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Sponge city construction in China: policy and implementation experiences

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Abstract

To deal with the three universal urban water problems – namely storm floods, water pollution and water shortage – China has implemented a comprehensive solution: the Sponge City Construction Project. Sponge cities aim to reduce runoff and pollution, and also to restore downstream ecologies. They combine low impact development methods with grey infrastructures, large-scale flood control projects and rehabilitation. This paper describes Chinese experiences of construction and financing for implementation of sponge cities, which could provide references to other countries for building sustainable, climate-resilient cities and urban water management systems. It illustrates the objectives and methods of the sponge city design and demonstrates the differences in configuration and funding structures in cities of different climates and economic conditions. The total construction area involved in the pilot cities covers 449 km^2. The configurations are distinct due to different economic conditions, climates and land forms: a humid district inclines to drainage-efficient approaches and pollution control devices, while a semi-humid district prefers green infrastructures and rainwater reuse facilities. The Chinese government plays an important role in the funding of sponge cities: Chinese central government provided CNY (¥)20.7 billion for the construction of 16 cities during 2015–2017, while the rest came from local governments and non-governmental investors.

Keywords: Funding source; Low Impact Development (LID); Sponge city; Urban design; Urban rainwater management

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1. Introduction

Urban water problems have escalated in response to urban population and area growth. Urban regions are exploding worldwide. In the last 30 years, China's urban area has expanded dramatically from 7,438 km^2 in 1981, to 22,439 km^2 in 2000, and to 43,000 km^2 in 2011. The average expanding speed is 1,800 km^2/y (Liu *et al.*, 2014). Rapid urbanisation is accompanied with growth in impervious surfaces and pollution load (Gnecco *et al.*, 2005; Vizintin *et al.*, 2009), hence leading to higher surface runoff peak flow (Miller *et al.*, 2014; Remondi *et al.*, 2016), larger runoff volume (Trudeau & Richardson, 2016; Zope *et al.*, 2016), and heavier water pollution (German *et al.*, 2005; Lee *et al.*, 2007; Huang *et al.*, 2010), manifesting more urban pluvial floods and black malodorous waters (Astaraie-Imani *et al.*, 2012; Liu *et al.*, 2014; Chen *et al.*, 2015). In 2014, 641 out of 654 surveyed cities in China suffered from frequent floods (TFUFPSI, 2014). However, a city can be troubled with both too much water (flood) and too little (water shortage). Jiang (2009) claimed that 45% of Chinese cities in 2009 faced deficiency in water supply, while more than one million people in 30 metropolitan areas suffered from water shortage. With an ever-growing urban population, water becomes the most critical resource that limits a city's development.

In the face of urban water challenges, ecosystem-friendly urban design and management becomes a common solution for many countries. In the USA, Best Management Practices (BMP) (FHWA, 2000; Martin *et al.*, 2007; Geosyntec Consultants, 2010) and Low Impact Development (LID) (Elliott & Trowsdale, 2007) have been proposed. BMP refers to devices and systems to control water pollution from both industry and storm water. LID practices, such as porous pavements and rainwater harvesting facilities, are micro-scale infrastructures that attempt to preserve the natural hydrological characteristics (Coffman, 2002). Water Sensitive Urban Design (WSUD) in Australia (Morison & Brown, 2011), addresses storm water quantity and quality problems but also pays attention to ecology protection and resilience fostering. Sustainable Urban Drainage Systems (SUDS) in the UK try to prevent urban storm floods and water pollution by upgrading drainage systems (Ellis & Lundy, 2016); this involves diversifying the drainage routes instead of totally relying on conventional channels, purifying the water during draining processes and reusing rainwater. These practices treat stormwater on scales ranging from a street block to an entire catchment. They all share the goals of minimising the impact of urban water drainage on natural environments, preventing urban floods and controlling water pollution. They all use devices such as storage tanks, filtration and infiltration measures, constructed wetlands and retention ponds (Marsalek & Chocat, 2002).

In a similar way, in an effort to deal with the comprehensive 'rainstorm–water shortage–water pollution' problem, Chinese academics and the government have together proposed the concept of a 'sponge city', and the Chinese government has established policies to ensure its implementation. In the past, Chinese urban water management has lagged far behind urban development. Urban design takes no account of local eco-systems or the natural water cycle. Traditional urban water management involves only water supply and rapid drainage, relying completely on a pipeline system and water pumps. This approach is now proved to be unsustainable in the urban climate change context, and it strongly impacts downstream aquatic systems, causing environmental degradation. In realising that the traditional approach is neither economically nor environmentally effective anymore, China has been shifting its management paradigm. Megacities, such as Beijing and Shanghai, made the first domestic attempts in modern urban stormwater management by introducing rainwater harvesting facilities separately during 2006–2010. The results were good but the practice was not widely implemented due to the lack of related laws and regulations. In 2014, the Chinese Ministry of Housing and Urban-Rural Development (MHURD) demanded sizeable cities to compile their own urban water (rainwater) drainage and waterlogging prevention plan according to a released outline. The objectives for urban rainwater management are thereby determined as rainwater quantity control, rainwater pollution control and rainwater harvesting. In the meantime, Chinese scholars have consulted and summarised foreign experiences and applied new methods in their research. Based on their studies and consulting with experts, the Chinese MHURD proposed the concept of the sponge city, and established construction guidelines in 2014 (MHURD, 2014). In the spring of 2015, the Chinese Ministry of Finance committed to support the pilot sponge cities with 400–600 million yuan per city (MF, 2015). Later in 2015, the Chinese MHURD established an evaluation method and performance appraisal system for sponge city construction (MHURD, 2015). In 2016, the regulations for sponge city planning (MHURD, 2016a) and the national standard (MHURD, 2016b) for sponge city construction were established.

Similar to other ecosystem-friendly urban design philosophies, the purposes of a sponge city are to prevent or lighten urban pluvial flood disasters, to minimise the impact of urbanisation on natural hydrological processes, to protect and rehabilitate downstream aquatic environments, and to improve urban water body functions. A sponge city is a distributed solution like LID, but with three unique features: its large implementation scale, multiple objectives and a unique funding structure.

China's sponge cities were implemented rapidly on a large scale: in 2015, China initiated the Sponge City Construction Project (SCCP), when 16 cities were chosen as pilot cities and building started almost at the same time; in 2016, 14 cities were selected as the second group of demonstration sites. The project plans to transform 20% of China's built-up area into sponge city regions by 2020, reaching 80% of China's built-up area by 2030.

Sponge cities emphasise both protecting downstream waters and mitigating urban pluvial flood. Therefore, the managed area includes both an urban built-up region and natural/rural outskirts. The strategy combines grey infrastructures with green infrastructures, as it includes distributed measures in the built-up region with large-scale flood control engineering and afforestation projects.

China's sponge cities have found a unique solution to the funding problem. Findings indicate that a limitation of financial sources has been a main challenge for the implementation of environmental management infrastructures worldwide, especially in developing countries (Tortajada, 2016). Projects for eco-friendly cities, such as rainwater quality control or urban greening, primarily aim at long-term public benefits and are seldom financially rewarding, and hence these projects usually depend on governmental investment. Yet in rapidly expanding regions, governments sometimes cannot afford to meet the demand for sufficient infrastructure. The USA issues municipal bonds and charges fees for rainwater drainage and pollution abatement to raise funds. However, this method is not so applicable in countries with less developed financial markets and less sound legislation systems. Considering its own conditions, the Chinese government decided to provide major financial support for the SCCP, assisted by a large amount of non-governmental investment through public–private partnership (PPP) projects.

Such large-scale implementation in the biggest developing country can cause pervasive economic, social and environmental influences. Therefore, summarising the policies and extracting the engineering experiences could provide the foundation for future policy making and further research. Based on the technical document from the first group of pilot cities in the SCCP, this study investigated and analysed China's current policies and implementation plans for sponge cities, demonstrated sponge city objectives and approaches, and discussed regional characteristics and differences. This paper provides a multifaceted, detailed profile of China's methodology and practices in urban rainwater management, and might be useful for implementation or policy making for eco-cities or urban rainstorm management in other countries.

2. Methods

Literature and policies for Chinese sponge cities were investigated. The information was mainly from documents and announcements by Chinese ministries and commissions, such as '*China's Sponge City Construction Guide*' (MHURD, 2014) and '*Performance Appraisal and Assessment Methods for Sponge City Construction (Tentative)*' (MHURD, 2015).

Statistical analyses were conducted based on data from the initial 16 pilot cities in the SCCP. These 16 cities were selected from 26 competitors under the principles of feasibility and representativeness, judged from implementation plans and the cities' conditions. As a result, they have climates typical to the majority of China and cover a wide range of economic conditions. Their implementation plans will be templates for sponge city construction in other regions with similar climates and economic conditions. Therefore, these cities should be able to represent the characteristics of other cities of their kind and be adequate for statistical analysis and result interpretation. The project quantities, investments, financial sources, etc., were extracted from the implementation plans; pilot cities were classified by economic development stages, climate and city scale; then conclusions were drawn by comparing the implementation characteristics of each city type, the funding structures of groups of different city sizes and their economic development stages.

There are two climate types in the 16 pilot cities. Qianan, Hebi, Baicheng, Jinan and the Xixian New District have a semi-humid, temperate continental climate with annual precipitation between 400–800 mm, while the other 11 cities have a humid subtropical monsoon climate with 800–1,600 mm annual precipitation.

The pilot cities were preliminarily divided into four types according to China's newest standard for city size classification (China's State Council, 2014). However, GDP per capita for several cities are considerably lower or higher than their groupmates, so to better depict the economic features, we altered the division accordingly to ensure that the economic and developing conditions are similar in each group (Table 1).

According to China's current eastern, middle and western provincial division, we divided the pilot cities into three groups (Table 2). This division primarily considers economic and development level, and then location, so it is able to reflect the combined influences of local economy and climate on sponge city configuration and the choice of proposed measures. The regional economic conditions levels up from the west to the east. Table 2 shows more detailed information of the three groups.

Table 1. Division of the SCCP pilot cities by city size.

Type	Population (million)	Cities
Small-size	≤ 0.5	None
Middle-size	0.5–1	Baicheng, Qianan, Guian New District
Large-size	1–5	Chizhou, Hebi, Pingxiang, Zhenjiang, Jiaxing, Suining, Changde
Extra-large	5–10	Xixian New District, Jinan, Nanning, Xiamen
Megacity	>10	Chongqing, Wuhan

Table 2. Division of the SCCP pilot cities by eastern, middle and western districts.

District	Cities	Average Per Capita GDP (USD)	Precipitation (mm)
Eastern	Qianan, Jinan, Zhenjiang, Jiaxing, Xiamen	13,910	650–1,530
Middle	Baicheng, Wuhan, Hebi, Changde, Chizhou, Pingxiang	8,499	410–1,600
Western	Suining, Chongqing, Nanning, Xixian New District, Guian New District	7,185	520–1,300

The cities in the east and middle are generally slightly richer in water resource than cities in the west. Each group covers at least three city sizes, so it should reflect the region's general conditions.

To compare the extent of implementation of various types of engineering measures, and to reveal the city's preferences for those measures, we unified the work quantities and compared the relative implementation extent u. To be specific:

$$u_{i,j} = w_{i,j}/\bar{w}_j \tag{1}$$

where $u_{i,j}$ is the relative implementation degree (RID) of engineering measure j in city i; $w_{i,j}$ is the quantity of measure j in city i, and $\bar{w}_j$ is the average work quantity of measure j of 16 pilot cities.

The RID of a specific city type is represented with the averages and deviations of relative implementation degrees of cities in that category, so that:

$$a_{k,j} = \Sigma u_{i,j}/m \tag{2}$$

$$a_{k,j}^{-} = a_{k,j} - s_{k,j}/2 \tag{3}$$

where $a_{k,j}$ is the RID of measure j for city type k; k is 1 or 2 when representing climate types, while it is 1, 2 or 3 when representing the eastern, middle and western districts, respectively, and has values between 1–4 when representing types of different city sizes; m is the number of cities in city group k; $s_{k,j}$ is the standard deviation of the RIDs of measure j in city group k; $a_{k,j}^{-}$ is the lower boundary of the RID for one city type, reflecting the inter-city differences of one measure in the same category.

3. The concept and implementation of a sponge city

3.1. Objectives and approaches

The philosophy of sponge city design is to transform urban regions into environments like sponges that absorb, contain and slowly release rainwater. In other words, the purposes of a sponge city are to reduce rainwater runoff peak volume, to extend runoff convergence time, to increase the infiltration and evapotranspiration within built-up areas, and eventually to mitigate the impacts of urbanisation on local and downstream hydrological processes. The SCCP identified six categories of indicators for performance assessment on flood control, aquatic environments, water resources, water security and other aspects. The indicators include the control rate of annual runoff volume (CRARV), wastewater reuse rate, rainwater reuse rate, groundwater table, pluvial flood control and prevention ability (China's

MHURD, 2015; Zhang *et al*., 2016). The most crucial indicator is CRARV, which is the percentage of water that could be contained or used within a certain sponge city region (i.e. not flowing outside) in the design rainfall. The CRARV is the foundation for establishing the goals for all the other indicators for water quantity and water quality, and consequently it is the basis of the implementation plan of sponge cities. Therefore, in this study we took the CRARV alone for analyses. CRARV goals are established according to local natural runoff volume before urban development. China's Sponge City Construction Guide divided the mainland region into five districts of different CRARV goals (shown as α in Figure 1), considering rainfall quantity, rainfall pattern and rainwater reuse demand.

To achieve the water quantity and quality goals, relying completely on LID measures in built-up region is neither sufficient nor cost effective. China's SCCP integrated LID measures with grey infrastructures such as wastewater treatment plants, sewage system rebuilding and pumping stations, assisted by large-scale flood control projects, afforestation and river way treatment measures. It involves six functions (namely: infiltration, retention, storage, purification, reuse and drainage) and 24 engineering measures in total (China's MHURD, 2015) (Figure 2; Table 3).

3.2. Implementation in pilot cities

The CRARV goals of the 16 pilot cities (Figure 1) vary from 70–85%. No city in the northwest (annual precipitation under 400 mm) with a CRARV goal over 85% was selected, for two reasons: (i) the cities there have less rainfall, so problems like pluvial flood and water pollution are not as

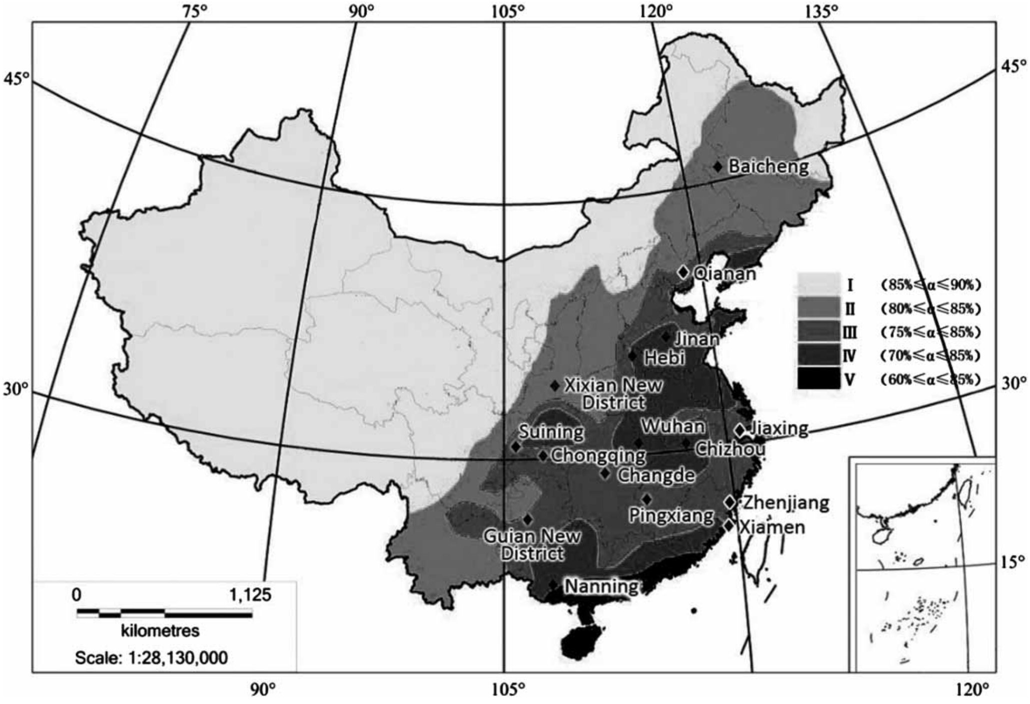

Fig. 1. Established control rate of annual runoff volume (CRARV) goals in the mainland and the locations of pilot cities in the Sponge City Construction Project (SCCP).

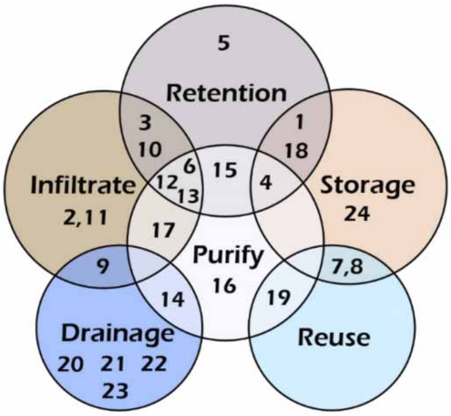

Fig. 2. Functions of engineering measures undertaken by the SCCP (numbers in the figure indicate the sequence numbers in Table 3).

Table 3. Engineering measures undertaken in the SCCP.

Location	Engineering measures					
Built-up region	1	Green roof	9	Infiltration pipes/ ditches	16	Early runoff discarding
	2	Pervious pavement (concrete/brick)	10	Infiltration tank	17	Artificial soil infiltration
	3	Sunken lawn	11	Infiltration well	18	Artificial lake
	4	Bio-retention pools[a]	12	Artificial pond	19	Wastewater treatment
	5	Detention pool	13	Artificial wetland	20	Pumping station
	6	Detention tank	14	Grassed swale	21	Drainage system reconstruction
	7	Rain water tank	15	Vegetation buffer zone	22	Canals & ditches building
	8	Rain pit				
Suburban region	23	River way treatment	24	Afforestation	(18	Artificial lake)

[a] Includes rain garden, parterre, eco-tree pool, etc.

urgent; (ii) these cities are relatively underdeveloped, so local governments in most cases have no advantage in financial incomes or managing experiences while it costs more to build and maintain infrastructures like sunken lawns, artificial water bodies and artificial wetlands there.

The total construction area of the pilot cities reaches 449 km^2, with an average construction area per city of 28.06 km^2. The construction areas in the eastern, middle, western district are 145.94 km^2 (33%), 162.31 km^2 (36%), 140.75 km^2 (31%), respectively, showing no considerable variation either in total or average (Figure 3). The total construction area of cities with a humid climate and cities with a semi-humid climate are 128.6 km^2 and 320.4 km^2, with little difference in the average construction area per city as well. Therefore, when discussing the differences in engineering quantities between groups of the three districts or different climate types, the factor of construction area has been neglected. However, the average construction area per city is distinctly different between groups of different city sizes

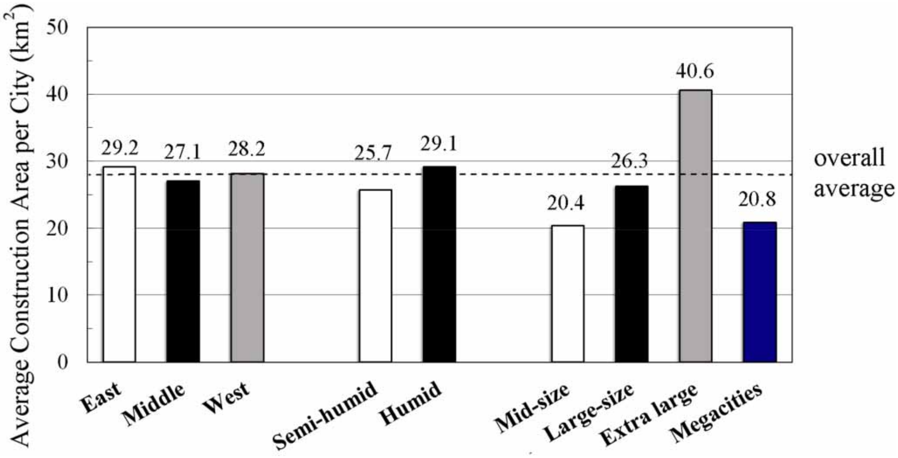

Fig. 3. The average construction area per city of the various city types.

(Figure 3). The four extra-large cities have all planned a larger construction area, leading to a high average, and the largest site covers 60.18 km^2 (Nanning city). The site area is generally smaller in both middle-size cities and megacities, for different reasons. In the middle-sized cities, large-scale implementation is usually unaffordable for local governments, while in megacities with huge population and dense infrastructures, it is not practical because a wide area of reconstruction can obstruct busy cities, adding non-financial costs.

Sixteen measures have been used in the pilot cities, including pervious pavements, sunken lawns, pipeline reconstruction, green rooves, artificial wetlands and others (Figure 4; Table 4).

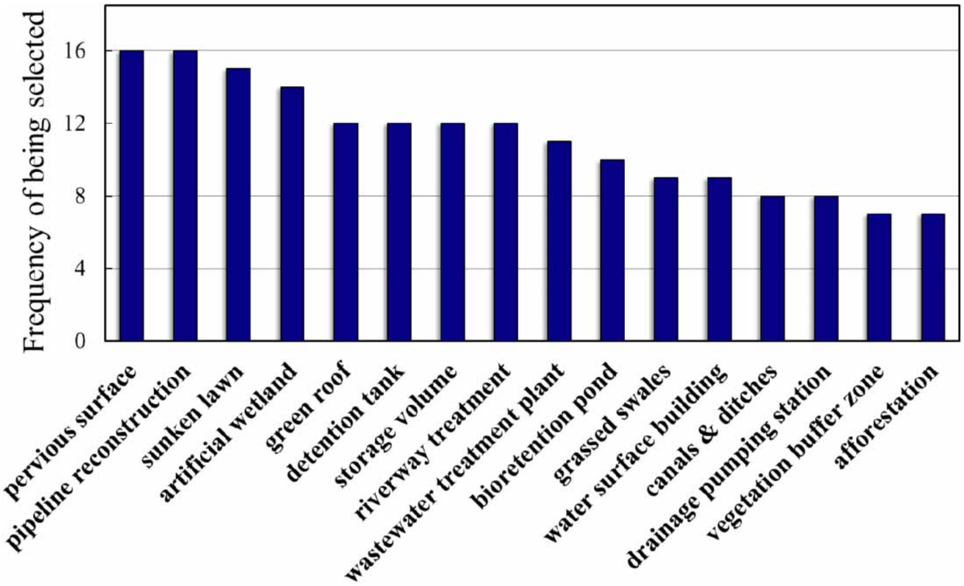

Fig. 4. Common measures undertaken by pilot cities in the SCCP (measures unlisted due to very few applications are Nos 10, 11, 16 and 17 in Tables 3 and 4).

Table 4. Common engineering measures and quantities used in pilot cities in the SCCP.

No.	Measure	Quantity	No.	Measures	Quantity
1	Green roof (hm^2)[a]	801	15	Vegetation buffer (hm^2)	52
2	Previous pavement (hm^2)	2,422	18	Artificial lakes (hm^2)	496
3	Sunken lawn (hm^2)	2,513	19	Wastewater treatment (t/d)	935,000
4	Bio-retention tank (hm^2)	1,050	20	Pumping station (m^3/s)	20,912
5, 6	Detention tank (m^3)	1,748,001	21	Pipeline reconstruction (km)	2,170
7, 8	Storage volume (m^3)	775,863	22	Canals & ditches (km)	163
12, 13	Artificial wetland/ponds (hm^2)	1,891	23	River way treatment (km)	470
14	Grassed swales(hm^2)	172	24	Afforestation (hm^2)	10,561

[a] $1\ hm^2 = 10{,}000\ m^2$.

The pervious pavement and pipeline reconstruction were the most frequently applied. All the pilot cities installed sizeable pervious pavements made by pervious bricks or concrete, with the coverage ranging from 22–354 ha in different cities. Pipeline reconstruction refers to rain and sewage diversion, extension of current drainage systems, and pipeline installations for new wastewater or pumping stations. In most cities the pipeline to be reconstructed or installed was about 100 km in total, though there are several cities that only installed small quantities as needed.

Sunken lawns were the second most popular measure. Because of the lower installation and maintenance cost, as well as the scenic benefit, many pilot cities applied this measure in parks and residential districts in built-up regions. Most pilot cities installed over 100 ha of sunken lawn, except for Chongqing, which applied large quantities of green rooves, storage devices and afforestation instead.

Artificial wetlands, artificial ponds and artificial soil infiltration are all used to purify and retain rainwater runoff at the end of catchments. Artificial wetlands and ponds are quite similar in function and in structure, differing only in size. Therefore, in this paper the two measures are both categorised as 'artificial wetland'. They have been adopted by 14 pilot cities, with the construction area varying from 5.35–270 ha. Most cities installed artificial wetlands at outlets of catchments in the form of wetland parks. These parks not only purify urban runoff and protect downstream water bodies but also function as leisure facilities.

Green rooves, detention tanks (including detention pools and ponds), storage devices and river way treatments were applied by the same number of cities. Detention pools have a single function and are usually used to assist wastewater treatment plants, green spaces or other measures, whereas detention ponds have scenic benefits and are mostly used in parks. Storage volume refers to the use of rainwater tanks, rainwater pits and other devices that gather rainwater for reuse (mostly for landscape), and in many cases are equipped with purifying devices. River way treatment includes river dredging, river way broadening, and river bank strengthening. The relatively high level of uptake of these measures proves that the concept of sponge cities does not end with runoff control in urban built-up regions, but also looks at management of surrounding environments, aiming at improving the general water system resilience of urban catchments and rehabilitating the natural water cycle characteristics of downstream catchments. A wastewater treatment plant was installed by 11 pilot cities, with capacities of 20,000–420,000 t/d. (Bio-retention ponds are given different names when used at different locations or in different sizes, such as rain gardens, bio-retention zones, high parterres and bio-tree pools; the form used differs in response to landscape and construction conditions on the site.)

3.3. Engineering measures taken in sponge city design

Under the principles of the sponge city, the pilot cities undertook distinct configurations of engineering measures to adapt to various climates, construction conditions, economic level, water demands and other conditions, resulting in conspicuous differences in the amount of work needed for the same measures. This section compares the configurations undertaken in cities within each of the three divisions (economic conditions, climate and city scale) already identified.

In terms of deviations of the three classification methods, the economic conditions division showed the largest intragroup variation. The average RID variance of the three groups in this division is 1.06, whilst for the climate division it is 0.955 and for the city-scale division it is 0.91. This is probably due to the complexity of the district divisions. The eastern, middle and western divisions are determined primarily by developing status and then by location, so the cities in one group hold idiosyncrasies in both climate and economy. The intragroup variations for the climate division and city-scale division are mainly caused by other factors such as design ideas, historical culture, and the particularities of individual cities. Although there are several considerable intragroup differences in each division, due to the limited data, any further subdivision would result in too few samples in one group. Hence, only three divisions were made to grasp the dominant elements at a basic level.

Two climate groups showed different preferences in measures undertaken (Figure 5), except for three measures: pervious pavements, grassed swales and detention tanks. The RID of pervious pavements is 1.05 for the semi-humid group and 0.98 for the humid group; for grassed swales it is 0.52 and 0.58 for the two groups, respectively; and for detention tanks it is 0.72 and 0.76, respectively. More pilot cities have humid climates, so the humid group has more diverse engineering measures. The average RID of the 16 measures for the humid group is 0.76 while that for the semi-humid group is 0.56. Since the pilot cities with a humid climate are either coastal or have complex river systems, they generally face heavier flood disasters and contamination loads, which led to the wider application of wastewater treatment plants, river way treatment, drainage channel building and other drainage-effective, grey infrastructures. The semi-humid group have lower flood risks, and tend to assume measures with higher scenery benefits but lower runoff control capacity, such as sunken lawns, artificial water bodies and vegetation

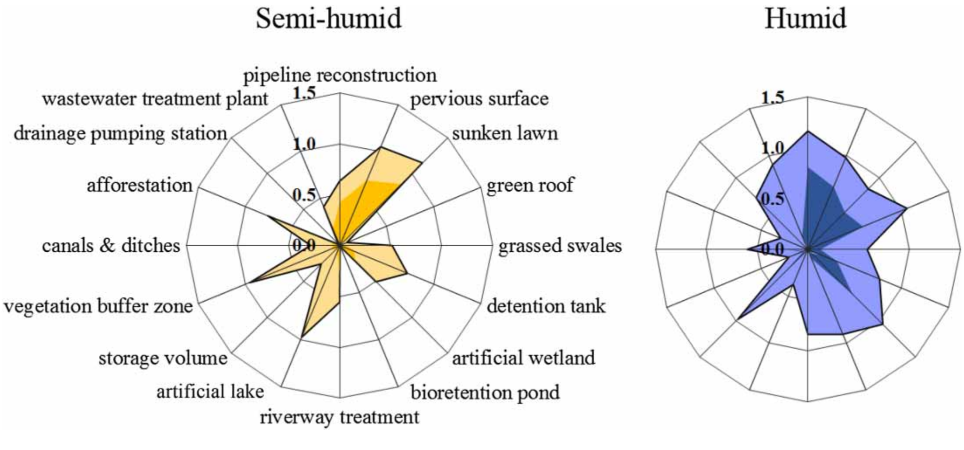

Fig. 5. The relative degree of implementation of city groups divided by climate (the paler colours represent $a_{k,j}$ while the darker parts represent $\overline{a_{k,j}}$).

buffer zones. Although green rooves also offer scenery benefits and cooling effects for buildings, in semi-humid areas where annual precipitation is unevenly distributed, roof plants are unlikely to survive dry seasons without watering. Hence, this option was not chosen by any semi-humid city. Likewise, the limited implementation of bio-retention ponds and artificial wetlands in semi-humid cities primarily results from the same reasons, since they would create more maintenance costs and undesired water demand.

The city-scale groups showed the most distinct variation between groups among the three divisions (Figure 6). The average RIDs are 0.87, 0.55, 0.75, and 0.85 for the middle-size, large-size, extra-large and megacity groups, respectively. Unexpectedly, the RIDs of the large-size group are generally smaller than the others, even than the middle-size group with smaller construction area. This is probably because river way treatment and artificial wetlands in several cities cover a wide range and affected the group average. Although the construction area per city is particularly high for extra-large cities, the RIDs are not large compared to other groups. It is because: (1) measures like large wastewater treatment plants and artificial wetlands involve broader coverage and systematic installation; (2) the measures selected are distributed on a wider range. On overall observation, no apparent linear relationship was found between economic level and RIDs of measures. Economic condition weighs in deciding alternatives, but it is not the dominant factor.

The three groups of the eastern, the middle and the western district showed obvious differences, with the average of RIDs being 0.56, 0.67, and 0.88 respectively. However, only pervious pavements, sunken lawns and green roof have relatively small intragroup variation (Figure 7). The average variances of

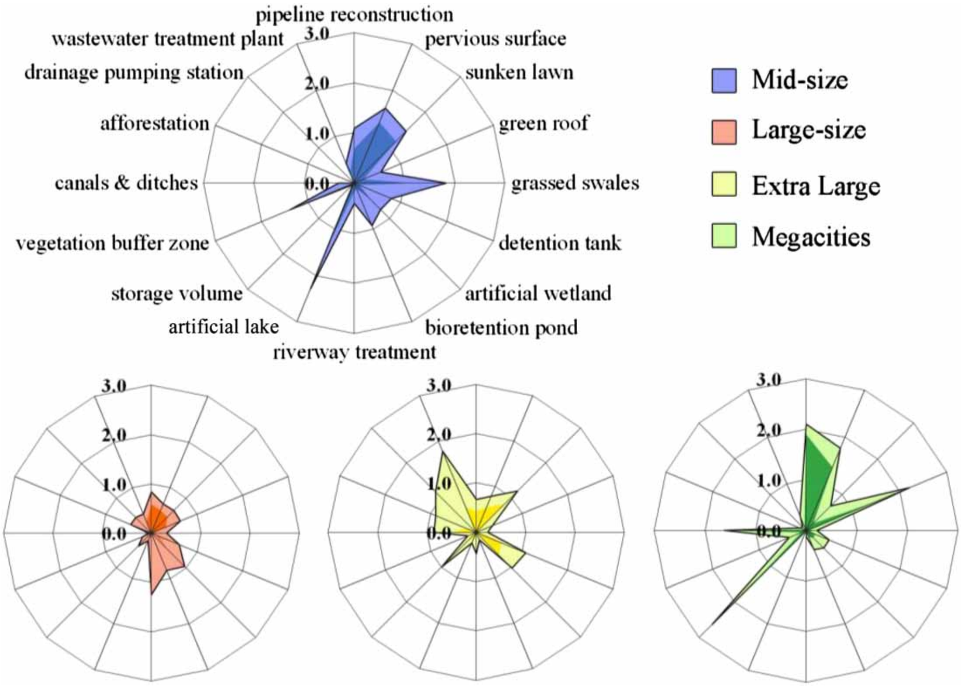

Fig. 6. The relative implementation degrees of city groups divided by city size (the paler colours represent $a_{k,j}$ while the dark parts represent $\overline{a_{k,j}}$).

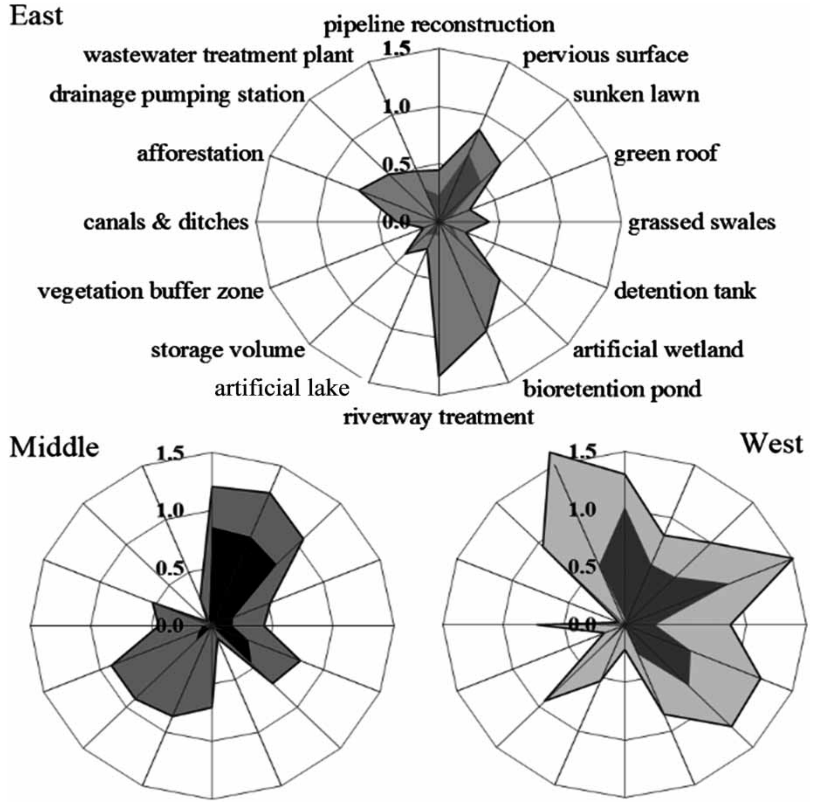

Fig. 7. The relative implementation degrees of measures in the eastern, middle, western district (the pale colours represent $a_{k,j}$ while the dark parts represent $\overline{a_{k,j}}$).

those measures are 0.33, 0.39, and 0.43, respectively. The RID of pipeline reconstruction in the eastern group is smaller than the others, and so are the RIDs of canals and ditches, storage volume, green roof, pervious pavement, sunken lawn and other LID measures, while the situations for river treatment is to the contrary. The middle district group focused on pipeline reconstruction, pervious pavement and sunken lawn. Several cities in this group also applied sizeable rainwater reuse devices, vegetation buffer and artificial lakes. The work quantities of the western group are generally heavier, with extra focus on pumping station, drainage system and green roof, but the application of afforestation or vegetation buffer is almost none. This group installed pumping stations at places with higher flood risks, to compensate for the loss in flood control capacity by applying more LID measures.

The attribution is both naturally and economically related. Because landscape in the eastern district is lower and plainer, and river-lake systems are more complex, generally the flood/runoff control is the dominant issue while the demand for rainwater reuse is smaller. Therefore, the CRARV goal of eastern district is the lowest among the three districts, the work quantities are generally smaller and local SC designs attempt to drain the rainfall runoff rapidly through natural water systems and canals. Moreover, the eastern district is more economically developed, so local governments are able to afford the public-beneficial, large-scale projects like river way treatment, which hardly attract business investment. The cause for the western configuration feature is also twofold: firstly, urban greening projects respond to the demands of better urban landscape and living feeling; secondly, LID measures could be easily applied in residential districts, commercial districts and other built-up regions, which can attract business investment through policies like establishing building standards or setting bonus for ecological friendly constructions; while the large-scale greening projects like afforestation and vegetation buffer building, which seldom attract non-governmental investments, are unlikely to realise without strong financial support from the government.

4. Financial support for sponge city construction

4.1. Funding sources for implementation

China is in a process of rapid urbanisation. The progress of the SCCP would have been much slower if the project had followed the conventional financial method, relying completely on government finance. Therefore, developing multiple funding sources was a crucial premise for the SCCP to proceed as planned. The strategy was to include non-government investors into the financial framework. This section illustrates the practical experiences of the SCCP financing, and could be interesting for readers in the environmental management field, especially in developing countries.

There are three funding sources for China's sponge city construction: central government finance, local government finance and non-governmental investment (Figure 8). The pilot cities in the SCCP required a total investment of CNY(¥)111.55 × 10^9, in which central government undertook ¥ 20.7 × 10^9, local governments undertook ¥42.96 × 10^9, and the rest (¥ 47.89 × 10^9) came from non-governmental investment.

Central governmental investment refers to the special subsidy for the SCCP from the state revenue. This subsidy was given to local governments three times during 2015–2017: ¥600 million per year for direct-controlled municipalities, ¥500 million per year for provincial capitals, and ¥400 million per year for other cities, totalling ¥6.9 × 10^9 each year. According to the literature, the UK government decided

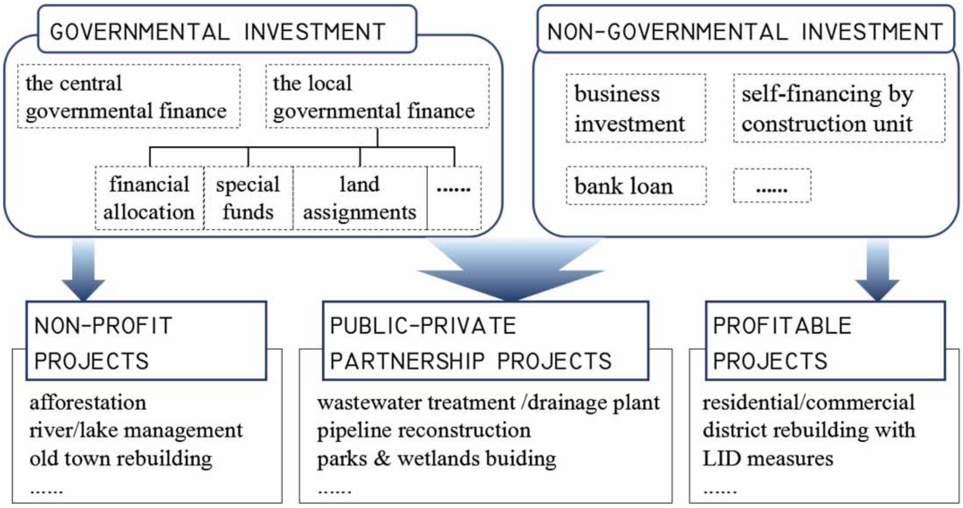

Fig. 8. Funding sources for sponge city construction.

to input £1,976,000 (about ¥16.98 million) every year for the implementation of SUDS (Ellis & Lundy, 2016). By comparison, the Chinese government clearly plays a more important role in its eco-city building. Local governmental investment means the payment by local provincial or municipal government, sourcing from fiscal revenue, special funds or land transfer. Non-governmental investment mainly includes business investment, bank loan and self-financing by construction units (or property owners).

Generally speaking, non-profit projects like afforestation, river/lake management and old town rebuilding, rely on government financial support (Figure 8). Some of the profitable projects, mainly comprising residential/commercial district rebuilding with LID measures like green roof, greenspaces or pervious pavements, are financed and implemented by property owners. Governments attract construction units to do so through setting awards or subsidies, or by establishing strict environmental regulations. Aside from all mentioned, many projects adopted public-private partnership (PPP) mode, supported by both government and society. In the pilot cities, the investment of PPP projects reached ¥ 50.4×10^9.

PPP is an essential tool in completing SCCP funding. Operation modes adopted comprise Design-Build-Finance-Operate (DBFO), Build-Operate-Transfer (BOT), Build-Own-Operate (BOO), Transfer-Operate-Transfer (TOT), and Rehabilitate-Operate-Transfer (ROT). Chinese loan requirement for SC PPP projects is that registered capital should be no less than 20% of the total investment, with the shortage filled by social investors, loan or other financing channels. The registered capital comprises governmental and non-governmental input, with the latter being the majority.

PPP projects involve a wide range of measures, which could be classified as public welfare, quasi-public welfare or commercial by repaying routes. Commercial projects are paid by users, franchised by the government, including most wastewater treatment plants, and several pumping stations, pervious parking lot and a few parks. Quasi-public welfare projects are primarily for public welfare, although with acceptance of users, low fee could be charged; these projects, such as regional environment management, scenery artificial lakes, are paid by users or through the increment of surrounding land value and governmental subsidy. Public welfare projects are non-profit projects, like aquatic environment rehabilitation, flood control and wetland restoration, paid by government purchases.

4.2. Regional differences in funding structure

In the economic district division, the middle district received the most investment while the western group received the least (Figure 9, Table 5), although the investment per unit construction area is highest in the east and lowest in the west (Figure 10). Three districts received similar financial support from the central government. The local governmental investment is larger than non-governmental investment for the eastern group while the middle and the western group showed the contrary, which is related to local financial capacity and measures undertaken. The eastern group applied more non-profit measures (namely, river dredging, afforestation and bio-retention ponds) which are unappealing to social investors, while the district is more economically developed so that such configurations are feasible. The middle group applied both profitable measures like artificial lakes in public regions, pipeline reconstruction and vegetated buffer zone, and non-profit measures like LID measures, with almost equivalent support from government and society. The western group applied more profitable methods like wastewater treatment, pumping station, LID measures, to attract more investors, lightening government pressure.

As for the city-scale division, the large-size group received the largest investment, although this was primarily due to it having the largest number of cities (Figure 9). The average investment per unit area of the megacity group is the highest and that of the extra large-size group is the lowest (Figure 10).

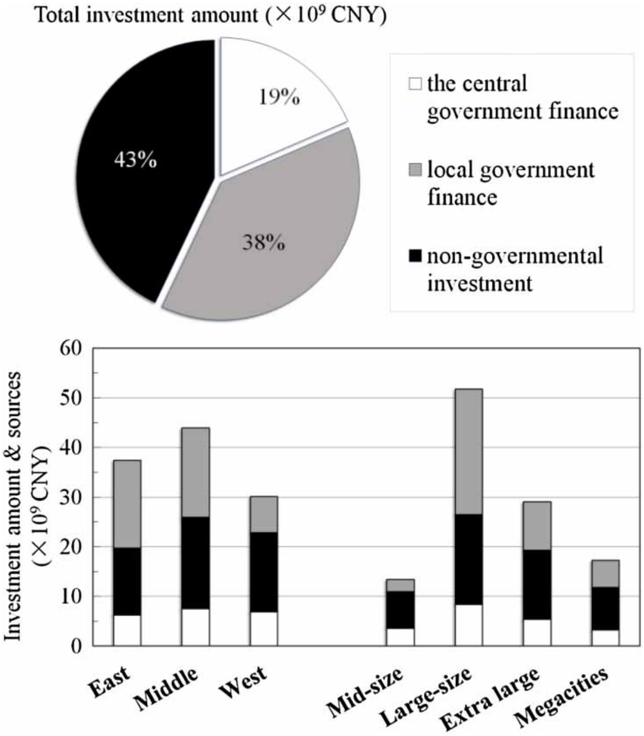

Fig. 9. Funding structures for pilot cities in the SCCP.

Table 5. Investment sources for the pilot cities in the SCCP ($\times 10^9$ CNY).

	The central government finance	Local government finance	Non-governmental investment	Total
Total	20.70	42.96	47.90	111.55
East	6.30	17.70	13.45	37.45
Middle	7.50	18.04	18.44	43.98
West	6.90	7.22	16.00	30.12
Middle-size	3.60	2.41	7.38	13.39
Large-size	8.40	25.22	18.14	51.76
Extra large	5.40	9.80	13.87	29.07
Megacities	3.30	5.52	8.50	17.33

However, the reverse between the large-size and extra-large group is probably due to the high average construction area per city in the latter, as well as the effect of isolated cases, which was proved by the higher intragroup deviation of large-size group (nearly four times of each average intragroup deviation of other three groups). Except for the extra large-size group, the investment on unit area increases along with city size, or rather, local economic conditions.

As for the funding source, all groups acquired about 20% of total investment from central government while the middle-size group relies a bit more on this than the others. Local governmental input and non-government investment varies more. The situation of the large-size group is almost opposite to the other groups, while the middle-size group apparently differs from the extra-large group and the megacity group.

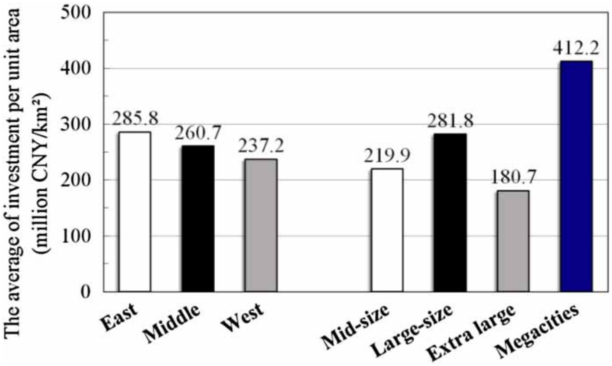

Fig. 10. Investment per unit construction area of different city groups.

The larger investment of the large-size group required stronger support from government, which is feasible due to better local fiscal revenue compared to the middle-size group, while for the extra-large group and the megacity group, local economic prosperity guarantees a good return of investment in public infrastructures so that business investors are attracted, taking the burden off governments. For the middle-size cities, local governments provided less support but the rest of the smaller total financial requirement could be filled with business investment, through a prudent choice of measures. Unexpectedly, the extra-large group and the megacity group have very similar funding source structures despite the disparity in average investment per unit area, with slightly higher local governmental input in the megacity group.

5. Summary and future perspectives

5.1. Comparison between sponge cities and international practice

Against the background of climate change and rapid urbanisation, the urban water crisis has concerned the world. Many countries have presented their unique solutions with which China's sponge cities have similarities and differences. Like many other solutions, the sponge city aims to alleviate the hydrological impacts of urbanisation, managing urban pluvial flood and mitigating water quality deterioration. But the construction of China's sponge cities has three distinct features: (i) the large scale of its implementation: the first batch of the 16 pilot cities in the SCCP cover a total construction area of 449 km^2, with an average construction area per site of 28.9 km^2; (ii) its more comprehensive approach: it puts an emphasis on both water quality and quantity, and on both flood mitigation and eco-system rehabilitation, combining LID measures with large-scale river management and afforestation projects; (iii) the stronger support from government: during 2015–2017, the Chinese central government was due to provide CNY(¥) 20.7×10^9 (19%) for the pilot cities in the SCCP, while local governments were due to shoulder ¥ 43.0×10^9 (38%).

5.2. The Chinese experience of characterised design and financing for sponge cities

Experiences from the pilot sponge cities show that two key factors determine the measures used to achieve the three water management goals: climate and government revenue.

Chinese cities with humid climates tend to use powerful grey infrastructure (such as wastewater treatment stations, channel building and river way treatment), while drier cities prefer green infrastructure that can survive dry seasons because of the scenic benefits. It should be noted that these humid Chinese cities are either coastal or have complex river systems; the choices made by a city with a wet climate but no river could be very different.

Financially strong municipal governments have a wider choice of public-beneficial, large-scale measures, while other cities choose to apply more small-scale LID measures, or profitable measures (such as wastewater treatment). This is because these measures can be installed in residential or commercial districts and can therefore be paid for by private investors. Sufficient financing is the crucial premise for the large-scale of the SCCP and participation by the three parties (central and local government, and non-government investors) are all essential. Two methods are used to include non-government investment: (i) some profitable projects can rely partly on corporate or bank investment via the Public-Private-Partnership (PPP) mode; (ii) setting environmental requirements for construction or establishing subsidiary policies can attract proprietors to pay for certain small-scale LID measures.

5.3. The future for sponge cities

The second batch of 14 demonstration cities in the SCCP have already largely been selected. Based on the experiences of the pilot cities in the SCCP, sponge cities and other eco-cities should adjust their measures to local conditions with respect to local natural water bodies and hydrological characteristics. Therefore, sponge city designers should take local social and natural environments into account when deciding engineering configurations.

The purpose of the sponge city is multi-dimensional: to control storm flood and water pollution, to restore eco-balance and eventually to improve living conditions. As a result, designing and building sponge cities is naturally inter-disciplinary work. How to truly break the bulwarks of individual disciplines is also one of the determining factors to building an effective sponge city. China has made a great start but there is still more work to do if we are to transform cities nationwide.

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