A review of the progress in Chinese Sponge City programme: challenges and opportunities for urban stormwater management

Feiran Li and Jianfeng Zhang*

Shaanxi Key Laboratory of Environmental Engineering, Key Laboratory of Northwest Water Resource, Environment and Ecology, MOE, Xi’an University of Architecture and Technology, Xi’an 710055, China

*Corresponding author. E-mail: zhangjianfeng@xauat.edu.cn

ABSTRACT

Urbanization has been the main driving force for China’s economic growth in recent years; however, the highly concentrated urbanized lifestyle has brought many environmental problems to residents, the most urgent of which is urban stormwater management. Some countries have proposed plans for urban stormwater management, such as Low Impact Development (LID), Water Sensitive Urban Design (WSUD), and Sustainable Urban Drainage Systems (SUDS). As a country with relatively underdeveloped urban stormwater management, China’s government proposed an ambitious urban stormwater management plan in 2014, called the Sponge City Programme, which means that a city is designed to act like a sponge, with good ‘resilience’ in adapting to environmental changes and coping with natural disasters. As of 2021, this programme has led to SCP projects in 30 pilot districts all over China, the Sponge City Programme construction impacts both urban development and residents’ lives. However, there are risks and challenges associated with these projects. Using government research documents as a framework, this paper carefully reviews the progress of the Sponge City Programme in recent years and shows the main challenges faced by the Sponge City Programme in terms of connotation, investment, and technology. On this basis, the paper puts forward practical suggestions for the development of the Sponge City Programme and details potential opportunities of new technology, ideology, planning, and flexible investment.

Key words: China, infrastructure construction, Sponge City, urban planning, urban stormwater management

HIGHLIGHTS

• Summary of Chinese government documents about Sponge City Programme.
• Review of actual construction.
• Analysis of construction mode of Sponge City Programme.
• Specific suggestions for development of Sponge City programme, under China’s special environment.

1. INTRODUCTION

In the 20th century, urbanization has become an important driving force for development in many countries (Shen & Zhou 2014). China’s rapid urbanization began with the Reform and ‘Opening-up’ policy in 1978. The proportion of China’s urban population to the total population increased from 17.92% (172.45 million) in 1978 to 59.58% (831.37 million) in 2018, the area of built districts in urban areas grew from 7,438 km² in 1981 to 58,456 km² in 2018, the number of cities with a population of more than 1 million grew from 37 in 1998 to 161 in 2018 (NBSC 2019). Some scholars predict that the proportion of China’s urban population to its total population will reach 70% by 2030 and 80% by 2050 (Xia et al. 2017a) as China is expected to continue to urbanise rapidly in the next two decades.

High-speed urbanization has promoted China’s ‘economic miracle’ (Yusuf & Saich 2008). However, its highly centralized housing model has also brought about many urban problems that are different from those in the traditional housing model (Tian 2015), such as deteriorating environment (Yuan et al. 2018), low quality of life (Fang & Wang 2015), reduced arable land (Tian 2015), air and water pollution (Carrascal Incera et al. 2017; Wang et al. 2017a), inefficient traffic flow (Shen et al. 2018), reduced groundwater levels (Kalhor & Emaminejad 2019), and urban heat island effects (Liu et al. 2020;
Zarrineh et al. 2020). These problems are commonly associated with urban development around the world (Fang et al. 2019; Wang et al. 2019b). Urban water management is the most urgent and complex practical problem related to urbanisation. Affected by climate change, the frequency of extreme climates is rising around the world. The intensity, frequency, and distribution range of short-term storms are increasing in some areas, and also affect the efficiency of urban drainage systems (Astarae-Imani et al. 2012; Kundzewicz et al. 2014; Hu et al. 2015; Salerno et al. 2018). The sub-optimal development of cities has caused changes in the subsurface, with increases in impervious surfaces leading to increased surface runoff and surface runoff velocity, and reduced concentration time (Dietz 2007; Hou et al. 2019). The inability of traditional urban drainage systems to adapt to increased urbanisation leads to an increased possibility of urban waterlogging during storms, which can have huge impacts on infrastructure and residents’ lives and property (Qin et al. 2013; Li et al. 2017; Chan et al. 2018) (Figure 1).

As the main cause of urban water problems, urbanization has caused great troubles in some developed countries in the last century (Fletcher et al. 2015). The understanding of the urban water cycle has been developed in response to this serious challenge, and urban stormwater management have evolved from a single goal (reducing flooding) to a multi-objective task, driving urban planning and the associated decision-making process (Obropta & Kardos 2007).

Worldwide, the following urban stormwater management policies have been developed and have become research hotspots. Low Impact Development (LID) is a commonly used urban stormwater management technique that originated in North America. The concept of LID was first used in a report on land use planning in Vermont, USA (Barlow et al. 1977). In 1997, Prince George’s County, Maryland, USA, compiled a municipal Low Impact Development Design Manual for Maryland. LID tends to use smaller-scale stormwater treatments, such as bioretention, green roofs, and pervious surfaces, rather than large-catchment hydrological restoration (Ahiablame et al. 2012). The concept of LID has been changing over time and has spread. In the most recent LID manuals issued by North Carolina State University in 2009, hydrological designs for urban development were established (Perrin et al. 2009). Additionally, the New Zealand government proposed the concept of Low Impact Urban Design and Development (LIUDD). LIUDD pays more attention to pollution control than pollution flow, the principles and methods of LIUDD have been developed as a policy framework in some countries (Ignatieva et al. 2008; van Roon 2011). Furthermore, the Water Sensitive Urban Design (WSUD) concept has been used in Australia since the 1990s, the use of the WSUD concept in a report prepared for the Western Australian Government is a sign of its widespread use (Whelans et al. 1994). Since then, the concept of WSUD has been continuously expanded and improved (Wong 2000; Lloyd & Chesterfield 2001), becoming a ‘philosophical approach to urban planning and design’ (Lloyd & Chesterfield 2002). The concept of stormwater management in WSUD has multiple connotations, and its aims include flood control, flow control, water quality improvement, and water reuse (ARMCANZ & ANZECC 2000). Although stormwater management is a subset of WSUD, urban drainage professionals began to promote WSUD in Australia from 1990. Stormwater management has been the principal application of WSUD in the early years of the technique (Fletcher et al. 2015). However, some scholars believe that stormwater management should be conducted within the framework of the urban water cycle (Lloyd 2006a). Nowadays, the use of WSUD is no longer limited to Australia (Ashley et al. 2013). For example, Joint Committee on Urban Drainage (JCUD) is operated jointly by the International Water Association (IWA) and the International Association on Hydraulic Engineering and Research (IAHR), which set up a specific WSUD working group in 2004 (Wong 2006b). Worldwide, various countries have developed stormwater management, including Best Management Practices (BMPs), Sustainable Urban Drainage Systems (SUDS), and so on. These are often made jointly by a mixture of central and local agencies, and have not become legislation (Sage et al. 2015). The understanding of these experiences can help other countries to avoid repeating mistakes and promote the development of stormwater management systems (Jensen et al. 2020).

As mentioned above, developed countries with a high degree of urbanization have conducted long-term studies on urban water management issues, and Chinese scholars have studied the experiences of these countries. In the 1990s, Chinese research on urban water management mainly focused on the design of drainage systems. After 2000, the research emphasis shifted to strategic studies, and urban water management became a multi-objective comprehensive systematic management issue (Wang et al. 2018). Meanwhile, China’s urban water problems have gradually increased during the 21st century. From 2006 to 2010, floods caused a total of 160 billion RMB in direct economic losses to more than 150 cities in China (Chenguan 2015). For example, a flood in October 2013 caused a total of $10.2 billion USD in damage to the Yangtze River Delta (Yu et al. 2015). Moreover, on 21 July 2012, Beijing experienced an unprecedented serious waterlogging disaster, which caused 79 deaths and 11.64 billion RMB in economic losses (Wang et al. 2018). Furthermore, flood disasters in other metropolises in China – such as Shanghai (Du et al. 2015), Shenzhen (Shi et al. 2007), Wuhan (Liu et al. 2014), and Tianjin
(Zhou et al. 2015) – have attracted public attention. Furthermore, about 45% of Chinese cities have insufficient water supply, and about 17% of Chinese cities have severe water shortage (Jiang et al. 2018). Inherent disadvantages of water resource exacerbate water-related problems in China. Affected by the monsoon, the temporal distribution of rainfall in China shows strong seasonality, with the rainfall between late spring and early autumn usually accounting for 70–80% of the total annual rainfall (Kundzewicz et al. 2020). This highly concentrated rainfall increases the burden on urban drainage systems for some Chinese cities (Xiao et al. 2020). The unbalanced distribution of rainfall in time and space, frequent urban waterlogging (Miller & Hutchins 2017), and flooding constantly threaten the lives and property of China’s inhabitants.

In the context of increased water risk, the Chinese government has begun to reflect on its urban development policy and explore appropriate urban water management. The President of China, Xi Jingpin, first presented the ‘Sponge City’ initiative at the Central Urbanization Working Conference in 2013 (Xia et al. 2017a). Although the term ‘Sponge City’ was first used by Australian scholars to describe the absorption effect of metropolitan areas on their surrounding population (Budge 2006), in President Xi’s speech, it is a vision of urban development, which has been interpreted as an urban stormwater management system with natural accumulation, natural infiltration and natural purification of stormwater. On 22 October 2014, the Ministry of Housing and Urban Rural Development (MHURD) issued a paper titled ‘Preliminary Technical Guidance for Sponge City Construction – Low Impact Development Rainwater System Construction’ (MHURD 2014) as an early guidance to promote the Sponge City Programme (SCP) nationwide; this guidance gives a concrete explanation of the Sponge City, which means that the city is constructed like a sponge, with good ‘resilience’ in adapting to environmental changes and coping with natural disasters. Compared with other urban stormwater management systems, the SCP covers a wider range of issues, including eliminating urban waterlogging, preventing flooding, improving water quality, restoring natural eco-systems, and mitigating heat island impacts. SCP have become a driving force to improve China’s urban development model. Soon after, the Ministry of Finance (MF), together with the MHURD and the Ministry of Water Resources (MWR) issued a paper titled, ‘Announcement on National Financial Support for Pilot Sponge City Development’ (MF 2014). This public document selected a first batch of 16 urban districts as pilot areas for the construction of SCP, and the number of pilot districts was expanded to 30 in 2016 (Jiang et al. 2018). These 30 pilot districts have different sizes and climatic conditions, demonstrating the Chinese government’s ambition to promote the SCP nationwide. The central government has pledged to invest 40–60 million RMB each year for the construction of SCP in pilot districts between 2015 and 2017, and is encouraging local governments to raise funds for construction of SCP through a flexible financing model (MF 2014). This investment will be used for the construction and renewal of urban water management measures intended to transform these districts in line with the standards of SCP (Li et al. 2017).

Since the concept of a Sponge City was first proposed, this field has attracted much research attention, with many papers being published on SCP from the perspective of technology and engineering (Fang et al. 2019). The new management thinking model demonstrated by the SCP is very important and valuable. Chinese governmental organizations are highly efficient and resolute, which has allowed great achievements in previous infrastructure construction. However, the SCP imposes new requirements on various participants, such as closer coordination between government departments at all levels and systematic comprehensive thinking of urban designers for stormwater management systems, which are challenging for the government to achieve. In China’s internal affairs rules, the government has an obligation to meet these challenges in order to achieve national development (Chan et al. 2018; Hou et al. 2020). This paper reviews the current research on the SCP, paying particular attention to management and implementation issues, in order to provide ideas for sustainable development and provide a summary of the progress of the SCP.

This paper is organized as follows. Section 2 details the development progress of the SCP, focusing on the construction of the 30 pilot districts using data and progress report from the Chinese government. Section 3 outlines the major challenges facing the implementation of the SCP and expounds on the connotations, economics, and technology of the three most urgent challenges in an attempt to identify the core limiting factors of the SCP. Section 4 reviews the possible development direction of the SCP based on its current development and shows the opportunities that are brought by the programme. Section 5 concludes the paper.

2. CONSTRUCTION PROGRESS OF THE SPONGE CITY PROGRAMME

In early 2017, the MHURD summarized the construction status of the SCP in pilot districts in its ‘Briefing on Progress of the Sponge City Development in Pilot Cities in 2016’. This briefing evaluated the first batch of 16 pilot districts in 2015 and the
second batch of 14 pilot districts in 2016 from the three aspects of construction area, projects, and investment amount (MHURD 2017). In 2017, the construction of the first batch of pilot districts had proceeded smoothly with an initial construction area of 313.78 km², accounting for 69% of the planned development area of 454.9 km², the number of started projects was 1,723, accounting for 63.9% of the 2,853 planned projects, and the amount invested was 46,907 billion RMB, accounting for 48.7% of the total estimated cost of all developments. In contrast, due to its later start time, the construction progress of the second batch of pilot districts was at an earlier stage, with a low proportion of started construction area, number of started projects, and amount invested, which accounted for 22.6%, 14.1%, and 8.6% of the planned total, respectively (MHURD 2017).

As shown in Figure 2, the construction progress of each of the first batch of pilot districts is different. Of all the districts, Jinan has the highest percentage of planned development area, with 76.9%, which covered 30.2% of planned projects; Wuhan has the highest percentage of projects under construction, with 80.9%; Chizhou, Wuhan, and Jinan have the highest percentage of planned development area, with 97.6%, 97.1%, and 92.5%, respectively. Meanwhile, Qianan only has 27.9% of planned development area and 16.9% of planned projects. These differences in construction progress may be due to construction difficulties and local government decisions. It is noteworthy that one of the selection criteria for the second batch of pilot districts was that the district must have a completed SCP project. Tianjin stands out among all of the second-batch pilot districts, with its projects under construction accounting for 56.4% of planned projects and 81.2% of planned development area. Shenzhen has 47.3% of the planned projects under construction, which accounts for just 7.6% of area under construction.

Additionally, planning has begun to extend the SCP to cities outside the pilot districts (Figure 3). Shows in 2017, the progress of the preparation of the Sponge City special plan for local government in 653 cities in China; 71 cities have received government approval, 135 cities have passed expert review, 164 cities have completed the Sponge City special plan draft, and 270 are preparing the Sponge City special plan draft (MHURD 2017).

3. MAJOR CHALLENGES

The construction goals of the SCP are exciting; however, the challenges facing the SCP change with its progress. At present, the main challenges are as follows.

3.1. Unclear connotations of the Sponge City Programme

In China, the construction of SCP mainly relies on the LID approach, focusing on the design and construction of independent urban units (e.g., communities, residences, office buildings, commercial buildings). Typical LID approaches such as bio-retention and the construction of pervious surfaces, green roofs, and rain gardens can increase the rainwater infiltration and storage capacity of the planning area (Li et al. 2017). For low- and middle-intensity rainfall, these measures are effective for reducing the risk of urban waterlogging, but the benefit is limited for high-intensity rainfall, when the design limit will quickly be exceeded (Gong et al. 2018). Operation and maintenance are important parts of the SCP. Due to climate change, the intensity and frequency of rainfall is expected to increase in the future, and stormwater management measures need to consider design redundant capacity or updates (Zhou 2014; Zhou et al. 2019). Regular inspection and maintenance

Figure 1 | The urbanization process in China from 1978 to 2018.
are necessary for all LID measures, the clogging and aging of measures can reduce the runoff control capacity of LID measures (Al-Rubaei 2016).

Guidance published by the MHURD pointed out that local government is the body responsible for coordinated, it needs to coordination planning, land, drainage, roads, transportation, gardens, hydrology, and other functional departments to jointly

Figure 2 | (a) The percentage of planned development area by 2017. (b) The percentage of planned project by 2017. (c) The percentage of the total estimated cost of all developments by 2017. (continued.)

Figure 2 | Continued.
build the SCP (MHURD 2014). In actual planning, different departments formulate related special plans such as urban water system planning, green space system planning, drainage and waterlogging control planning, and road traffic planning. These plans are often only developed by professionals from a specific field and have limited effect on urban stormwater management; it is a multi-driving complex issue. The SCP special plan is a simple integration of these plans, the result of which is that the construction of Sponge Cities is often not with foresight and systematic (MHURD 2016; Wang et al. 2017b; Xia et al. 2017b).

China is a huge country with a complicated climate and geography, and the distribution of rainfall and weather is highly uneven. The south and southeastern regions are humid and hot, and the west and northwestern regions are dry (Kundzewicz et al. 2020). Therefore, as a national initiative, the SCP faces different urban water problems in different regions, which requires special planning control indexes to be set for different districts. Although the MHURD guidance proposes numerous
planning control indexes such as runoff amount, peak runoff, runoff pollution, and rainwater utilization, the Volume Capture Ratio of Annual Rainfall is the primary control index, its significance refers to the percentage of rainwater captured by infiltration, storage and evaporation in the total annual rainfall in the design site (MHURD 2014). The aforementioned guidance defined a threshold value of the Volume Capture Ratio of Annual Rainfall of 80–85% in order to meet the target that the runoff emission after completion construction of SCP is the same as that before any development (the volume discharge ratio of annual rainfall for natural green land is 15–20%). The Volume Capture Ratio of Annual Rainfall is not the same for all cities. As shown in Table 1 and Figure 4, the guidance is set to five ranges of α (Volume Capture Ratio of Annual Rainfall) corresponding to different regions of the country (MHURD 2014). The main evaluation criterion for SCP formulated by the Central Government as the policy promoter is the Volume Capture Ratio of the Annual Rainfall (MF 2016; MHURD 2016).

The main basis for regional division is the daily rainfall, which may neglect the impact of different climate and soil conditions and geographic location on runoff generation, leading to inefficient local SCP planning (Xia et al. 2017b). In the actual construction of the SCP, many local governments focus on the single indicator control of the annual average runoff amount, while ignoring evapotranspiration and storage, which are equally important hydrological processes in the urban water cycle (Ma et al. 2017). The Peak Runoff of a rainfall event is a very relevant item to whether the city will experience

Table 1 | Five ranges corresponding to different regions

| Regions  | Volume capture ratio of annual rainfall |
|----------|----------------------------------------|
| Region I | 85% ≤ α ≤ 90%                          |
| Region II| 80% ≤ α ≤ 85%                          |
| Region III| 75% ≤ α ≤ 85%                         |
| Region IV| 70% ≤ α ≤ 85%                          |
| Region V | 60% ≤ α ≤ 85%                          |

Figure 4 | The regions of Volume Capture Ratio of Annual Rainfall (drawn according to (MHURD 2014)). Note: the site information of Hong Kong, Macau and Taiwan are temporarily unavailable.
waterlogging. The guidance published by the MHURD pointed out that, in heavy rainfall events, SCP measures can play a limited role in delaying the runoff peak. Traditional pipeline drainage systems are still indispensable for urban stormwater management (MHURD 2014; Li et al. 2017).

3.2. Sustainable investment model
In October 2015, the State Council issued ‘The General Office of the Start Council’s Advice on Promoting the Construction of Sponge Cities.’ This advice proposed phased goals for the SCP, namely that more than 20% of the area of built districts would meet the target control index by 2020 and more than 80% of the area of built districts would meet the target control index by 2050 (GOSC 2015). However, there is a huge gap between the existing urban infrastructure and the standard of SCP. The cost of SCP construction includes the transformation of old infrastructure: it will reach 0.10–0.15 billion RMB/km² (Xia et al. 2017b). Relying only on central government investment is not enough to cover the entire cost of SCP construction and operation. This huge gap needs to be filled through the Public-Private-Partnership (PPP) model. Water projects are similar to SCP projects, and its investment situation is enlightening to investment of SCP projects: private investors are expected to account for 50% of the total investment in water project construction in pilot districts in Wuhan, while local government and the central government are expected to contribute 40 and 10%, respectively (Liang 2018). Public-Private-Partnership refers to a specific procurement in which projects are executed with a broader contractual relationship between public and private entities to provide services or assets. The PPP model plays an important role in infrastructure project management (Marques 2008) and is very popular in infrastructure construction in developing countries that require huge investment (Tang et al. 2013).

Many scholars have used questionnaire surveys to study the feasibility of the PPP model as a funding channel for the SCP. Studies have shown that a funding model combining government investment and the PPP model is feasible for the SCP. The application of the PPP model can reduce the risk of local government debt and has great application potential for environmental management projects (Yang et al. 2017; An et al. 2018; Zhang et al. 2019). The Chinese central government is an important driving force for the application of the PPP model as a funding channel for the SCP. The central government encourage local governments to attract investment in the construction and operation of SCP through the PPP model (GOSC 2015). The MF set a reward threshold for the proportion of PPP model in total investment, pilot districts are awarded an investment bonus of 10% by the central government for the PPP proportion in projects that meet the desired standard (MF 2014). In the competitive evaluation of the construction results of pilot districts, the application of the PPP model is a separate evaluation item, including the proportion of investment in PPP model projects to the total project investment, and the proportion of the number of PPP model projects to the total number of projects (MHURD 2017).

However, private capital often lacks interest in public projects, as the huge upfront investment, policy uncertainty, distrust between government and capital, and implied risk of the SCP are all obstacles to the willingness of private capital to invest in the SCP (Zhang et al. 2016). The lifecycle costs and lifespans of some SCP projects are uncertain, and some benefits generated by SCP projects are difficult to monetise, such as improved environmental quality and quality of life for residents (Li et al. 2017; Xia et al. 2017b). The above problems show the application dilemma of the PPP model in the SCP construction, the existing PPP model is not applicable to the construction of SCP, and local governments must therefore explore special PPP models (Zhang et al. 2019). At present, SCP construction is still in its infancy, with most projects being in the construction stage with little in the way of quantitative studies on the social, environmental, and economic benefits of SCP projects. Private capital cannot predict the benefits of investing in SCP projects and lack motivation to invest in SCP projects through the PPP model (Zhang et al. 2016; Jiang et al. 2018). This and various other obstacles mean that financing has become the limiting factor for the SCP.

3.3. Disadvantages of technology and support tools
The SCP differs from the traditional mode of Chinese infrastructure construction. Systematic and far-sighted development planning advocates the restoration of ecological cycles, the active integration of stormwater management systems into ecological systems rather than transforming the environment through structural and technological measures (Jiang 2015). Integrated urban water models are essential tools for urban water management. Compared with other stormwater management concepts, SCP construction focuses on a wider range, including urban waterlogging, flooding and water cycle etc. However, there is lack of suitable simulation tool for SCP evaluation, which is a bottleneck of SCP construction (Nguyen et al. 2020). Developed countries have long been involved in the development of urban stormwater management systems.
For instance, the Storm Water Management Model (SWMM) was developed by the US Environmental Protection Agency (EPA) in 1971 (Tsibrintzis & Hamid 1998). After decades of development, SWMM and other stormwater models based on it are popular commercial stormwater models worldwide (Teng et al. 2017). These models are widely used in the study of various aspects of urban stormwater management, including feasibility evaluation, monitoring, and infrastructure planning (Wang et al. 2018). However, although such models play an important role in urban water management, they still face many challenges of application due to the complexity and diversity of urban water systems (Chen et al. 2018; Hou et al. 2019). Compared with other stormwater management systems, the later start time of the SCP is a disadvantage, and this point may cause it to lack compatibility with existing urban stormwater management systems models. China’s unique natural conditions and development model, coupled with the ambitions of the Chinese government, complicate the application of urban water models (Yin et al. 2020). Besides urban stormwater management, the connotation of the SCP covers flood disasters, water pollution, and water reuse. The Chinese government aims to build a comprehensive approach to combat all water-related problems. An ideal SCP model should be an integration of multiple sub-modules; however, this goal seems difficult now (Wang et al. 2019a; Nguyen et al. 2020). The gap between reality and goal necessitates a national strategy for SCP construction involving ‘learning-by-doing’, summarizing experience, and iterating technology during construction (Jiang et al. 2018).

3.4. Public perception of the Sponge City Programme

Additionally, as the beneficiaries of the SCP, residents’ complex perception for the SCP is a notable issue. Compared with traditional stormwater drainage systems, most SCP measures are scattered over a large overground area, and disturbance to residents’ lives during construction and operation may cause residents to resist the SCP construction (Flynn et al. 2012; Li et al. 2017). Although surveys have shown that most residents support the SCP, the public perception of some specific topics is unclear, such as financial resources, infrastructure measures (e.g., green roofs), the relationship between the SCP and urban waterlogging, and the willingness-to-pay for water-price surcharge (Wang et al. 2017b).

Moreover, some special issues concerning the SCP are worth noting, which stem from the main challenges above. These issues are discussed in the following section.

4. FUTURE OPPORTUNITIES AND DIRECTIONS

4.1. Systematic construction ideology of the Sponge City Programme

The concept of a Sponge City is abstract. The fundamental goal of the SCP is to minimize the impact of urbanization on the natural environment and establish a sophisticated urban water cycle system. The construction path of the SCP is complex and diverse, and comprehensive thinking about the urban water system is necessary and important for SCP construction (Farrelly & Brown 2011; McCormick et al. 2013). There is a need for comprehensive thinking that can integrate multiple aspects, including landscape, infrastructure, regulations, planning, water resources, finance, agriculture, monitoring, and property management (Jiang et al. 2018). It considers not only the roles of LID and storage functions of the city lake and river system, but also the issues of water quantity, quality, and eco-system, as well as human alterations to the whole urban water system (Xia et al. 2017b). Systematic comprehensive thinking can change the urban designer’s view on watershed scale, enhance the connectivity between source–community–region watershed scales, avoid the subdivision and isolation of the watershed during planning, and pay more attention to other control items such as peak runoff, runoff pollution, and rainwater recycling (Li et al. 2017). Furthermore, systematic comprehensive thinking in the SCP is beneficial for other non-water-related infrastructure projects in China. This can promote the transformation of the management ideology of all Chinese traditional infrastructure construction from a focus on technology and engineering to a new model involving management and governance thinking; however, this transformation requires the government to pay more attention to capacity building (Brown & Farrelly 2009) and collaborative research (Burns et al. 2015).

4.2. Sponge City planning by local governments

The development of every part of the SCP, such as planning, design, construction, evaluation, operation, maintenance, and monitoring, depends on the specific environment of the project location. The guidance of MHURD proposes construction aims and a general framework. However, in the process of construction, the capabilities of local government are an important factor in the construction process results, such as efficiently mobilizing local resources and formulating special management planning. These are the challenges facing local governments. It is necessary to develop local SCP construction manuals through cooperation between local governments and developers, planners, and engineers. This requires local government
to pay more attention to the training of government employees, planning and design professionals (Li et al. 2017; Yin et al. 2020).

4.3. Application of new technology

Under the background of SCP construction, a new research trend is comprehensive study into stormwater management systems and its related disciplines. The SCP construction in new urban areas is goal-oriented, which provides opportunities for the application of new technologies (Hou et al. 2020). Computer technologies have gradually become important auxiliary design tools; for example, Geographic Information System (GIS) and Remote Sensing (RS) technology are used to obtain high-precision underlying surfaces, and these data have been used to simulate runoff generation and pollution diffusion processes (Xia 2005). The monitoring of water quality and runoff is important in the SCP. The real-time monitoring of drainage systems, underlying surface, and urban rivers can be achieved using RS and machine learning, which can assist in emergency response for rainfall disasters and developing more efficient pollution treatment plans, providing a stronger basis for managers to make decisions (Xia et al. 2017b). Parameter uncertainty analysis can enhance the understanding and accuracy of models (Kanso et al. 2005; Yang et al. 2018). The comparison between simulation results and monitoring data can be used to improve the accuracy and precision of models for simulation results by adjusting model parameters (Mengistu et al. 2019).

4.4. Publicity and professional education of the Sponge City Programme

The SCP can establish a friendly environment for a healthy urban water cycle system; however, human behaviour is the major stakeholder of the urban water cycle, public participation is an important driver of infrastructure construction. Government guidance plays an important role in this aspect, and economic measures have proved to be effective for increasing public participation, such as ladder water price policy, tax reduction for water saving, and environmental fines (Yuan et al. 2011). Additionally, the government should strengthen publicity and education on water saving in schools or public places (Wang et al. 2017b), and encourage citizens to develop healthy water use habits (e.g., use water-saving toilets and taps). Another benefit of enhanced public publicity of water saving is that it can increase investment willingness and the understanding of private capital about the SCP.

4.5. Flexible investment promotion programmes

Exploring an economical and reasonable PPP funding model for SCP is a long-term process. Facing a huge investment gap, the government should play a greater role, mobilizing social resources to create favorable investment atmosphere for SCP construction, and use more flexible innovative funding models, such as tax-increments, development charges, value-capture taxes, loans, and special national debts (Jiang et al. 2018).

Non-financial administrative means of local government is required, such as streamlined permitting application procedure, or regulatory credits (Liang et al. 2020). Transparent and efficient regulatory systems and incentives are beneficial for every stakeholder, which can boost the confidence of private capital to invest in SCP projects, and increase support from residents who are disturbed by SCP construction (Li et al. 2017).

5. CONCLUSION

As a country with relatively underdeveloped urban stormwater management, China’s government has promoted the SCP, learning from advanced urban rainwater management experience worldwide (e.g., LID and WSUD) to establish a powerful management model to deal with water-related issues in all Chinese cities.

The SCP is a newcomer in stormwater management systems worldwide. Other mature stormwater management systems are ideal learning objects; there is a huge gap between the ideal goal and the actual SCP construction, which requires a lot of time and resources to resolve the lack of practice and infrastructure. Moreover, China’s rapid economic development driven by infrastructure has enhanced its soft power, such as experience in engineering, construction, and the application of new technology. These factors may lead to some local advantages of the SCP. Additionally, the increasingly extreme global climate is a background that brings new environmental problems for urban development, which are serious challenges to all urban stormwater management.

This paper gives a comprehensive review of the SCP and analyses the construction progress of 30 pilot districts. The SCP is effective for solving urban water-related issues; however, there are many challenges to reaching the final target. Connotation, investment, and technology are the three most important challenges to the programme. However, some opportunities are emerging due to the SCP construction, such as systematic comprehensive thinking and the application of new technology.
These opportunities mean that the SCP could be a starting point for a new means of urban development that can transform the traditional Chinese infrastructure construction model, establish a more holistic and sustainable viewpoint about urban development, and create a green, comfortable, and harmonious living environment for the Chinese people.

ACKNOWLEDGEMENTS

This work is supported by the National Key Project of Research and Development Plan of China (No. 2017YFC0403403-3).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Ahialahwe, L. M., Engel, B. A. & Chaubey, I. 2012 Effectiveness of low impact development practices: literature review and suggestions for future research. Water, Air, & Soil Pollution 223, 4253–4273.

AL-Rubaei, A. 2016 Long-Term Performance. Operation and Maintenance Needs of Stormwater Control Measures, PhD thesis, Luleå University of Technology, Luleå, Sweden.

An, X., Li, H., Wang, L., Wang, Z., Ding, J. & Cao, Y. 2018 Compensation mechanism for urban water environment treatment PPP project in China. Journal of Cleaner Production 201, 246–253.

ARMCANZ & ANZECC. 2000 National Water Quality Management Strategy: Australian Guidelines for Urban Stormwater Management. Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) and Australian and New Zealand Environment and Conservation Council (ANZECC), Canberra, ACT.

Ashley, R., Lundy, L., Ward, S., Shaffer, P., Walker, L., Morgan, C., Saul, A., Wong, T. & Moore, S. 2013 Water-sensitive Urban Design: Opportunities for the UK.

Astaraie-Imani, M., Kapelan, Z., Fu, G. & Butler, D. 2012 Assessing the combined effects of urbanisation and climate change on the river water quality in an integrated urban wastewater system in the UK. Journal of Environmental Management 112, 1–9.

Barlow, D., Burrill, G. & Nolfi, J. R.; Center for Studies in Food Self-Sufficiency 1977 A Research Report on Developing A Community Level Natural Resource Inventory System. Center for Studies in Food Self-Sufficiency, Vermont Institute of Community Involvement, Vermont, CT.

Brown, R. R. & Farrelly, M. 2009 Challenges ahead: social and institutional factors influencing sustainable urban stormwater management in Australia. Water Science and Technology 59, 653–660.

Budge, T. M. 2006 Sponge Cities and Small Towns : A New Economic Partnership. In Second Future of Australia’s Country Towns, Bendigo, Victoria, Australia, 11-13 July. Centre for Sustainable Regional Communities, LaTrobe University, Melbourne, Victoria, Australia.

Burns, M. J., Wallis, E. & Matic, V. 2015 Building capacity in low-impact drainage management through research collaboration. Freshwater Science 34, 1176–1185.

Carrascal Incera, A., Avelino, A. F. T. & Franco Solís, A. 2017 Gray water and environmental externalities: international patterns of water pollution through a structural decomposition analysis. Journal of Cleaner Production 165, 1174–1187.

Chan, F. K. S., Griffiths, J. A., Higgitt, D., Xu, S., Zhu, F., Tang, Y.-T., Xu, Y. & Thorne, C. R. 2018 Sponge city’ in China – a breakthrough of planning and flood risk management in the urban context. Land Use Policy 76, 772–778.

Chen, W., Huang, G., Zhang, H. & Wang, W. 2018 Urban inundation response to rainstorm patterns with a coupled hydrodynamic model: a case study in Haidian Island, China. Journal of Hydrology 564, 1022–1035.

Chenguang, L. I. 2015 Flood insurance: demand, supply and public policy. Insurance Studies 5, 006.

Dietz, M. E. 2007 Low impact development practices: a review of current research and recommendations for future directions. Water Air and Soil Pollution 186, 351–363.

Du, S., Gu, H., Wen, J., Chen, K. & Van Rompaey, A. 2015 Detecting flood variations in Shanghai over 1949–2009 with Mann-Kendall tests and a newspaper-based database. Water 7, 1808–1824.

Fang, C. & Wang, J. 2013 A theoretical analysis of interactive coercing effects between urbanization and eco-environment. Chinese Geographical Science 23, 147–162.

Fang, C., Cui, X., Li, G., Bao, C., Wang, Z., Ma, H., Sun, S., Liu, H., Luo, K. & Ren, Y. 2019 Modeling regional sustainable development scenarios using the urbanization and eco-environment coupler: case study of Beijing-Tianjin-Hebei urban agglomeration, China. Science of the Total Environment 689, 820–830.

Farrelly, M. & Brown, R. 2011 Rethinking urban water management: experimentation as a way forward? Global Environmental Change 21, 721–732.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D. & Viklander, M. 2015 SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. Urban Water Journal 12, 525–542.
Flynn, K. M., Linkous, B. W. & Buechter, M. T. 2012 Operation and Maintenance Assessment for Structural Stormwater BMPs. In World Environmental and Water Resources Congress, 20-24 May, Albuquerque, New Mexico. American Society of Civil Engineers, Reston, VA.

Gong, Y., Yin, D., Fang, X. & Li, J. 2018 Factors affecting runoff retention performance of extensive Green roofs. Water 10 (9), 1217.

GOSC. 2015 The General Office of the Start Council Advice on Promoting of Construction of Sponge City. Beijing, China.

Hou, J., Mao, H., Li, J. & Sun, S. 2019 Spatial simulation of the ecological processes of stormwater for sponge cities. Journal of Environmental Management 232, 574–583.

Hou, X., Guo, H., Wang, F., Li, M., Xue, X., Liu, X. & Zeng, S. 2020 Is the sponge city construction sufficiently adaptable for the future stormwater management under climate change. Journal of Hydrology 588, 125055.

Hu, S.-L., Han, C.-F. & Meng, L.-P. 2015 A scenario planning approach for propositioning rescue centers for urban waterlog disasters. Computers & Industrial Engineering 87, 425–435.

Ignatieva, M., Meurk, C. & Stewart, G. 2008 Low impact urban design and development (LIUDD) : matching urban design and urban ecology. Landscape Review 12, 61–73.

Jensen, D. M. R., Thomsen, A. T. H., Larsen, T., Egemose, S. & Mikkelsen, P. S. 2020 From EU directives to local stormwater discharge permits: a study of regulatory uncertainty and practice gaps in Denmark. Sustainability 12 (16), 6317.

Jiang, Y. 2015 China’s water security: current status, emerging challenges and future prospects. Environmental Science & Policy 54, 106–125.

Jiang, Y., Zevenbergen, C. & Ma, Y. 2018 Urban pluvial flooding and stormwater management: a contemporary review of China’s challenges and ‘sponge cities’ strategy. Environmental Science & Policy 80, 132–143.

Kalhor, K. & Emamnejad, N. 2019 Sustainable development in cities: studying the relationship between groundwater level and urbanization using remote sensing data. Groundwater for Sustainable Development 9, 100243.

Kanso, A., Gromaire, M.-C., Gaume, E., Tassin, B. & Chebbog, G. 2003 Bayesian approach for the calibration of models: application to an urban stormwater pollution model. Water Science and Technology 47, 77–84.

Kundzewicz, Z. W., Huang, J., Pinksavar, I., Su, B., Szwed, M. & Jiang, T. 2020 Climate variability and floods in China – A review. Earth-Science Reviews 211, 103434.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K. J., Muir-Wood, R., Brakenridge, R., Kron, W., Benito, G., Honda, Y., Takahashi, K. & Shrestyukov, B. 2014 Flood risk and climate change: global and regional perspectives. Hydrological Sciences Journal Journal Des Sciences Hydrologiques 59, 1–28.

Li, H., Ding, L., Ren, M., Li, C. & Wang, H. 2017 Sponge city construction in China: a survey of the challenges and opportunities. Water 9 (9), 594.

Liang, X. 2018 Integrated economic and financial analysis of China’s sponge city program for water-resilient urban development. Sustainability 10 (3), 669.

Liang, C., Zhang, X., Xu, J., Pan, G. & Wang, Y. 2020 An integrated framework to select resilient and sustainable sponge city design schemes for robust decision making. Ecological Indicators 119, 106810.

Liu, J., Wang, S.-Y. & Li, D.-M. 2014 The analysis of the impact of land-use changes on flood exposure of Wuhan in Yangtze River Basin, China. Water Resources Management 28, 2507–2522.

Liu, Y., Li, Q., Yang, L., Mu, K., Zhang, M. & Liu, J. 2020 Urban heat island effects of various urban morphologies under regional climate conditions. Sci Total Environ 743, 140589.

Lloyd, S. D. & Chesterfield, J. 2001 Opportunities and Impediments to Water Sensitive Urban Design in Australia.

Lloyd, S. D. & Chesterfield, C. J. 2002 Water Sensitive Urban Design – A Stormwater Management Perspective. Higher Education Research Data Collection Publications 1-38.

Ma, Z., Hu, J., Peng, P., Gao, Q., Qu, S., Song, W. & Liu, J. 2017 Assessment of climate technology demands in Chinese sponge city. Journal of Geoscience and Environment Protection 5, 102–116.

Marques, R. C. 2008 Comparing private and public performance of Portuguese water services. Water Policy 10, 25–42.

McCormick, K., Anderberg, S., Coenen, L. & Neij, L. 2013 Advancing sustainable urban transformation. Journal of Cleaner Production 50, 1–11.

Mengistu, A. G., Rensburg, L. D. V. & Woyessa, Y. E. 2019 Techniques for calibration and validation of SWAT model in data scarce arid and semi-arid catchments in South Africa. Journal of Hydrology Regional Studies 25, 100621.

MF. 2014 Announcement on National Financial Support for Pilot Sponge City Development. Beijing, China.

MF. 2016 Interim Measures for the Performance Evaluation of Special Funds for Urban Pipelines. Beijing, China.

MHURD. 2014 Preliminary Technical Guidance for Sponge City Construction –Low Impact Development Rainwater System Construction. Beijing, China.

MHURD. 2016 Interim Provisions on the Preparation of Sponge City Special Planning. Beijing, China.

MHURD. 2017 Briefing on Progress of Sponge City Development in Pilot Cities in 2016. Beijing, China.

Miller, J. D. & Hutchins, M. 2017 The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom. Journal of Hydrology Regional Studies 12, 345–362.

NBSC. 2019 National Bureau of Statistics of China (NBSC). China Statistics Press, Beijing.

Nguyen, T. T., Ngo, H. H., Guo, W. & Wang, X. C. 2020 A new model framework for sponge city implementation: emerging challenges and future developments. Journal of Environmental Management 253, 109689.
Obropta, C. C. & Kardos, J. S. 2007 Review of urban stormwater quality models: deterministic, stochastic, and hybrid approaches. *Journal of the American Water Resources Association* 43, 1508–1523.

Perrin, C., Milburn, L., Szpir, L., Hunt, W., Bruce, S., McLendon, R., Job, S., Line, D., Lindbo, D. & Smutko, S. 2009 *Low Impact Development: A Guidebook for North Carolina.* AG-716. North Carolina Cooperative Extension Service, North Carolina State University, Raleigh North Carolina.

Qin, H. P., Li, Z. X. & Fu, G. 2013 The effects of low impact development on urban flooding under different rainfall characteristics. *J Environ Manage* 129, 577–585.

Sage, J., Berthier, E. & Gromaire, M.-C. 2015 Stormwater management criteria for on-site pollution control: a comparative assessment of international practices. *Environmental Management* 56, 66–80.

Salerno, F., Gaetano, V. & Gianni, T. 2018 Urbanization and climate change impacts on surface water quality: enhancing the resilience by reducing impervious surfaces. *Water Research* 144, 491–502.

Shen, L. & Zhou, J. 2014 Examining the effectiveness of indicators for guiding sustainable urbanization in China. *Habitat International* 44, 111–120.

Shen, L., Du, L., Yang, X., Du, X., Wang, J. & Hao, J. 2018 Sustainable strategies for transportation development in emerging cities in China: a simulation approach. *Sustainability* 10 (5), 844.

Shi, P.-J., Yuan, Y., Zheng, J., Wang, J.-A., Ge, Y. & Qiu, G.-Y. 2007 The effect of land use/cover change on surface runoff in Shenzhen region, China. *Catena* 69, 31–55.

Tang, L., Shen, Q., Skitmore, M. & Cheng, E. W. L. 2015 Ranked critical factors in PPP briefings. *Journal of Management in Engineering* 29, 164–171.

Teng, J., Jakeman, A. J., Vaze, J., Croke, B. F. W., Dutta, D. & Kim, S. 2017 Flood inundation modelling: a review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software* 90, 201–216.

Tian, L. 2015 Land use dynamics driven by rural industrialization and land finance in the peri-urban areas of China: ‘The examples of Jiangyin and Shunde’. *Land Use Policy* 45, 117–127.

Tsibritzis, V. A. & Hamid, R. 1998 Runoff quality prediction from small urban catchments using SWMM. *Hydrological Processes* 12, 311–329.

Van Roon, M. R. 2011 Water sensitive residential developments: application of LIUDD principles and methods in the Netherlands, Australia and New Zealand. *Urban Water Journal* 8, 325–335.

Wang, S., Zhou, C., Wang, Z., Feng, K. & Hubacek, K. 2017a The characteristics and drivers of fine particulate matter (PM2.5) distribution in China. *Journal of Cleaner Production* 142, 1800–1809.

Wang, Y., Sun, M. & Song, B. 2017b Public perceptions of and willingness to pay for sponge city initiatives in China. *Resources, Conservation and Recycling* 122, 11–20.

Wang, H., Mei, C., Liu, J. & Shao, W. 2018 A new strategy for integrated urban water management in China: sponge city. *Science China Technological Sciences* 61, 317–329.

Wang, C., Hou, J., Miller, D., Brown, I. & Jiang, Y. 2019a Flood risk management in sponge cities: the role of integrated simulation and 3D visualization. *International Journal of Disaster Risk Reduction* 39, 101139.

Wang, J., Shen, L., Ren, Y., Ochoa, J. J., Guo, Z., Yan, H. & Wu, Z. 2019b A lessons mining system for searching references to support decision making towards sustainable urbanization. *Journal of Cleaner Production* 209, 451–460.

Whelans, C., Maunsell, H. G. & Thompson, P. 1994 *Planning and Management Guidelines for Water Sensitive Urban (Residential) Design.* Department of Planning and Urban Development of Western Australia, Perth, Australia.

Wong, T. H. F. 2000 *Improving Urban Stormwater Quality – From Theory to Implementation.* Engineers Australia, Sydney, Australia.

Wong, T. H. F. 2006a *Australian Runoff Quality: A Guide to Water Sensitive Urban Design.* Engineers Australia, Sydney, Australia.

Wong, T. H. F. 2006b Water sensitive urban design – the journey thus far. *Australian Journal of Water Resources* 10, 213–222.

Xia, J. 2005 Development of distributed time-variant gain model for nonlinear hydrological systems. *Science in China Series D* 48 (6), 713–723.

Xia, J., Shi, W., Wang, Q. & Zou, L. 2017a Discussion of several hydrological issues regarding sponge city construction. *Water Resources Protection* 33, 1–8.

Xia, J., Zhang, Y., Xiong, L., He, S., Wang, L. & Yu, Z. 2017b Opportunities and challenges of the Sponge City construction related to urban water issues in China. *Science China Earth Sciences* 60, 652–658.

Xiao, D., Liu, D. L., Wang, B., Feng, P. & Waters, C. 2020 Designing high-yielding maize ideotypes to adapt changing climate in the North China Plain. *Agricultural Systems* 181, 102805.

Yang, T., Long, R., Cui, X., Zhu, D. & Chen, H. 2017 Application of the public–private partnership model to urban sewage treatment. *Journal of Cleaner Production* 142, 1065–1074.

Yang, J., Jakeman, A. J., Fang, G. & Chen, X. 2018 Uncertainty analysis of a semi-distributed hydrologic model based on a Gaussian Process emulator. *Environmental Modelling and Software* 101, 289–300.

Yin, D., Chen, Y., Jia, H., Wang, Q., Chen, Z., Xu, C., Li, Q., Wang, W., Yang, Y., Fu, G. & Chen, A. S. 2020 Sponge city practice in China: a review of construction, assessment, operational and maintenance. *Journal of Cleaner Production* 280, 124963.

Yu, Z., Ji, C., Xu, J., Bao, S. & Qiu, J. 2015 Numerical simulation and analysis of the Yangtze River Delta Rainstorm on 8 October 2013 caused by binary typhoons. *Atmospheric Research* 166, 33–48.
Yuan, X., Zuo, J. & Ma, C. 2011 Social acceptance of solar energy technologies in China – End users’ perspective. *Energy Policy* **39**, 1031–1036.

Yuan, J., Lu, Y., Ferrier, R. C., Liu, Z., Su, H., Meng, J., Song, S. & Jenkins, A. 2018 Urbanization, rural development and environmental health in China. *Environmental Development* **28**, 101–110.

Yusuf, S. & Saich, T. 2008 *China Urbanizes: Consequences, Strategies, and Policies*. World Bank, Washington, DC.

Zarrineh, N., Abbaspour, K. C. & Holzkämper, A. 2020 Integrated assessment of climate change impacts on multiple ecosystem services in western Switzerland. *Science of the Total Environment* **708**, 135212.

Zhang, S., Chan, A. P. C., Feng, Y., Duan, H. & Ke, Y. 2016 Critical review on PPP research – a search from the Chinese and international journals. *International Journal of Project Management* **34**, 597–612.

Zhang, L., Sun, X. & Xue, H. 2019 Identifying critical risks in sponge city PPP projects using DEMATEL method: a case study of China. *Journal of Cleaner Production* **226**, 949–958.

Zhou, Q. 2014 A review of sustainable urban drainage systems considering the climate change and urbanization impacts. *Water* **6**, 976-992.

Zhou, Z., Qu, L. & Zou, T. 2015 Quantitative analysis of urban pluvial flood alleviation by open surface water systems in new towns: comparing almere and Tianjin Eco-City. *Sustainability* **7**, 13378–13398.

Zhou, Q., Leng, G., Su, J. & Ren, Y. 2019 Comparison of urbanization and climate change impacts on urban flood volumes: importance of urban planning and drainage adaptation. *Science of the Total Environment* **658**, 24–33.

First received 16 March 2021; accepted in revised form 15 September 2021. Available online 24 September 2021