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China's sponge cities alleviate urban flooding and water shortage: a review

Jie Han¹  · Chaoqi Wang¹ · Shihai Deng¹ · Eric Lichtfouse² 

Abstract

About one tenth of humans are impacted by water shortages around the globe. Water resilience is worsening under climate change because intensifying weather extremes induce more severe and increasingly frequent droughts and floods. In particular, China, as the world's most populous nation, has battled with persisting water shortages and devastating floods for decades. As a consequence, Chinese scholars have designed the sponge city concept in the early 2010s to relieve cities from the growing pressure of water shortages and floods. This is done by integrating a more natural, green infrastructure into existing urban drainage pipeline systems for absorbing, storing, and purifying rainwater in a sponge-like manner during rainfall events. Here we review the principles, design guidelines, construction items and assessment requirements of sponge cities and other similar strategies for urban stormwater management. We present four case studies of sponge cities in China in both newly constructed and renovated urban districts. Overall, China's sponge cities appear promising for green urbanization, to relieve cities from water scarcity, devastating floods and urban heat island effects, while restoring the ecological functions and aesthetics of urban natural environments.

Keywords Water scarcity · Flash flood · Stormwater runoff · Urban drainage · Low impact development · Green infrastructure · Urban heat island

Introduction

Over the past century, water consumption by humans has multiplied eight times as a result of population growth, economic booming and dietary alterations (PR 2021). Meanwhile, more than 10% of the world population is suffering from water shortages (Water 2021, Fig. 1). On the average, disasters related to weather, climate and water hazards have occurred every day over the past 50 years, during which

climate change is responsible for about \$202 million and 115 deaths daily, according to the World Meteorological Organization (WMO 2021). Among natural hazards, floods are the third leading cause of casualties, resulting in nearly 60,000 deaths in the past 50 years (UNFCCC 2021).

China has been battling with recurring floods and water scarcity for decades (Han et al. 2021; Han and He 2021). The amount of renewable freshwater resources per capita in China is 2994 m³/year on average, which is only about a quarter of the global average and slightly above the threshold of 2000 m³/year for 'moderate water shortage', according to the Falkenmark indicator of water scarcity (Damkjaer and Taylor 2017; Falkenmark et al. 1989; Liu et al. 2017; NBSC 2021). Moreover, the distribution of water resources is highly uneven between the north and south part of the country. For example, the water resources in eleven provinces in northern China are below 1000 m³ per capita per year—the critical Falkenmark threshold of 'severe water scarcity'—while seven other provinces fall into the category of 'severe to moderate water scarcity' of 1000–2000 m³/year. Under the monsoon climate, even some southern regions experience seasonal water scarcity across the country. In addition

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Fig. 1 Cities around the world have been battling with water shortages and devastating floods. Urbanization, droughts, and extreme rainfall events are major factors. Images from the Internet



Battling with water scarcity & floods

to the natural water scarcity, rapid urbanization and industrialization have also been quickly depleting water resources in China in the past few decades.

Paradoxically, heavier rainfall and devastating floods have become increasingly common in China since the 1990s. Throughout the year of 2021, floods have affected 59.8 million people in the country and left 590 people dead or missing, resulting in a direct economic loss of \$36.7 billion, according to the Ministry of Emergency Management of China (MEMC 2022). In particular, Zhengzhou, the capital of the populous Henan Province in northern central China, was struck by the heaviest rain in a millennium with more than 300 people killed and 124,000 residents displaced, making this event one of the worst natural disasters in 2021. In Europe, record rainfall also led to devastating floods in July 2021. More than 220 individuals died within three days, mostly in Germany, and flash floods destroyed buildings and homes (CNN 2021). Overall, there is an urgent need to improve all society sectors such as urbanization, industrial activities and agriculture, to adapt to and counteract water shortages and floods. Here, Chinese sponge cities appear as a promising example.

Sponge cities

In the five decades between 1945 and 1997, urbanized areas in the United States increased from 6 to about 26 million hectares, an increase in more than 3.3-fold. The amendment to the Clean Water Act in 1987 first put forward the best

management practices for rain and flood management, that is, using wetlands and rainwater infiltration ponds to store and purify stormwater runoff to reduce runoff pollution. In 1990, the Prince George's County in Maryland first put forward the low-impact development, in an effort to combine ecological restoration and facility construction to enhance the county's hydrological cycle (Ma et al. 2021; Xie 2016). Compared with the best management practices, which aimed to achieve total runoff reduction on a catchment scale, the low-impact development focuses more on using small and decentralized facilities to reduce runoff. The concept of low-impact development emphasizes the use of natural ecology including hydrological and soil characteristics to improve water quality. Particularly, the low-impact development aims to restore some urban sites to natural and pre-developed conditions to reduce runoff.

The design concept of low-impact development gained more acceptance in the United States in the early 2000s. Likewise, the Council on Sustainable Development in the United States put forward the concept and use of green infrastructures. The American Planning Association stated that green infrastructure is an interconnected network of open spaces and natural areas such as tree-planting along streets, wetlands, parks, forests, and other vegetation areas. The green infrastructure alleviates, in a natural and passive manner, urban runoff flows, waterlogging, and flooding issues, while it also reduces runoff pollution and improves urban water quality. Given the important role of green infrastructure in stormwater management, the Public Utilities of Seattle proposed the green stormwater

infrastructure, as a class of nature-based utilities in urban stormwater management. The green stormwater infrastructure includes rain gardens, permeable pavement, and green roofs, which are widely adopted today in the development of sponge cities.

Similar practices were also developed early in other countries. The United Kingdom, for instance, was one of the first countries in the world that had modern municipal drainage infrastructure. The average annual precipitation in the country typically exceeds 1000 mm. In large parts of its west regions, near the Atlantic Ocean, there are often short and heavy rainfalls with annual precipitation exceeding 1500 mm. In some communities, aging drainage infrastructures and their limited design capacities cannot cope with the continuing urbanization and population growth. As a response, the sustainable urban drainage systems were proposed in 1999 to alleviate these issues. A complete set of guidelines on sustainable urban drainage systems were issued in 2000, providing a separate design manual for Scotland, Northern Ireland, England, and Wales. It was not until 2010, however, that the UK Parliament passed the Flood and Water Management Act, which officially launched the sustainable urban drainage systems throughout the United Kingdom. The idea of sustainable urban drainage systems is to maximize the use of the existing watershed before the urban development, and to minimize the impact on the quantity and quality of stormwater runoff (Oladunjoye et al. 2022).

The concept of sponge city is a holistic approach in planning, construction and management of urban water resources for more resilient ecological and drainage infrastructures. Proposed by Chinese scholars in the early 2010s, sponge city guidelines were integrated into urban development policies by the Chinese government since 2014. Similar ecological models include the low-impact developments in the United States, the sustainable urban drainage systems in the United Kingdom, the water sensitive urban design in Australia and the low impact urban design and development in New Zealand (Chan et al. 2018). The unique aspect of the Chinese concept of the sponge city is to manage stormwater in a sponge-like manner by absorbing, storing and purifying water in soils, lakes and vegetation (Fig. 2). A sponge city integrates natural ecological resources and constructed infrastructures into one resilient stormwater management system (EPA 2000a). Unlike traditional pipeline-based drainage systems, the sponge city management offers many benefits such as relieving waterlogging at the source, reducing pollution by runoffs, conserving freshwater, alleviating the urban heat island effect by vegetation cooling, and aesthetic value for inhabitants.

Sponge city is capable of restoring urban ecologies and rebuilding urban hydrological systems (Lan 2021). The universal construction of large and impermeable surfaces in urban environments weakens the function of natural grounds in aiding water infiltration, purification, and re-circulation. By restoring those surfaces through



Fig. 2 Water cycle in a sponge city. By contrast with traditional urban drainage systems based on pipes and channels, initiated in Paris and other European cities during the first half of the nineteenth century (Burian and Edwards 2012), the sponge city integrates green infrastructures that allow infiltration, purification, and storage of rainwa-

ter. Sponge cities alleviate urban flooding and heat island effect, conserve freshwater resource, improve quality of runoffs, and restore the ecological functions and landscapes of urban environments. Adapted from Chan et al. (2018) with variations

permeable paving, the natural drainage system can be restored partially, allowing rainwater and floods to seep into the ground more quickly. This mechanism, which can significantly reduce the flows of surface runoff during heavy falls and simultaneously decrease the pollution of waterbodies by inflows of surface runoff, can purify the water and replenish urban groundwater aquifers (Fig. 2). In the meantime, sponge cities can alleviate the heat island effect, creating a more amenable living environment for city dwellers. Guidelines and examples on how to build a sponge city are given in next sections.

Planning and construction

The sponge city maximizes the infiltration, conservation, and natural purification of rainwater by integrating existing natural resources such as trees, lakes, rivers and wetlands with constructed facilities such as pipes, dams and permeable pavements. This system also diminishes the pressure on stormwater drainage systems in heavy rainfall events. Compared to conventional roof or ground rainwater collection, which store collected rainwater in reservoirs, the sponge city pays more attention to the natural infiltration, storage and natural purification of rainwater.

Sponge cities do not necessarily demolish or replace the traditional drainage system, but accentuates the city's own ecological and landscape infrastructure. There

are two approaches to build a sponge city, one for the building of new cities in a natural environment and one for renovating existing cities. For new cities, urban planners should minimize the alteration of natural hydrological characteristics to favor infiltration and storage of rainwater in grass swales, rain gardens and natural wetlands. For existing cities, issues of urban waterlogging and sewage overflows can be alleviated by constructing permeable pavements, green rooves, sunken greenbelts, underground water storage and buffering facilities.

Planter boxes and other low-impact development tools

The low-impact development approach is considered to be an effective approach to reducing runoffs and pollutant loadings at sources according to the United States Environmental Protection Agency (EPA). In 1999, the EPA issued two public guidelines, namely the "Low-impact development design strategies: an integrated design approach" and the "Low-impact development hydrologic analysis". Apart from a detailed hydrologic analysis, the latter provides a series of computational tools and models that can be used for determining the requirements for low-impact development in stormwater management (EPA 2000b). In general, there are four primary types of low-impact development tools for

Fig. 3 a Planter boxes, b a bioswale, c a rain garden, and d a permeable pavement. Adapted from EPA (2018)

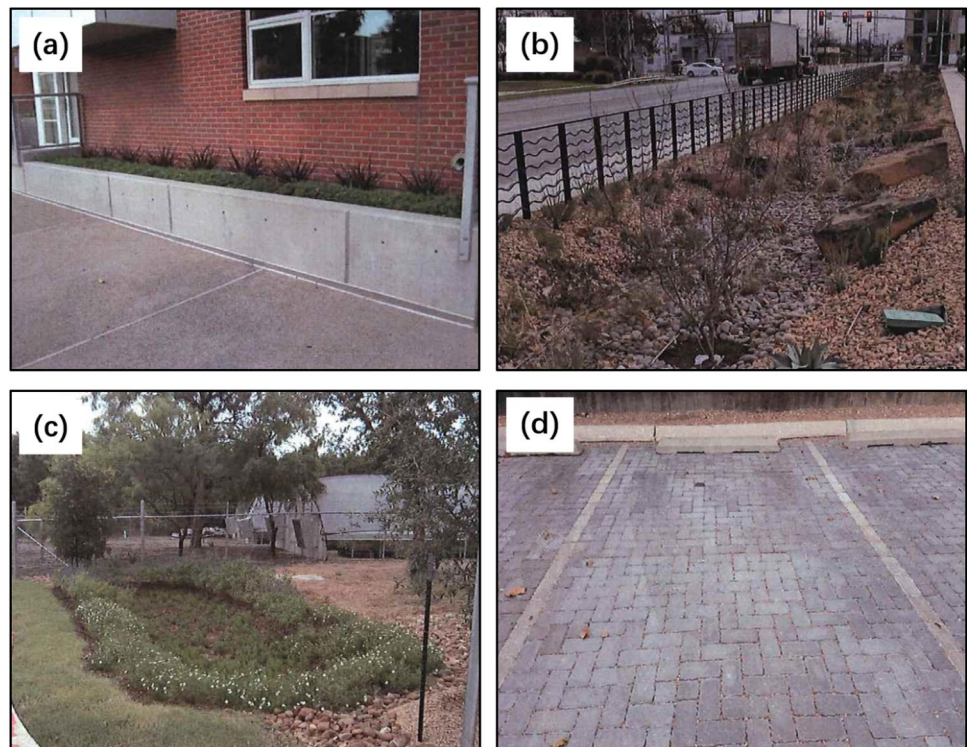


Table 1 Assessment items and requirements for the sponge city development in the 'Assessment standard for sponge city effects, a Chinese national standard (GB/T 51345-2018). The standard is pub-

lished online in English and freely accessible on the International Water Association publishing site. Adapted from Wang et al. (2020)

Assessment item	Assessment requirement
1. Volume capture ratio of annual rainfall and runoff volume control	<p>(1) For new development areas, the volume capture ratio must be not smaller than the lower limit of the value specified according to the 'Zoning map of volume capture ratio of annual rainfall in China' (Fig. 3), and runoff control volume must be not smaller than the corresponding runoff volume calculated using the volume capture ratio.</p> <p>(2) For re-development areas, according to technical and economic comparison, the capture ratio is not recommended smaller than the lower limit specified according to the 'Zoning map of the volume capture ratio of annual rainfall in China' (Fig. 3), and the corresponding runoff volume calculated from the volume capture ratio.</p>
2. Implementation effectiveness of the source reduction project	<p>Residential area</p> <p>(1) Volume capture ratio of annual rainfall and the runoff volume control:</p> <p>(i) for new development projects, the ratio should be not lower than the lower limit of the value specified according to the 'Zoning map of the volume capture ratio of annual rainfall in China' (Fig. 3), and the calculated corresponding runoff volume; and</p> <p>(ii) for redevelopment projects, according to technical and economic comparison, the ratio is not recommended lower than the lower limit of the value specified according to the 'Zoning map' (Fig. 3), and the calculated corresponding runoff volume, or meet the similar control requirements of urban planning.</p> <p>(2) <i>Runoff pollution control</i> annual runoff pollutant reduction, in terms of suspend solids (SS) is not recommended less than 70% for new development projects and 40% for redevelopment projects or meet the similar control requirements of urban planning.</p> <p>(3) <i>Peak runoff control</i> for the design storm events of minor and major drainage systems, the peak runoff discharge is not recommended exceed the original value before the development of the new development projects; for redevelopment projects, the peak runoff discharge must not exceed the value before the redevelopment.</p> <p>(4) Impervious land surface ratio is not recommended larger than 40% for new development projects; and should not be larger than the original ratio for redevelopment projects, but not recommended larger than 70%</p> <p>Roads, parking lots and open squares</p> <p>(1) <i>Roads</i>: runoff pollution should be controlled according to the requirements of planning and design of the projects. For roads with flood prevention and drainage functions, the drainage function and capacity should be maintained.</p> <p>(2) <i>Parking lots and open squares</i>:</p> <p>(i) Volume capture ratio of annual rainfall and runoff volume control:</p> <p>(a) for new development projects, the ratio should be not smaller than the lower limit of the value specified in the 'Zoning map' (Fig. 3), and the corresponding runoff volume calculated using the volume capture ratio; and</p> <p>(b) for redevelopment projects, the ratio is not recommended lower than the lower limit of the value specified in the 'Zoning map' (Fig. 3), and the corresponding runoff volume calculated.</p> <p>(ii) <i>Runoff pollution control</i>: annual runoff pollutant reduction (in terms of SS) is not recommended less than 70% for new development projects, and 40% for redevelopment projects.</p> <p>(iii) <i>Peak runoff control</i>:</p> <p>(a) for the design storm events for minor and major drainage systems, the peak runoff discharge is not recommended exceed the original value before the development of the new development projects;</p> <p>(b) for redevelopment projects, the peak runoff discharge must not exceed the value before the redevelopment.</p> <p>Park and protective greenspace</p> <p>(1) For new development projects: the runoff control volume must be not smaller than the calculated runoff volume corresponding to the volume capture ratio of annual rainfall equals to 90%; and for redevelopment projects, after economic and technical comparison, the runoff volume control is not recommended less than the calculated runoff volume subject to the volume capture ratio of annual rainfall equals to 90%.</p> <p>(2) The area should receive the runoff from surrounding areas according to the requirements of planning and design of the projects.</p>
3. Road surface ponding and local flood control	<p>(1) Combine grey and green infrastructure solutions in a way that maximizes the role of green infrastructure facilities in detention and reduction of the peak runoff values, and</p> <p>(2) Surface ponding should not occur under the design storm events of minor drainage system</p> <p>(3) There must be no local flooding under the design storm events of major drainage system</p>
4. Urban water quality	<p>(1) The grey and green infrastructure solutions should be combined reasonably to fully utilize the role of green infrastructure in the control of runoff pollution, combined sewer overflows (CSOs) and water quality purification.</p> <p>(2) During dry weather conditions, no sewage or wastewater is discharged directly without treatment.</p> <p>(3) During wet weather conditions, the pollution discharges from separated sewer systems because of mis-connections or CSOs must be controlled, and should not lead to malodorous water bodies; or the discharges from overflow outlets of the mis-connected separate systems and CSOs should be controlled, such that the volume control rate of annual overflow should be not less than 50%, and the monthly average SS concentration discharged from overflow treatment facilities should not exceed 50 mg/L.</p> <p>(4) No malodorous waterbody: transparency > 25 cm (in case the water depth is less than 25 cm, the index value is taken as 40% of the water depth), dissolved oxygen > 2.0 mg/L, redox potential > 50 mV, ammonia nitrogen < 8.0 mg/L.</p> <p>(5) Should be not inferior to the water quality before the sponge city infrastructure is installed. When there is upstream inflow to the river system, the water quality of the downstream river cross sections is not recommended worse than the upstream inflow water quality during the dry weather conditions.</p>
5. Natural ecological pattern management and shore line for ecology conservation	<p>(1) The surface area of natural waterbodies is not recommended reduced before and after urban development, and the natural topography and landscape pattern should be restored and rehabilitated maximally. Natural flood channels, flood plains and ecologically sensitive areas, such as wetlands, forest and grass lands must not be occupied; or the management and control requirements of the blue green lines should be met, according to urban planning.</p> <p>(2) The ecological shoreline of the new and redevelopment of urban water bodies is not recommended not less than 70%, except for the dock for production and necessary shorelines reserved for flood control and protection according to urban planning.</p>

Table 1 (continued)

Assessment item	Assessment requirement
6. Variation trend of the groundwater depth	The descending trend of annual average groundwater phreatic level should be alleviated.
7. Urban heat island effect mitigation	The average daily temperature difference between the urban areas and the surrounding suburbs during summer seasons—June to September—should have a descending trend, comparing to the same period in history, subtracting the impacts of natural temperature variation.

infrastructure projects: planter boxes, bioswales, rain gardens and permeable pavements.

Planter boxes are small bioretention lots that can effectively control runoffs, especially when they are installed throughout the site. By directing runoffs into planter boxes, the soils and vegetation can purify the runoffs before they enter the catch basin. Typically, each planter box has a container full of soil mixture, a mulch layer and underdrains. These often blend well with their surroundings, even in highly urbanized areas (Fig. 3a).

Bioswales play a critical part in both the conveyance of stormwater runoffs and the improvement of water quality. They can quickly absorb low flows and direct large flows to downstream storage during heavy rainfall events. Water quality is improved as the first flush of stormwater runoff infiltrates into bioswales, and large flows are filtered through gravels and vegetations as they flow through the bioswale (Fig. 3b).

Rain garden is another bioretention facility with aesthetic appeal and effective means of stormwater management. Rain gardens are generally built on lower grounds to receive infiltrates of runoffs from rooves and pavements through the surrounding soils, and have the appearance of 'landscape basins' to increase aesthetic appeal (Fig. 3c).

Permeable pavement is a versatile and widely used form of stormwater management. It allows rainwater runoffs to easily infiltrate into the underneath gravel layer through the small voids or aggregate-filled joints on the pavement. Permeable pavement can be easily retrofitted into existing site plans, such as parking lots and sidewalks, to replace impervious surfaces without altering the overall design (Fig. 3d).

In China, the sponge city national initiatives took place in the 2010s, after similar ideas had been proposed in developed countries. However, it should be pointed out that the sponge city, including its models and concepts, are not merely an identical set of technical guidelines equivalent to those earlier approaches and practices such as low-impact development, green stormwater infrastructure, and best management practices. Indeed, China's national initiatives on sponge city development are currently the most comprehensive plans on policies and technical requirements on low-impact development for urban stormwater management.

The set of plans offer guidelines on all aspects of the sponge city, from planning to construction and monitoring. This includes early-stage planning of urban ecosystems comprising of 'green' and 'gray' infrastructures, as well as technical specifications and requirements on hydrological parameters such as control of runoff volumes and peaks. These guidelines aim to address aggravating water shortage and flooding crises.

Design guidelines

In October 2014, the Ministry of Housing and Urban–Rural Development of China issued an early version of the 'Technical guide for sponge city construction—low-impact development rainwater system construction'. This guide laid down the theoretical and technological framework for the development of sponge city by specifying the requirements and methods of urban planning, engineering design, construction, management and maintenance of low-impact stormwater management in urban environments (MHURD 2014). The guide made it clear that low-impact stormwater management systems should not alter the existing hydrological parameters of the site in development, and that the 'volume capture ratio of annual rainfall' and the 'runoff control volume' should both be assessed as key performance indicators. In addition, the guide reiterated that low-impact systems should work synergistically with existing pipe and drainage systems on urban stormwater management, and be integrated into urban water conservation and flood control systems.

Table 1 provides an overview of the assessment items and requirements in the 'Assessment standard for sponge city effects', a Chinese national standard for sponge city development (GB/T 51,345–2018). An English version of the standard has been made freely available on the International Water Association website (Wang et al. 2020). Three earlier national standards, namely the 'Technical code for design of outdoor wastewater engineering' (GB 50,014–2006), 'Technical code for rainwater management and utilization of building and sub-district' (GB 50,400–2016), and the 'Technical code for urban flooding prevention and control'

(GB 51,222–2017) are used as its primary references. There are five required indicators for assessment:

- the volume capture ratio of annual rainfall and runoff volume control,
- the implementation effectiveness of the source reduction project,
- the control of road surface ponding and local flood,
- urban water quality,
- natural ecological pattern control and shoreline for ecological conservation.

Additionally, the variation trend of groundwater depth and the mitigation of urban heat island effect can be used as optional indicators for assessment.

Development of sponge cities in China

China can provide valuable references for the development of sponge cities in densely populated countries and regions (https://en.wikipedia.org/wiki/Sponge_city). Since 2014, China has started implementing the sponge city national initiatives, covering 657 cities nationwide with a total budget estimate of 1.5 trillion US dollars. Thirty cities and areas, including new development areas and older urban districts, were selected as pilot areas based on their local climate, precipitation, geographic location, and socioeconomical development (Fig. 4).

Table 2 shows the categorized lists of the pilot areas. Each pilot area is required to have a size no less than 20 square km, with a three-year construction or transition timeframe for sponge city development. Of these, the Xixian New Area, where the iHarbour campus of Xi'an Jiaotong University is located, was selected as one of the pilot areas. The task plan is to leverage from the experiences and lessons learnt from 'pilot cities' and then to formulate a set of practices and policies that can be readily applied to cities nationwide. As of December 2019, these pilot areas had completed nearly 1000 square km of construction or renovation under the sponge city initiatives. According to the national initiatives, more than 80% of the areas in urban districts of pilot cities should meet the requirements of the sponge city standards by 2030, including new site constructions in new development areas and renovations in older urban districts. In the following subsections, we detail four case studies of sponge cities in China.

The Shangyu District of Shaoxing, Zhejiang province

The Shangyu District is one of the provincial key-construction towns in the Zhejiang province with a total planning

area of 2.8 square km (Fig. 5). The sponge city project of the Shangyu District was conducted in two stages, where the first-stage construction covered an area size of 112,510 m². The project set up a complete urban water resources management system by absorbing and retaining surface runoffs at source and combining low-impact 'green infrastructure' with stormwater drainage pipework. Water quality was improved and new landscape water bodies were created after the sponge city construction, without increasing the volume of stormwater runoffs to the surrounding areas of the district. The main performance indicators include the volume capture ratio of annual runoff ($\geq 70\%$ by volume, i.e., the ratio of the average annual rainfall volume controlled through natural and artificial infiltration, retention, purification and other measures, as compared to the average total annual rainfall volume), flood control standard (one-in-100-year storm events, by recurrence interval), annual runoff pollutant reduction from non-point sources (total suspended solids in annual runoff should be reduced by 37% or more), and utilization of rainwater resource (rainwater utilization should be increased to 4.9% or more, by volume).

The major facilities used in this project include permeable pavement, sunken greenbelts, self-purifying landscape water bodies and rainwater reuse systems (Fig. 6). Outdoor grounds mainly used permeable concrete paving (73.6%, by area), modified asphalt and granite paving (19.3%, by area), permeable ceramic brick paving (5.1%, by area), and high-resistance bamboo outdoor flooring (1.9%, by area), which is corrosion-resistant, high-strength and durable. The total size of permeable paving areas is approximate 45,000 m². The sunken greenbelt is a piece of grassland that is cultivated with native herbs and is no more than 200 mm below the surrounding roads or pavements. The total area of sunken greenbelts built in this project was about 3000 m². In addition, a total area of 10,773 m² of self-purifying landscape water bodies were constructed in the project, with a controllable depth of 100 mm and a storage capacity of nearly 1100 m³.

To improve water quality, aquatic plants were grown in waterfronts and shoring areas to purify ground runoffs entering the landscape water body. The rainwater collection and reuse system were installed within the sunken greenbelts. The system has a maximum storage capacity of 200 m³ and comprises seven modules, namely rainwater collecting and converging pipes, a diverting well, screen baskets, coarse filters, modular containers, a rainwater treatment device buried underground and a valve well, before the water reaches the point of use. The recycled rainwater is used for greenbelt sprinkling, road flushing and car washing, with an approximate daily usage of 24,400 m³. After completing the project, the volume capture ratio of annual rainfall reached 87% (by volume) within the district, exceeding the design target of 70% (by volume) and nearly doubled the equivalent

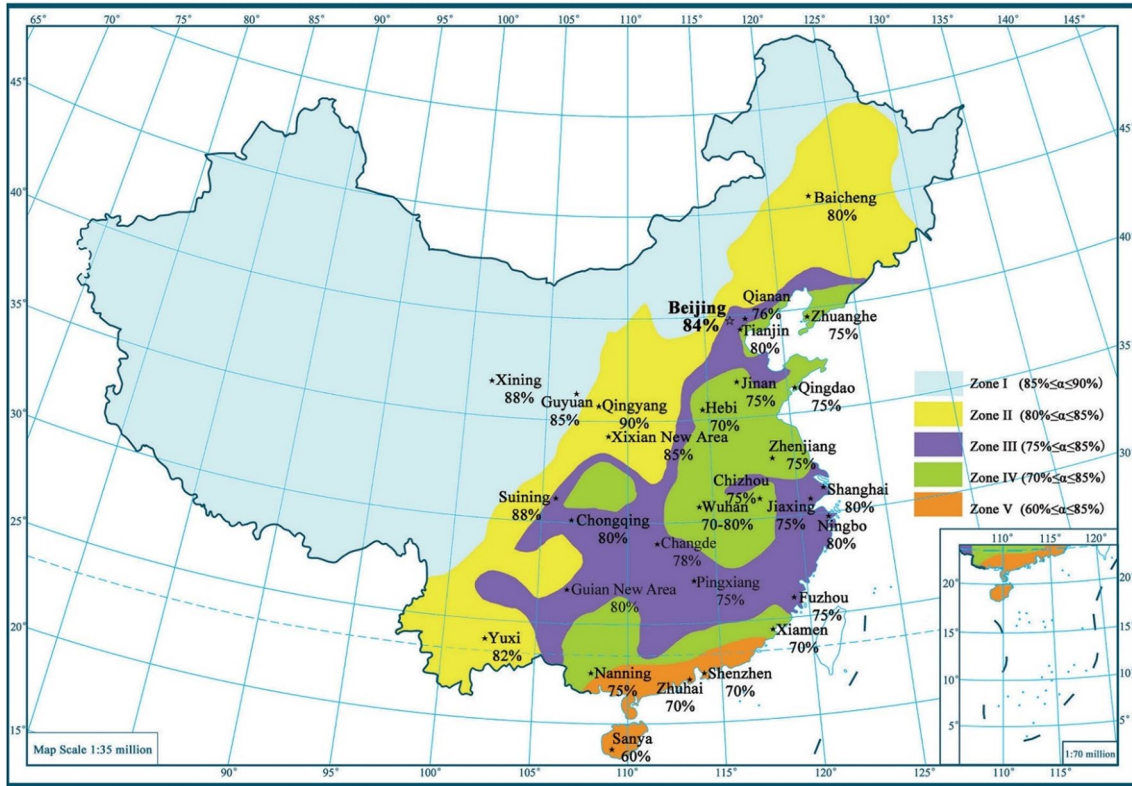


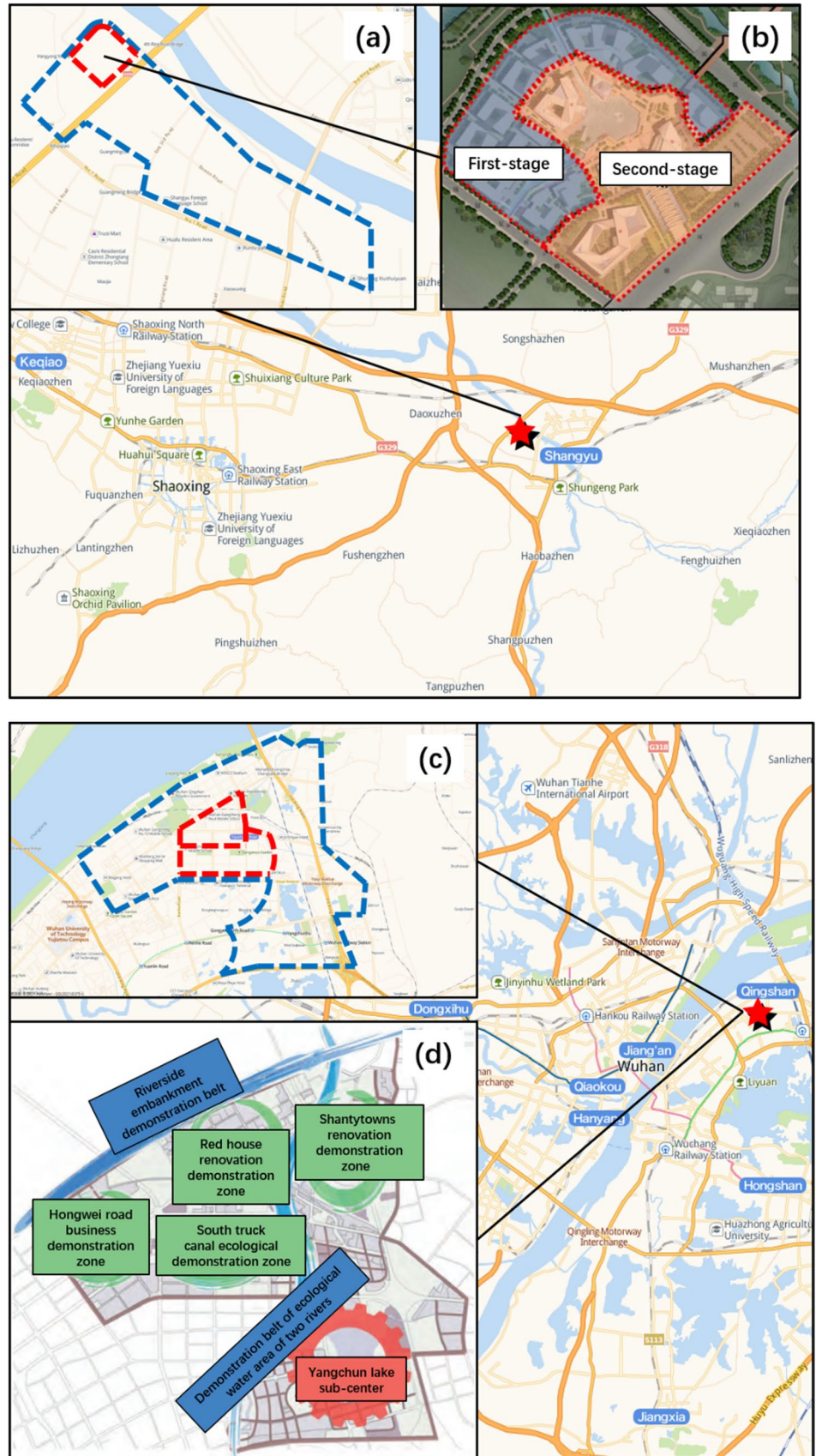
Fig. 4 Locations and volume capture ratio targets of 30 pilot areas for the sponge city development in China. Map shows the zoning of volume capture ratio of annual rainfall in China under the current national initiatives. The notion “ α ” denotes the volume capture ratio of annual rainfall. Based on the “assessment standard for sponge city effects” (Wang et al. 2020), the volume capture ratio of annual

rainfall is defined as the ratio of the average annual rainfall volume controlled through natural and artificial infiltration, retention, purification and other measures, as compared to the average total annual rainfall volume. Information on Hong Kong S.A.R., Macau, and Taiwan is temporarily unavailable. Adapted from Yin et al. (2021)

Table 2 Distribution of pilot areas in China under the sponge city national initiatives

Classification	Scale	Number of pilot areas
Annual total runoff control rate zoning	Zone I	2
	Zone II	4
	Zone III	12
	Zone IV	9
	Zone V	3
City size (population)	Supercities, more than 10 million inhabitants	4
	Megacities, 5–10 million	3
	Large cities, 1–5 million	7
	Medium-sized cities, 500,000–1,000,000	9
	Small cities, less than 500,000	7
City level	Municipalities directly under the central government	4
	Deputy provincial city	6
	Prefecture level	16
	State-level new district	2
	County-level city	2
Location	South	18
	North	12

Fig. 5 Top: location of the Shangyu District in Shaoxing, Zhejiang province: **a** Planned area for sponge city development, **b** first- and second-stage construction. Bottom: location of the Qingshan District in Wuhan, Hubei province: **c**, and **d** planned areas for sponge city renovation in the project



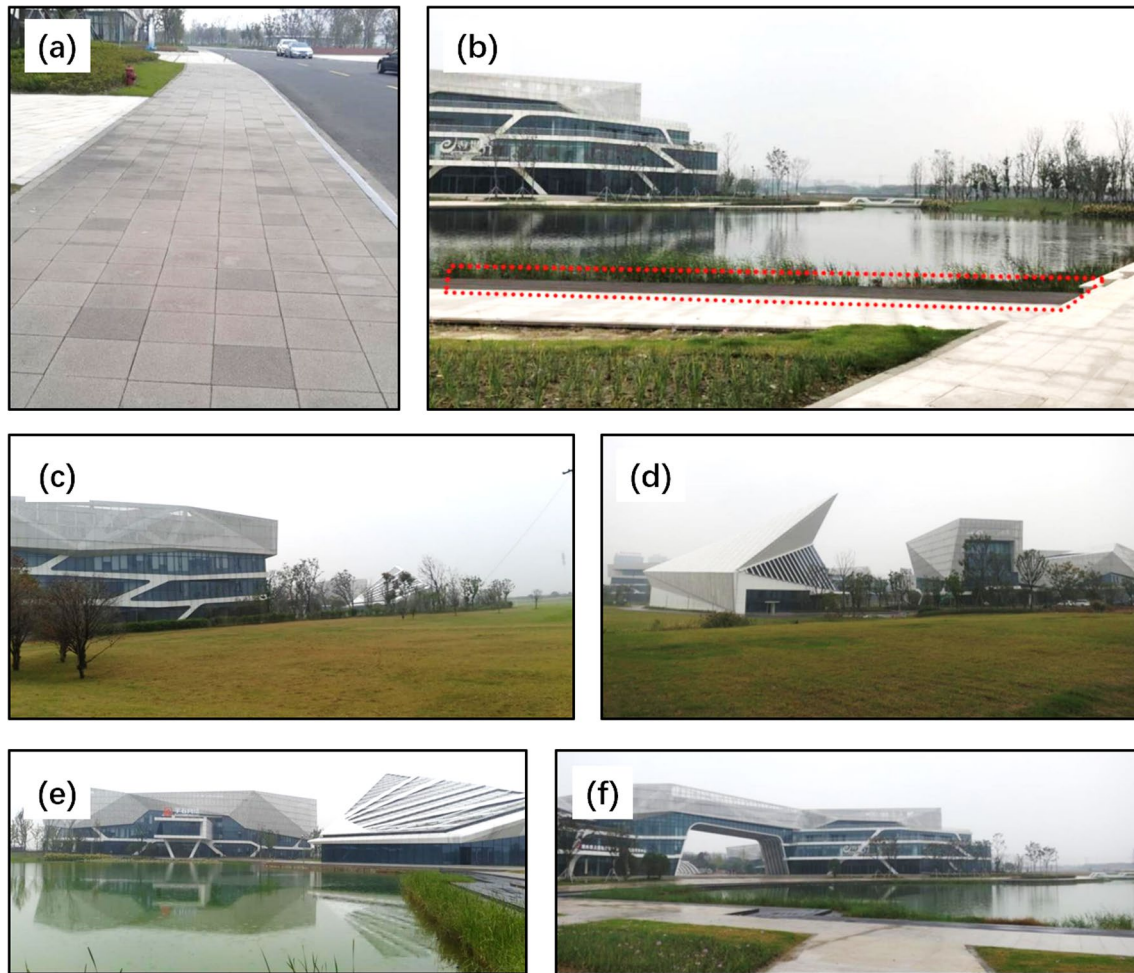


Fig. 6 Materials and facilities used in the sponge city construction project in Shangyu District in Shaoxing, Zhejiang province: **a** permeable ceramic brick pavement, **b** outdoor high-resistance bamboo flooring, **c** and **d** sunken greenbelts; **e–f** self-purifying landscape water body

volume capture ratio (45%, by volume) under the traditional development model.

The Qingshan District of Wuhan, Hubei province

In 2015, the city of Wuhan became one of the first batch of 16 pilot cities for the sponge city development through a competitive evaluation process. The sponge city renovation of the South Trunk Canal in Qingshan District adopted the private–public-partnership model with capital investments from the government and private entities. With a capital expenditure of \$196 million USD, the South Trunk Canal project was one of the two key projects of sponge city development in Wuhan, which covered a total area of 3,840,000 m², benefiting nearly 100,000 residents. The project took 2 years to complete, affecting 13 municipal roads, 59 apartment complexes, two parks and recreation areas, three drainage pipelines and one water pipeline (Fig. 7).

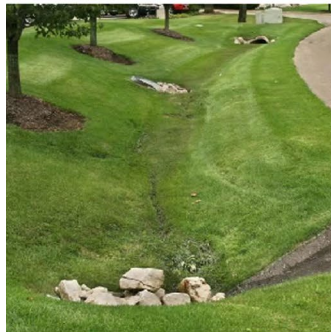
The Qingshan District is one of the older urban districts in the city of Wuhan. Prior to the sponge city renovation, there were persistent issues and nuisances associated with its aging infrastructures such as high groundwater tables, hard pavements, inadequate green spaces, and waterlogged roads. The renovation project laid down a set of performance targets, including the volume capture ratio of annual rainfall ($\geq 70\%$ by volume), annual runoff pollution reduction from non-point sources (total suspended solids in annual runoff should be reduced by $\geq 50\%$ or more), flood control standard (one-in-50-year storm events, by recurrence interval), total rainwater utilization rate (rainwater utilization should be more than 25% by volume) for irrigation, road washing and other ecological purposes. Take the renovation project in the South Trunk Canal Park and recreation area as an example. The project utilizes permeable pavements, rain gardens, grass swales and ecological barges to store rainwater and runoffs (Fig. 7). Landscape vegetation such as jujube trees, aquatic plants and other ornamental plants was

Fig. 7 Stormwater runoff management in South Trunk Canal Park and recreation area in Qingshan District, Wuhan, before and after the sponge city renovation project. Rainwater from outside of the park, e.g., on sidewalks, passes through the rain garden, conflues in the grass swale, and enters the ecological wetland, i.e., detention basin. Inside the park, rainwater passes through terraced green fields and then flows into lower sponge facilities such as sunken greenbelts, i.e., stormwater catchment lawns, which receive rainwater and overflow to the ecological wetland. Adapted from Wang (2021) with changes

Water flow in a city sponge park



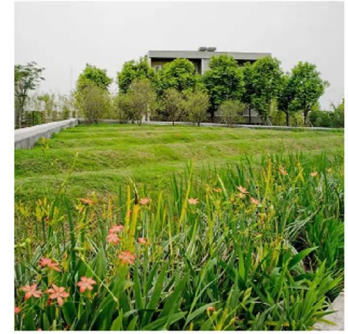
Rain garden



Grass swale



Wetland



Terraced green field



Sunken greenbelt

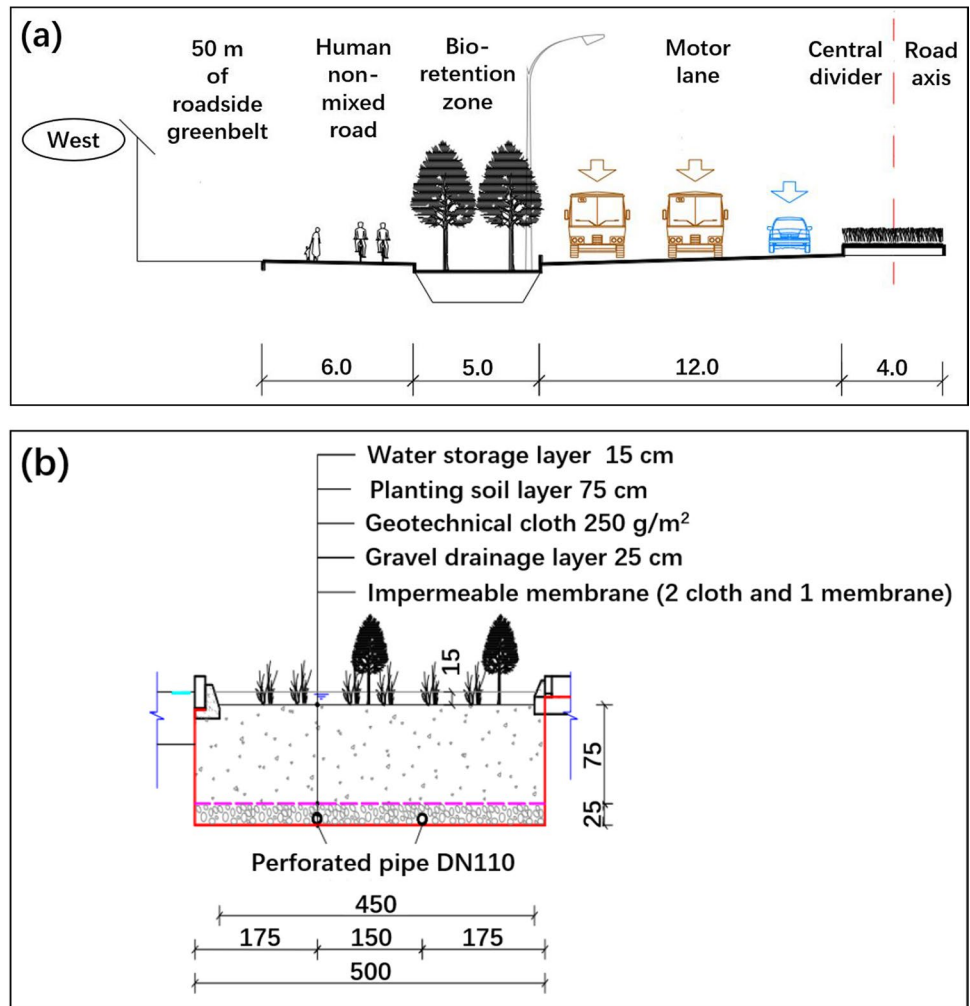


planted on site. Water-viewing decks, pavilions, children's sandpits and fitness equipment were installed for leisure use.

The Xishan road in the development zone of Urumqi, Xinjiang

In 2021, Urumqi was selected as one of the first pilot cities for sponge city renovation. The Xishan Road in the

Fig. 8 Xishan Road in the economic and technological development zone of Urumqi, Xinjiang province: **a** cross section of the road after the sponge renovation, and **b** structure of the bioretention zone



economic and technological development zone is one of the key projects of sponge renovation in the Urumqi pilot area. The Xishan Road, which runs from north to south, is a trunk road with a length of approximately 840 m and a section width of 50 m. After the renovation, the 5 m width planted areas on both sides of the road was re-built as bioretention facilities, i.e., rain gardens, which was 0.15 m lower than that of the road surface. Road runoff was diverted to these facilities, where filter basins were used to intercept pollutants in the initial runoff after flushing the road surface. Any runoff from the sidewalk would enter the bioretention facilities directly.

After the renovation, the Xishan Road mainly uses the bioretention zone to infiltrate and to purify road runoff. After the project was completed, the volume capture ratio of annual rainfall reached 85%. The project also achieved a 75% reduction of suspended solids in annual runoff. Since the runoff was effectively diverted to and stored in the bioretention zone, better utilization of rainwater resource was also achieved with overall water usage being reduced significantly for the planted areas along the Xishan Road. A

cross section of the renovated road and the structure of the bioretention zone are shown in Fig. 8.

The Xincheng Park in the Guangming District of Shenzhen, Guangdong province

The Guangming District of Shenzhen was selected as a pilot area for sponge city renovation. Located in the Guangming District, the Xincheng Park has an area of about 5.858 km², mostly green spaces (5.306 km²) with hills, forests and ponds. The Xincheng Park was one of the earliest low-impact development projects in the country, and is recognized as a milestone in the sponge city development in China. The low-impact development at the Xincheng Park had a design target of 70% for the volume capture ratio of annual runoff, which is equivalent to 28 mm precipitation on site, with the goal to increase rainwater infiltration and moisture contents in soils in the park.

The park uses grass swales to divert rainwater runoff and to replenish groundwater. It was estimated that annual

precipitation in the park area amounted to $4.5 \times 10^5 \text{ m}^3$, greatly exceeding the water used for landscaping purposes in the park. To utilize the rainwater resource, three reservoirs were constructed in the park, each having a storage capacity of 300 m^3 . Water used for landscape irrigation, road, square and ground washing was supplied by rainwater collected in the park after coarse filtration. Water used by park visitors was supplied separately by municipal water supplies. The maximum daily and hourly water consumption for irrigation and washing were 589 m^3 and 60 m^3 , respectively. When the stored rainwater was insufficient, municipal water supply was used as an augmenting source for irrigation. Pollutant-intercepting baskets were installed at all rainwater inlets in the park. Ponds, wetlands, seepage wells, and other sponge facilities were constructed in the park. Roads, parking lots, and visitors' squares in the park were renovated with permeable pavement. Figure 9 shows the site layout and a grass swale of the Xincheng Park after the low-impact development and renovation project in the park.

Perspective

Before the sponge city development in most parts of China, structural facilities were generally relied upon as the primary means of controlling floods, yet this approach had met with numerous issues including low-cost–benefit ratios and environmental impacts. As a consequence, the government looked at what other countries were doing to solve those issues in the early 2000s. In Japan, the approach of combining ecological restoration and facility construction was widely viewed as a sustainable approach in the long term for rain and flood management. The Japanese authorities had amended the laws and regulations multiple times in a persisting effort to find the most effective and amenable approach for stormwater management. In Germany, laws and regulations on water resource management were already well established at that time, which allowed citizens to participate in the decision-making of alleviating issues caused by rain and floods. The same approach could be adopted in China to facilitate the sustainable development and management of sponge cities (Ma et al. 2021).

In November 2014, the Ministry of Housing and Urban–Rural Development of the People's Republic of China released the 'Technical guide for sponge city construction—low-impact development rainwater system construction'. This guide specified the principles of design and constructions for sponge cities, that is, to build a low-impact design rainwater system by applying a variety of ecological functions, such as infiltration, purification, drainage, and storage to make cities function as a sponge to soak up and release water (MHURD 2014a). The 'Assessment standard for sponge city effects', which specified the assessment

items and requirements for sponge city infrastructure, was published as a recommended national standard (GB/T 51,345–2018). This standard was published in English by the International Water Association and can be downloaded free of charge (MHURD 2014b).

Compared with other similar guidelines, the advantages of the technical guide by the Ministry of Housing and Urban–Rural Development of China (MHURD) were as follows. First, it articulated the importance of planning and design in the sponge city development. Secondly, it made ecological conservation and restoration a priority in the sponge city development. Thirdly, it provided a detailed set of technical instructions for the sponge city development, which included pre-construction design, engineering design during the construction phase, and the asset management and maintenance after the construction. While the technical guide has provided a very useful reference for alleviating the severe flooding and waterlogging issues in urban environments and for rainwater management in general, it had several apparent shortcomings and limitations which need to be improved as the sponge city developments continue nationwide. Specifically, we propose the following changes and additions to improve the current guidelines for better sponge city development or other similar practices in future.

First, the 2014 guide did not provide enough information on rainwater purification and runoff treatment to allow more direct re-use of water collected from rainfall events. This is especially relevant when low-cost options and designs are already in use in similar low-impact development, and that such application e.g., irrigation may be desirable in park facilities or for landscaping purposes. Second, refine the technical standards, threshold values, and methods to incorporate field-validated results and findings from the past sponge city developments, and to balance between performance and practicality. Thirdly, the 2014 guide provided similar target values for reducing total annual runoff. More contingencies could be allowed for local authorities to establish their own target values under the local hydrological conditions. Fourthly, an open and robust database with accurate and real-time inputs of hydrological and environmental monitoring data is crucial for the operation and maintenance of sponge city facilities. Therefore, future guidelines on sponge city developments could incorporate specific requirements of field surveys and monitoring. Finally, as extreme rainfalls and droughts have become increasingly common as a realistic threat to many cities in the recent decade, more laws and regulations can be established to facilitate the sponge city development, including the public consultation, consenting, and financing of these projects.

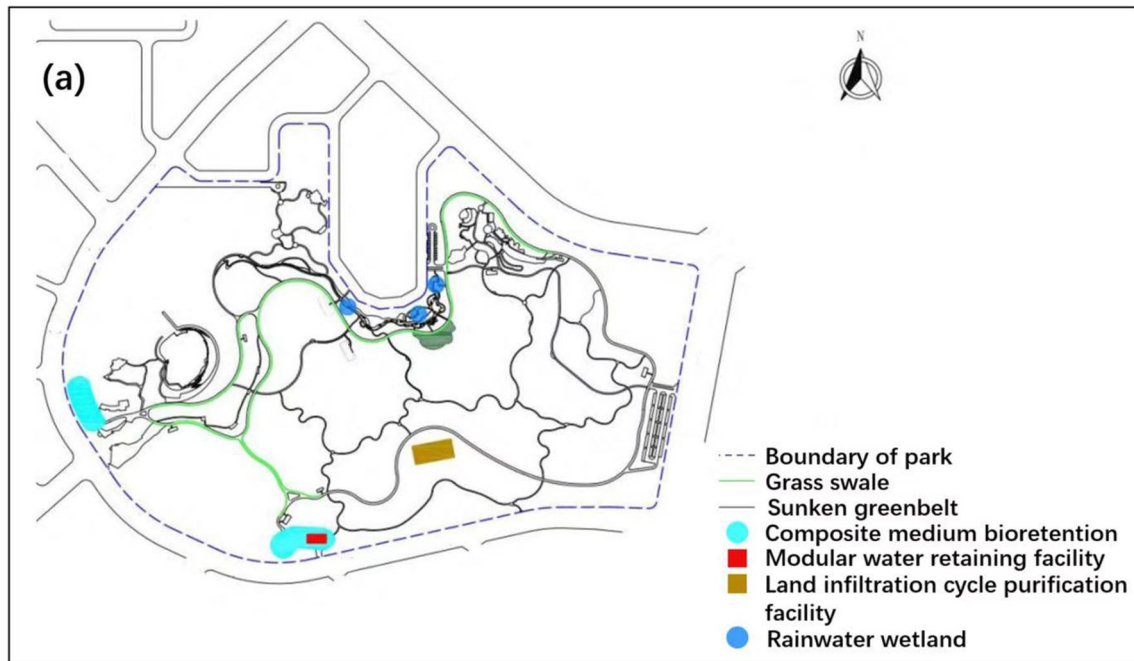


Fig. 9 Xincheng Park in the Guangming District of Shenzhen, Guangdong province: **a** site layout after renovation, and **b** a grass swale in the park. Image also shows permeable pavements alongside the grass swale

The General Office of the State Council of the People's Republic of China specified that, by 2030, at least 80% of the areas in developed urban zones in the country need to meet the 70% target volume capture ratio of annual runoff (SCC 2015). Eventually most cities in China, including the populous 'megacities', will adopt the sponge city model of development. Many of the pilot areas selected for the sponge city development in China, including Shenzhen (Zone V), Wuhan (Zone IV), Beijing (Zone III), and Shanghai (Zone III) are megacities having a population of 10–30 million with population densities in the range of 1300–5400 per square km. The 30 pilot areas were selected based on their annual precipitation, climate zone, population, local ecology, existing watershed, and conditions of their drainage

infrastructure. The sponge city development relies on a suite of versatile ecological and constructed facilities that enable the sponge-like functions of natural land and water bodies in managing the water resource in urban environments. It is inevitable that some of those facilities, e.g., terraced green fields, large ponds, and wetlands would require sizable areas of land, e.g., in city parks, which make them difficult to be constructed in populous, land-constrained metropolitan areas. Other features such as permeable pavement, rain gardens and grass swales can be retrofit on existing infrastructure in metropolitan areas without requiring additional land use. Also, some storage facilities are installed underground or on building rooves, e.g., green rooves, which requires no additional land use. It is worth to note that some megacities,

such as Wuhan and Shanghai, already have plenty of rivers and streams going through their metropolitan areas which make them amenable to be transformed to part of the sponge city green infrastructure.

It is worth to note that retrofitting existing urban communities with sponge city features is a common practice in pilot areas of sponge city developments in China. Apart from the Qingshan District of Wuhan in Hubei, China, there are many other examples of successful retrofitting of existing urban areas with the sponge city infrastructure and functions, without demolishing any part of the existing drainage or building infrastructure. One example was the North Village at Kunshan in Suzhou municipality. Two sets of sponge city facilities, including permeable pavement, rain gardens, ecological parking space and other amenities, were installed with no or minimal demolition work to control the annual runoff and non-point source pollution and to improve the landscape of the Zhonghua Garden, where the North Village was located (Cai and Meng 2022). Similar work was completed at Yihao Homes, a residential community area in Shanghai, China. The community had an aging drainage system with a high density of buildings and limited spaces available, which effectively made any large-scale demolition or renovation work impractical within the community. Nonetheless, the community successfully completed its sponge city retrofit by renovating existing drainage systems, rooves, pavements, parking spaces, and existing grounds. Where practical, the existing green grounds were preserved in the community, while new rainwater landscape infrastructures were introduced. The construction of permeable pavement and combined sewer separation significantly improved the community's resilience to floods and made better use of natural water sources by irrigating with stored and naturally purified water (Chen 2022).

Given that the annual total runoff is one of the key targets of sponge city development in China, it is useful to look at how it compares with other practices. The target volume capture ratios of annual rainfall in 30 pilot areas of the national initiatives of sponge city development in China ranges from 60% to 90% by volume, with generally lower targets set in cities with higher population densities. In the United States, the Water Quality Volume (WQV) standard limits runoff pollution by targeting high-frequency low and medium rainfall events, and by setting annual rainfall volume capture rates for those events. While different states of the United States have adopted variations, the general consensus is that the annual rainfall capture rate should be higher than 80% (by volume). In the northeastern United States, an annual rainfall capture rate of 90% (volume) is roughly equivalent to capturing the initial precipitation of 0.8–1.2 inch (20.3–30.5 mm). Some states use one-inch rainfall as the control standard (Li et al. 2014; Zhou

2018). Zhou (2018) calculated the design rainfall events at four representative cities in Zhejiang province, China based on the annual total runoff capture rates in the sponge city initiatives and the annual rainfall capture rates of the WQV in the United States. The results showed that an annual rainfall capture rate of 75% (volume) would be equivalent to a WQV range of 79–87% (volume) in typical cities in Zhejiang, which is in line with the target range (80–95% by volume) in the WQV. The annual runoff capture rate of 87% (volume) in the Shangyu District of Shaoxing in Zhejiang after completing the sponge city project is likely to yield a WQV higher than 90% (volume).

Ma and Jiang (2022) presented a comprehensive analysis on the 'interactions' among urban landscape, urban development, and ecosystem services in the process of developing sponge cities, and proposed to bring the ecosystem service framework into the spatial planning and performance evaluation of sponge cities. Specifically, the authors developed a five-step process for maintaining ecosystem services and the implementation of various policies on the development of sponge cities, i.e., situation assessment, ecosystem supply, scenario development, scenario assessment, and selection of design for sponge city development (Ma and Jiang 2022). Fu et al. (2022) stated that sponge cities have a key role for urban communities to manage extreme rainfalls and better adapt to climate change, but it may not be a 'remedy' for urban flash flooding. The authors put forward a series of proposed community-based measures for the future development and improvement of sponge cities, including resilience mapping, property-specific risk mitigation measures, flood insurance, and social resilience buildings (Fu et al. 2022). Building on the sponge city concept, Peng et al. (2022) developed a sponge watershed approach with a "source-flow-sink" framework, and applied it in the Sishui Basin, Zhengzhou, China to rebuild the city and towns that previously suffered disastrous rainfalls and improved their resilience to heavy floods. Through the construction of hydrological, hydraulic, and flood loss curve models, the effects of flood control by the sponge watershed were analyzed and evaluated under various scenarios (Peng et al. 2022). The authors demonstrated the potential of the sponge watershed approach in flood management and used it to improve the climate resilience of global watersheds.

Finally, experiences in other countries revealed that, although ecological restoration is at the core of sponge city development, it is often impractical to rely solely on the ecosystem to handle the huge amounts of drainage, for instance, in areas undergoing rapid development with a large population. One example is that some megacities in China, e.g., Zhengzhou, are prone to severe waterlogging. In those places, it is necessary to incorporate the design of the drainage engineering infrastructures on the sponge city renovation to avoid disastrous events caused by extreme

rainfalls. Another example was that the Tokyo Metropolitan Government had spent 15 years and 2.6 billion US dollars on building 'G-Cans', the world's largest underground flood tunnel, which played a pivotal role in alleviating monsoon-season flooding in the greater Tokyo region after being put in use. In the United States, water resources management including low-impact designs, from which rain gardens and permeable pavements were derived, were generally implemented at a federal level. Different states then adopt and refine those guidelines to better suit their needs and meteorological or environmental conditions. Compared with the practices in the United States where purification was more universally adopted in managing rainwater and runoff, the Chinese approaches of sponge city development primarily rely on conventional methods and facilities such as sunken greenbelts and filtering ponds to remove coarse pollutants (Li et al. 2018). The sustainable urban drainage systems, which have been used in the United Kingdom, intend to maintain the original hydrological conditions in the region and to minimize the impact of sustainable urban drainage systems on the quantity and quality of downstream runoff (Oladunjoye et al. 2022). Compared with similar practices in other countries, the most important feature of sustainable urban drainage systems is that it tries to avoid interference with existing facilities and only does renovations while keep existing facilities in use. China has a large number of urban communities that are impractical for direct renovation or re-construction as sponge cities, where the UK's experience on sustainable urban drainage systems may be referred to as useful guidance in these areas (Ma et al. 2021; Lashford et al. 2019).

Conclusion

China's sponge city initiatives demonstrate an alternative strategy to tackle water shortage and flooding issues faced by many cities today under a changing climate. By integrating nature's green infrastructure into urban stormwater management systems, the sponge city model utilizes nature's own capacity in absorbing, storing, and purifying rainwater infiltrates and runoffs, offering a more holistic and resilient approach to manage runoffs, pollution and water resources in urban environments when compared with traditional pipe-and-channel drainage systems, the 'gray infrastructure'. In many countries and regions, including China, the latter has been challenged by extreme rainfall events and floods in recent years. The sponge city also restores the ecological functions of the urban natural environment by storing and purifying runoffs while improving its landscape and aesthetics. Like other low-impact development concepts, the sponge city model offers a smart and sustainable approach by integrating the power of nature in the urban water cycle,

instead of relying solely on engineering systems and gray infrastructure. With its national initiatives already underway, China's sponge city development may offer valuable experiences for cities worldwide who are battling with water shortages and floods in tackling climate change (Chen et al. 2022; Earth 2021; Fawzy et al. 2020; Korkmaz and Kariper 2020).

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Declarations

Conflict of Interest The authors declare no conflict of interest in this work.

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