨峰值过后利用退水闸错峰排放^[53]。

回溯全球DUSFF理论与实践发展, 结合最新设计导则及龚晓露

等^[54]、张鑫男等^[18]学者的研究成果,可将DUSF界定为:综合利用部分城市公共空间,在不影响其平时功能的前提下,经空间改造或同步建设形成的可短时存储雨水的调蓄设施,是海绵城市超标雨水径流处理系统的重要组成部分。

3.2.2 DUSF分类

目前,学界主要依据管理方式、竖向空间、用地性质对DUSF进行分类。依据其功能平急转换时是否需人工参与管理决策,可将DUSF划分为主动管理型和被动转换型^[55-56]。主动管理型DUSF可视为城市中的微型滞涝区,启动其临时调蓄功能需要满足一定的灾害条件,并通过路面、管道或水泵引流;被动转换型DUSF则主要依靠竖向做功,积水达到一定深度时便会被动流入DUSF。

依据设施所处的竖向空间,可将DUSF分为地上、地下和湖泊3类^[54]。依据其所嵌入的城市用地性质,则可划分为公园绿地型、防护绿地型、广场用地型、停车场用地型、体育用地型和市政用地型等类型。不同用地性质对DUSF的空间设计方案与功能转换逻辑影响显著:公园绿地型DUSF在平时便发挥一定的基础调蓄功能,应急时则转变为集中调蓄状态;而广场用地型、体育用地型、停车场用地型等硬质空间需通过引流口、临时围挡和排水闸门等构造措施在既有设施体系中“嵌入”应急调蓄功能,日常降雨保持排水畅通,暴雨内涝时按预案启闭形成临时滞蓄区,灾后快速排空并恢复使用。

3.3 实时技术赋能DUSF

在应对突发性的内涝灾害时,尽管功能平急转换的理念具有突出的优越性,但针对DUSF“如何启用、怎样恢复”的难题仍缺乏系统性解决方案。一方面,若DUSF启用过早或不及时,其削峰效果会大幅减弱;另一方面,若不能及时排空积涝,也会带来一定的安全风险,如行人可能失足跌入水中,积涝中的致病菌群可能引发公众疾病^[57],长期积涝可能造成不耐淹植物死亡进而提升维护成本等。为此,2019年以来,学界涌现出大量采用临近降雨预报、物联网在线监测及优化控制技术等等来管理DUSF的研究。需要强调的是,应用实时技术的DUSF属于主动管理型,参照《城镇排水系统实时控制技术标准(征求意见稿)》,可以按照设施的控制水平将其进一步划分为单元级(本地化自主决策)和系统级(分布式协同决策)。

在计量分析中,共筛选出涉及时技术应用的重点文献80篇(英文75篇,中文5篇)。从全球分布看,美国以27.27%的占比位居第一,其次是中国和澳大利亚,分别为20.45%和9.09%,英国、加拿大、爱沙尼亚等国家和地区也为该领域的发展做出了贡献。表1列举了近年来发表在高水平国际期刊上的单元级与系统级DUSF管理研究案例,并比较了其场地面积、所采用的实时技术及设施绩效^[58-71]。

3.3.1 单元级管理

单元级管理指对单体DUSF运行状态进行优化控制,主要通过在线监测降雨量与积水深度来动态管理设施出流,进而调节暴雨中每个汇水区的峰值出流,缓解下游排水压力。

地上DUSF方面,荷兰阿姆斯特丹自由大学^[58]和意大利卡利亚里大学团队^[59]先后提出不同的智慧蓝绿屋顶方案,其原理是通过增加屋顶蓄水层和智能阀门,以6 h为周期预测降雨量,动态调节蓝绿屋顶的蓄水、用水情况,可削减极端暴雨下70%~97%的屋顶出流;美国田纳西州立大学团队提出使用实时技术优化雨水花园设计,使其调蓄能力比传统生物滞留池提高约11%^[60];加拿大魁北克国立科学研究院团队近年来持续关注景观雨水滞留池的实时控制与峰值出流削减,最早由卡琳·比洛杜等于2018年提出:在场地末端增设一处雨水滞留池和自动阀门,根据池内水深和未来6 h降雨量设定多个阀门开度,可削减46%的暴雨峰值出流^[61];而后团队成员沙达布·希谢加尔等进一步完善了优化算法,按照30 min/次的频率调整阀门状态,使峰值出流削减了73%~95%^[62]。另外,尼尔斯·坎德勒等在建筑周边设置可淹没停车场,使单个城市汇水区的峰值出流削减了50%以上^[63]。周怀宇等针对城市小型水体的调蓄容积在暴雨前往往无法得到释放的问题,基于以5 min为周期的预测算法实现景观雨水滞留池的提前排空与峰值启用,使汇水区峰值出流削减了多达45%^[64]。

地下DUSF方面,孙蓝心等基于以5 min为周期的预测算法,优化深圳海绵社区的地下蓄水模块,削减了23%~58%的峰值径流^[65];谢明坤等开发了一套基于物联网在线监测的绿色基础设施监测与控制系统,实时评估并同步调节雨水调蓄模块的性能,使场地雨水收集率达到75%^[66]。钟晔等使用基于预先设定规则的控制技术调节调蓄模块末端排水口的开闭状态,显著提升了其在暴雨时的运行效率^[67]。

3.3.2 系统级管理

系统级管理指在相互关联的城市排水区内,通过实时协同管理多个单元级DUSF,确定优先排水区与错峰排水区,进而减缓高内涝风险区的排水压力^[72-73]。丹麦科技大学团队提出将道路作为临时行泄通道,实时组织超标雨水径流排往公园、滑板场、足球场等临时蓄水场地以实现错峰排放^[68,74],相关案例通过管理占研究区域总面积7%的道路,显著削减了暴雨时哥本哈根社区的雨污合流制溢流总量。爱沙尼亚塔林理工大学团队则构建了道路蓄滞单元,利用占塔林市旧城区总面积约6%的开放空间使内涝节点数量减少了30%^[69];周怀宇等以“智慧内排水屋顶”系统管理了占街区总面积11%的屋顶,使街区内涝面积减少了30%,并使一处高风险下穿道路的内涝时长和深度分别减少了50%和28%^[70];该研究团队还以长沙市望城坡老旧小区为例,利用占社区总面积5%的智慧水广场,使社区的内涝面积减少了46%~48%,并使最大水深降低近40%^[71]。

表 1: 实时技术赋能 DUSF 研究案例

类型	研究对象	面积 (hm ²)	实时技术			绩效	来源
			临近降雨 预报	物联网 在线监测	优化 控制		
单元级	多层蓝绿屋顶	—	√	—	√	削减 70% ~ 97% 的屋顶出流	参考文献 [58-59]
	雨水花园	—	√	√	—	蓄水能力提高 11%	参考文献 [60]
	雨水滞留池	142.00	√	—	√	峰值出流平均削减 46%	参考文献 [61]
	雨水滞留池	311.00	√	√	√	峰值出流削减 73% ~ 95%	参考文献 [62]
	可淹没停车场	12.00	—	√	√	峰值出流削减 50% 以上	参考文献 [63]
	雨水滞留池	0.85	√	√	√	汇水区出流峰值削减多达 45%	参考文献 [64]
	海绵社区地下雨水模块	1.14	√	—	√	峰值径流削减 23% ~ 58%	参考文献 [65]
	雨水调蓄池	1.25	—	√	√	雨水收集率达到 75%	参考文献 [66]
	雨水调蓄池	215.00	—	√	√	调蓄池处理量提升 5% ~ 30%	参考文献 [67]
	系统级	道路行泄通道与临时蓄水景观	150.00	—	√	√	雨污合流制溢流量平均削减 12.4%
道路滞蓄单元		41.90	√	—	√	内涝节点数量削减 30%	参考文献 [69]
高密度街区内排水屋顶		130.00	√	√	√	街区内涝面积削减多达 30%	参考文献 [70]
智慧水广场		450.00	√	√	√	内涝面积削减 46% ~ 48%	参考文献 [71]

3.4 DUSF空间优化路径

由综述可知,虽然国内外普遍认为DUSF在城市排水防涝和应急响应体系中具有较大的应用潜力,但也有学者指出在高密度建成区推广DUSF仍面临研究与实践瓶颈^[64,70-71]。基于用地识别、全灾害周期配置和系统级管理3个维度,本研究进一步梳理了文献中对DUSF优化路径的探讨与建议,旨在为DUSF规划设计提供新的研究思路与实践指导。

3.4.1 DUSF的用地识别优化

在城市排水防涝体系中,DUSF的作用原理与城市蓄滞洪区和雨洪公园类似^[75],注重将城市微观尺度的公共空间转化为临时性调蓄设施。然而,目前对存量公共空间防灾功能的研究主要评估其可达性与

供给是否充足,关注这些空间在地震、火灾、公共卫生事件中的安置、疏散、隔离能力,对短时超标雨水径流的应对能力研究相对不足^[76-77]。造成这一不足的主要原因有以下几方面:1)缺乏对DUSF空间原型与设计导则的系统性归纳,导致缺少有效识别方法来评估各类公共空间的改造潜力;2)在以实现年径流总量控制率达标为主要导向的情况下,存量区域的SSF常基于固定重现期进行设计,而对于超出常规的紧急情况,则缺乏科学的雨水调蓄指标分配机制,导致难以在中小型降雨控制和内涝应急之间调蓄容积;3)各类城市公共空间与主要径流行泄通道衔接不足,上下游SSF缺乏协同^[78-80];4)园林绿化、水务、街道等不同行政部门或单元对DUSF的管理权责尚不清晰,协同调度方式亟待优化。例如,李鹏程等以上海中心城区为例,提出“韧性六步法”以识别和布局DUSF用地^[81];周怀宇等在智慧水广场研究中提出可叠

加坡度、围合性、渗透性、距行泄通道与内涝点距离等指标来识别潜在DUSF用地^[71]。

3.4.2 DUSF的全灾害周期配置优化

当前已有研究开始运用遗传算法、模拟退火算法等多目标优化技术平衡各类雨水调蓄设施的水量调控、生态效益与管理成本^[82-84]。然而，此类方法通常基于固定的暴雨重现期和目标函数，尚未考虑“抵御-响应-恢复”的全灾害周期^[85-86]。城市规划和景观设计学科常用的韧性指标评估法虽已取得较大进展，但仍难以完整反映内涝灾害周期中各项城市功能从失效到恢复的过程^[87-88]，这限制了对不同DUSF配置方案的比较。为此，国内外学者提出以系统性能曲线（system performance curve, SPC）方法应对这一挑战。例如，米歇尔·布鲁诺等以“韧性三角”构建了城市功能正常发挥比例（0~100%）与灾害时序的关系^[89]；塞思·N·穆古梅等应用SPC优化排水管渠的配置^[90]；王运涛等则利用SPC描述不同城市用地类型在洪涝灾害中的恢复过程^[91]。最新研究中，李嘉达等利用SPC比较了静态与实时管理下DUSF对美国盐湖城内涝韧性的贡献，发现应用实时技术能显著提升城市从内涝中恢复的速率^[92]。周怀宇等借助SPC评估了不同实时控制周期下DUSF对内涝节点数量的影响，验证了实时技术的内涝调节效果^[71]。因此，后续研究可进一步借助SPC比较不同DUSF配置方案下的城市恢复效率，并将韧性指标纳入优化目标函数，以系统评估配置效果。

3.4.3 DUSF的系统级管理优化

引入实时技术显著提升了DUSF应对突发内涝灾害的能力。目前，基于峰值出流或积水深度的DUSF单元级管理方法已较为成熟，而聚焦上下游协同的系统级管理研究仍相对较少。其主要瓶颈在于系统级管理对城市空间数据需求庞大，且城区尺度的风险预测计算资源消耗巨大，还需将水文水动力机理模型与城市信息模型深度对接，因而在秒级周期内探索全局最优解的目标较难实现^[93]。相较而言，单元级管理主要考虑的是设施自身溢流或积水风险，其运算消耗相对较少，可以直接借助成熟的水文水动力机理模型完成。随着人工智能技术的爆炸式发展，基于人工神经网络的代理模型能在一定程度上解决机理模型的计算速度和误差容忍缺陷。代理模型主要通过大量离线数据训练来消解计算压力，已被应用于城市内涝风险预测和城市空间管理^[93-95]。在最新研究中，本杰明·D·鲍斯等和罗鑫燃等利用多智能体强化学习与长短期记忆网络等机器学习算法，将系统级管理中的全局风险预测时间从分钟级缩减到秒级，且在监测误差等干扰下仍能保证一定的预测稳定性^[96-97]。这些技术有望为实现上下游DUSF的系统管理提供新路径，但相关研究仍处在探索初期，仍需进一步深入。

4 结论

本文采用文献计量方法，对当前DUSF的研究热点与趋势进行了可视化分析，系统梳理了其概念起源与分类体系，并列举了实时技术在单元级和系统级DUSF管理中的研究案例。在此基础上，本文进一步从用地识别、全灾害周期配置和系统级管理3个维度归纳了DUSF的空间优化路径。

研究趋势显示，自2019年起DUSF相关研究显著增长，研究热点已从早期的概念构建逐步转向问题导向，并进入实时技术深化阶段。美国、中国和澳大利亚是该领域的主要贡献国，推动了DUSF在全球范围内的应用与发展。本文阐明DUSF概念源于我国“平急两用”政策及多功能SSF设计实践，可依据管理方式、竖向空间和用地性质对DUSF进行分类。目前，国内外已有多个成功案例验证了DUSF在内涝防治中的有效性。研究前沿方面，实时技术的引入大幅提升了DUSF应对内涝灾害的主动性和精准性，且已形成单元级和系统级两类DUSF实时管理思路，重点可利用临近降雨预报、在线监测与优化控制来提升DUSF的运行效率。

总体而言，DUSF为城市规划和景观设计学科开展城市内涝防治与韧性研究提供了重要契机。首先，在管渠、蓄水池、泵站等传统雨水调蓄系统之外，DUSF是不可忽视的调蓄空间，因此需建立系统化的DUSF用地识别方法，明确其空间原型与设计导则，并完善跨部门、跨学科的协同机制，高效衔接存量公共空间与超标雨水径流处理系统。其次，改进多目标优化配置框架，在DUSF空间配置体系中纳入可反映全灾害周期中城市功能变化的韧性指标，以实现更全面的性能评估。另外，应积极吸纳多学科前沿技术，尤其是基于人工智能的全局风险预测与空间协同技术，探索城市尺度SSF的协同调度方法，从而提升城市系统对内涝灾害的响应速度和管理效能。

需要指出的是，本综述主要聚焦于DUSF实践案例和空间优化路径，对于临近降雨预报、物联网在线监测和优化控制等方法在不同城市环境下的运用，尚缺乏对其具体算法框架与调控周期的系统化比较分析；此外，关于跨学科空间协同在内涝治理中的作用机制及DUSF的长期成效评估，仍有待进一步深入研究和实证验证。

图 1. DUSF 在城市雨水调蓄系统中的应用

图 2. 文献筛选方法

图 3. 所筛选 DUSF 相关中英文文献发表数量变化

图 4. 所筛选英文文献聚类时间线分析

图 5. 所筛选英文文献关键词突现分析