Chapter 3

Chinese version of water-wise cities: Sponge City initiative

Nanqi Ren, Xiuheng Wang and Shunwen Bai

School of Environment, Harbin Institute of Technology, Harbin, China

3.1 INTRODUCTION

By the end of 2018, China had 669 cities of which 297 were national or local central cities (prefecture-level and above) of large sizes and population. Altogether, these cities occupy an urban area of 200,897 km^2, with an average population density of 2546 people/km^2. According to the National Bureau of Statistics of the People's Republic of China, the urbanization rate of the permanent population has increased from 10.64% in 1949 to 59.58% in 2018. During this period, China experienced the largest and fastest urbanization process in the history of the world. Along with the rapid urbanization and social economy, the original hydrological and ecological environments in China have been severely damaged, resulting in obvious urban water environmental problems (Cheng & Hu, 2011; Jia *et al.*, 2013). For instance, two-thirds of China's cities are suffering from water shortage. Poor water quality was identified in 61.3% of the groundwater monitoring sites in 202 cities. According to the China Flood and Drought Disaster Bulletin, 83 cities were flooded in 2018, with a direct economic loss of 16 billion Yuan, equivalent to 0.18% of the GDP that year. With the manifold pressures from population growth, resource constraint, and economic development, novel concepts and principles are needed to guide urban water systems planning towards sustainable development.

Editors: Xiaochang C. Wang and Guangtao Fu
doi: 10.2166/9781789060751_0053

Consequently, the Sponge City strategy has been set by the central government. On 12 December 2013 at the Central Urbanization Work Conference, President Xi Jinping emphasized the need to prioritize stormwater reservation in the building of urban drainage systems, the utilization of natural forces for water discharge, and the construction of 'Sponge City' with natural storage, infiltration, and purification as sole connotations. A national program was subsequently initiated for implementing pilot projects of Sponge City Construction (SCC) in selected cities with financial support from the central government. Efforts were also made in the standardization of SCC technologies and methods for project evaluation, such as the Evaluation Standard for Sponge City Construction (GB/T 51345-2018) approved in 2018. All these marked the beginning of a new era to transform the urban water environment from grey-based systems into more flexible, resilient, and sustainable systems.

Consequently, research on SCC technologies and applications is burgeoning in recent years. As SCC aims at developing a systematic strategy to deal with complicated urban water problems, the first effort was to interpret and advance technological guidelines at the national level, associated with the identification of opportunities and challenges to promoting an overall SCC progress (Chan *et al.*, 2018; Griffiths *et al.*, 2020; Ren *et al.*, 2017; Thu *et al.*, 2020; Xia *et al.*, 2017). Another effort was to solve urban water problems through the development of sponge-based technologies such as permeable materials (Shen *et al.*, 2020) or greening plants (Li *et al.*, 2019). In addition, as SCC often involves large-scale public projects that are subject to public financial support, efforts were also made to improve the financial sufficiency, including investigations on public willingness to pay for SCC projects (Wang *et al.*, 2020), and identifications of risks in cooperative arrangements such as public-private partnerships (Zhang *et al.*, 2019). Besides, there were studies focusing on the establishment of methodological frameworks to improve performance evaluation and decision support (Chang & Su, 2020; Meng & Li, 2020; Thu *et al.*, 2020).

3.2 PROBLEMS TO SOLVE

Before the proposal of the Sponge City strategy, many countries in the developed world proposed various strategies for urban rainwater management, which have greatly changed the traditional way of thinking and gradually shifted focus from individual technical development to a comprehensive governance strategy advancement.

In the United States, a number of strategies have been proposed and widely adopted since the 1970s, such as the proposal of Best Management Practice (BMP) in 1972 for non-point source pollution control (Karr & Schlosser, 1978), Low Impact Development (LID) in 1990 (Carlson *et al.*, 2015), and Green Infrastructure (GI) in the early 1990s (Hiltrud & Pierre, 2011). BMP focuses on measures for flood peak flow and pollutant control, groundwater recharge and storage, and ecological sensitivity management. The core of LID is to control the development area as close to the natural hydrological cycle as possible through decentralized and small-scale source control and ultimately achieve stormwater runoff and pollution control. GI aims to form an interconnected and unified green network system composed of natural regional elements.

Also, in the 1990s in Australia, Water Sensitive Urban Design (WSUD) was proposed with primary concerns on rainwater utilization to combat water shortage under arid climates (Sharma *et al.*, 2016). In the UK, Sustainable Urban Drainage System (SUDS) has been adopted to solve the problems of frequent flooding and ecological pollution through optimized regional drainage system design (Ellis & Lundy, 2016). In 2006, the Active, Beautiful, and Clean Waters Programme (ABC) was launched in Singapore (Lim & Lu, 2016) as a comprehensive urban environment improvement measure. The purpose of ABC is to transform drainage channels and reservoirs into clean and beautiful rivers and lakes, integrate them into the entire urban environment and provide new urban public space for citizens.

The abovementioned strategies and measures have, so far, been widely applied worldwide for comprehensive urban water environmental planning. These experiences are no doubt beneficial in China for Sponge City Construction. However, for solving the current problems associated with rapid urbanization in Chinese cities, what we need to do is not just an adaptation of the existing experiences to local situations but the development of novel Chinese models based on similar concepts.

Most Chinese cities are facing the common problems of uncontrolled urban runoff, lack of water resources, and pollution of the water environment, which have considerably restricted the sustainable development of the economy and society.

Urban runoff is a problem that may not be easily coped with by the current urban water systems in China. On one hand, uncontrolled urban runoff results in frequent waterlogging, causing huge economic losses and casualties. On the other hand, urban runoff is the cause of urban nonpoint source pollution and the destruction of the ecological environment. Surface runoff in rainy days usually carries pollutants into urban water bodies through mixed rainwater and sewage overflows. Due to insufficient baseflow in urban river channels and shortage of source water to replenish urban lakes, as well as the high pollutant loading from point and nonpoint sources, some urban water bodies have become black and odorous, bringing about a serious urban water environmental problem of public concern.

Statistical data show that the per capita water resource in China is far below the world average level. With the rapid industrialization and urbanization, urban water demand continues to increase, and there is an unbalanced supply–demand relationship in many cities. The water shortage problem will be further deepened in the coming years. Meanwhile, urban sewage discharge is also increasing year by year, but the existing sewage treatment facilities and their treatment capacities cannot meet the increasing needs. Although investments in water and wastewater related infrastructure has been increasing, the development speed of sewage treatment plants and auxiliary facilities (including sludge disposal systems) are still lagging behind the speed of economic growth and urban and industrial development. The overall quality of the water environment has not been improved as expected, and even continues to decline in some cities. Water shortage also threatens urban water safety and public health.

Table 3.1 summarizes the statistical data from 2014 to 2018 on urban water-related conditions in China.

It should also be pointed out that, as a large country, there are great differences between cities in different regions in terms of their natural conditions and development level. Facing the complicated problems of the water environment,

Table 3.1 Urban water-related data from 2014 to 2018.

Year	2014	2015	2016	2017	2018
Urban population density (person/km^2)	2419	2399	2408	2477	2546
Number of cities with waterlogging	125	168	192	104	87
Direct economic losses caused by waterlogging (100 million CHY)	1573	1661	3643	2142	1615
Percent of centralized drinking water supply in cities of prefecture-level and above (%)	96	90	90	91	91
Water resource per capita (m^3/person)	1999	2039	2355	2074	1972
Total urban water supply (100 million m^3)	547	560	581	594	615
Urban sewage discharge (100 million m^3)	445	467	480	492	521
Percent of urban sewage treatment (%)	90	92	93	95	95
Investment in fixed assets of urban public water supply facilities (100 million CHY)	475	620	546	580	543
Investment in fixed assets for the construction of urban public drainage facilities (100 million CHY)	900	983	1223	1344	1530
Investment in fixed assets for the construction of urban public sewage treatment and recycling facilities (100 million CHY)	404	513	490	451	803
Investment in fixed assets for the construction of urban public utility tunnel facilities (100 million CHY)			295	673	619

Data source: summarized by authors based on original data from https://data.stats.gov.cn (National Bureau of Statistics of China).

the governance of urban water requires systematic solutions to be worked out under governmental leadership and coordination, and the participation of all related sectors. Sponge City is a new form of city that conforms to the requirement of development in China, and it is also a new concept to lead the formulation of a theoretical and methodological framework for aquatic ecological environment governance, with stress on the interlinkage between the social water cycle and the natural water cycle. The construction of a Sponge City aims to solve the problem of urban waterlogging, to improve the urban water environment with the elimination of urban black and odorous waters as the core objective, and more importantly, to make cities more sustainable.

As a governmental oriented action, Sponge City Construction stresses an overall improvement of the urban water environment. Related to the national development goal and institutional context, Sponge City distinguishes from other approaches proposed so far in other countries. In addition to water quantity and quality, it stresses the social and natural attributes of the entire water cycle to balance environmental and economic interests.

3.3 CONVENTIONAL SOLUTIONS: GRAY ENGINEERING MEASURES

The Sponge City initiative in China is deeply committed to solving multiple urban water problems. To better understand the context and significance of Sponge City, this section will introduce the status quo of China's current urban water systems along with the systematic problems.

3.3.1 Urban water system 1.0

In ancient times, transport aqueducts were developed to meet water supply and discharge demands for centralized urban residents, forming the primary urban water system 1.0 as shown in Figure 3.1 (De Feo *et al.*, 2014). With a small population size (several thousand to tens of thousands) and agriculture as the

Figure 3.1 Depiction of Urban water system 1.0 (figure by authors).

main production activity, such a type of system model could ensure human access to adequate and safe water and sanitation through natural water circulation and purification.

3.3.2 Urban water system 2.0

Unexpected challenges, i.e. water-related diseases spreading and industrialization, stimulated the revolution of urban water systems. From the late 1800s to the early 1900s, drinking water and wastewater treatment technologies and infrastructures were emerging in succession and brought about the formulation of urban water system 2.0. This is a common system model applied over the world until now, even in many industrialized countries including China. As depicted in Figure 3.2, urban water system 2.0 is a conspicuously linear model consisting of a series of large-scale centralized infrastructure, including water supply and wastewater treatment plants.

China's urban development has long relied on urban water system 2.0 to meet the needs for water supply, sanitation, and drainage. However, as the rate of urbanization often exceeds the rate of construction of new water infrastructure, a series of urban water problems have emerged (Figure 3.3). From 1978 to 2014, the urbanization rate in China increased from 18 to 55% and socio-economic development proceeded at a very high speed, as indicated by the GDP increase of 174 times. In the meantime, urban domestic water consumption also increased by several times, resulting in an imbalance between the growing demands and available freshwater resources. In many cities, pollutant loading has exceeded water environmental capacity, albeit most of the wastewater treatment plants have made efforts to meet the effluent discharge standards. It is usually a challenge for

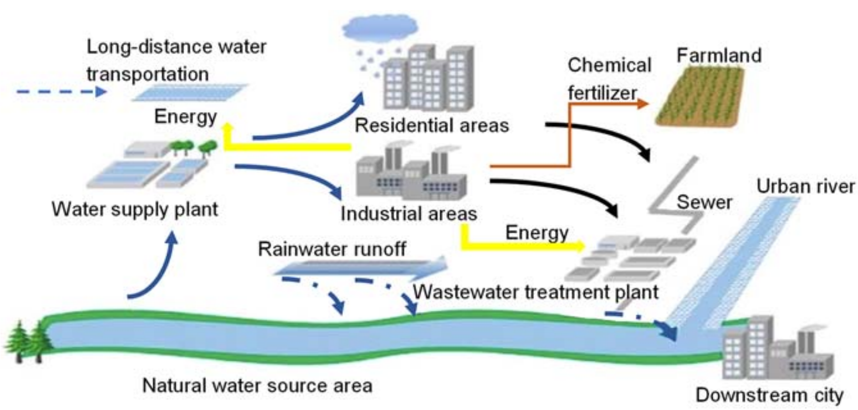

Figure 3.2 Depiction of urban water system 2.0 (figure by authors; the blue, grey, brown and yellow arrows represent water flow, wastewater flow, resource supply, and energy supply, respectively).

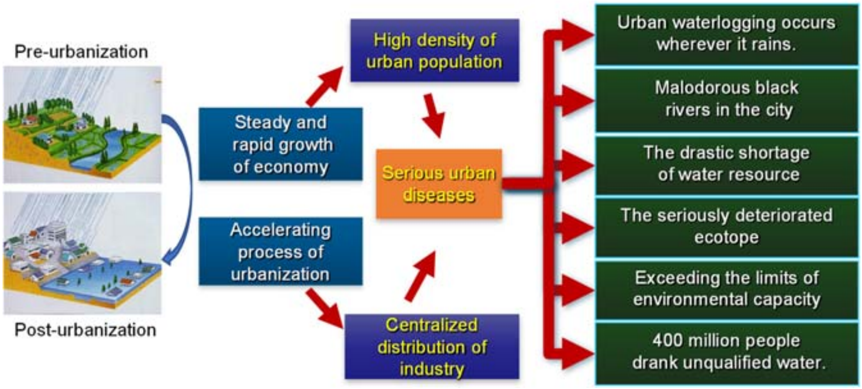

Figure 3.3 Major urban water problems generated along with rapid urbanization and social economy growth (figure by authors).

water and wastewater systems to be designed in a way to accommodate the ever-increasing demands and pollutant loading by following the water system 2.0 model. Other factors, such as climate change, the extension of impervious covering, and shrinkage of water areas aggravate the urban water problems as well, resulting in insufficient groundwater recharge and increasing surface runoff (Jia *et al.*, 2013). Water system 2.0 is also incommensurate to the desire of citizens for urban liveability and water landscape.

Under the water system 2.0, either combined or separate sewer systems are adopted for wastewater and stormwater runoff transport. For a combined system, domestic sewage, industrial wastewater, and rainwater runoff are collected and mixed in the same pipe system, and then transported to a sewage treatment plant for combined treatment before final discharge to a receiving water body. During periods of heavy rainfall, however, the water volume may far exceed the capacity of the combined sewer system or the treatment plant, so overflow occurs occasionally and the excess volume of the mixed wastewater flows directly to nearby streams, rivers, or other water bodies. The so-called combined sewer overflows (CSOs) contain not only stormwater but also untreated human and industrial wastes, toxic materials, and debris, which may cause serious pollution of the receiving waters. In contrast, a separate sewer system consists of separate pipelines to collect municipal wastewater and surface runoff for transport to different destinations (sewage treatment plant and receiving water, respectively). So, sewer overflow can be prevented and the sewage treatment plant can be operated as usual during rainy periods. Due to rapid urbanization, the drainage systems in many cities are mixtures of both combined and separate sewers. There is always the problem of malfunctioning of different sewer systems to result in point source pollution of water bodies, even though the coverage of sewer collection and treatment is not low.

Improper operation and maintenance of urban drainage systems is another problem in some cities where groundwater seeps into sewer pipes and results in the dilution of sewage water to increase the volume of inflow to the sewage treatment plants. Similar problems may occur when there is a misconnection between sewage pipes and rainwater pipes in some locations of a separate sewer system. Due to improper design of the outfalls in some cities, the effluent may not be discharged smoothly into the receiving water body and large volumes of water can be discharged back to the sewage treatment plant. Sediment deposition in drainage pipelines sometimes becomes an additional pollutant source when it is scoured out from the rainwater outlet or the combined sewer outlet.

Facing the abovementioned water problems, various fragmented engineering measures have been taken to enhance system 2.0 (Table 3.2). Similar to other countries, water issues are under the responsibilities of different governmental agencies and authorities.

The provision of engineering infrastructure is necessary and effective but needs large investment for their construction, which may pile pressures on the economy for sustainable development. For example, the investment cost of the South-to-North Water Transfer Project is as high as 500 billion CHY, and the unit cost of water transfer is 8–10 CHY per cubic meter. Another example is the upgrading of wastewater treatment facilities for meeting the increasingly stringent effluent discharge standard, which has caused the unit treatment cost to climb to 1 CHY per cubic meter while gaining little net benefit in environmental improvement (Wang *et al.*, 2015).

The system 2.0 may be enhanced by these engineering measures, but the system's inherent problems are inevitably amplified, especially those related to hydrological and ecological issues. For instance, from the hydrological standpoint, channelization is a measure widely used for flooding control while environmentally, it may result in the loss of self-purification ability, ecological function, and landscape values for urban rivers.

For these reasons, the enhancement of system 2.0 by fragmented engineering measures may not be adequate to overcome the shortcomings of a linear system due to its strong dependence on resource consumption and unsustainability. There is a growing requirement for China to take new measures to build urban water systems to be more sustainable, resilient, and multi-functional.

3.4 TOWARDS A MULTI-PURPOSE WATER-WISE SYSTEM: SPONGE CITY

3.4.1 Urban water system 3.0 as a new approach

The establishment and advancement of Sponge City marks the beginning of a new era to transform China's urban water system into a multiple-purpose water-wise system. In this regard, an innovative urban water system 3.0 is proposed based on technology advancement and a specific domestic context. Figure 3.4 shows the

Table 3.2 Fragmented engineering measures to enhance system 2.0 and outlook for future water systems (summarized by authors).

Goals	Elements in System 2.0	Responsible Authorities and Their Actions to Enhance System 2.0	Endeavors in Future
Water supply	River and groundwater	Ministry of Water Resource	Develop new water source
Drinking water quality	Water supply plant	Long-distance water transportation and reservoir construction	Non-potable water supply
		Minister of Health of the People's Republic of China releasing new drinking water sanitary standard in 2006	Water conservation
Water environment quality Eliminating black and malodorous waters	Centralized sewage treatment plant (STP) sewer system	Ministry of Environmental protection releasing action plant for water in 2015 Upgrading STP discharge standards in 1996, 2002 and 2015 Ministry of Housing and Urban-Rural Development STP construction	Decentralized system for in situ reuse Balance environment and economic benefits
Flood/waterlogging prevention	Urban river stormwater system	Ministry of Water Resource channelized river for flood discharging Ministry of Housing and Urban-Rural Development/Local Authorities sponge city construction,16 cities started LID in 2015	Natural hydrological cycle protection Urban resilience
Recreation aesthetics	Urban river	Local authorities Inland rivers replenished by long-distance transported water revetment in garden/artificial landscape	Natural landscape Ecology recovery habitability

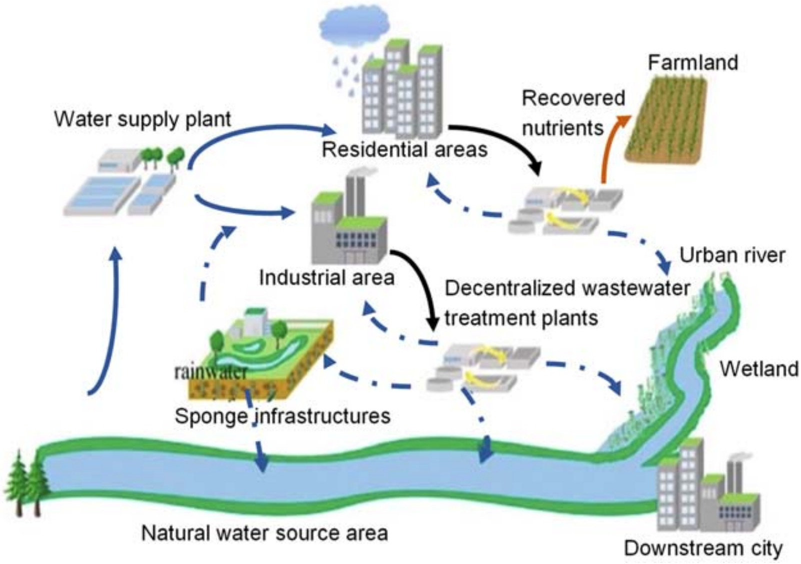

Figure 3.4 Depiction of urban water system 3.0 (figure by authors; blue, grey, brown and yellow arrows represent water flow, wastewater flow, resource supply, and energy supply, respectively).

structural and functional characteristics of urban water system 3.0, which is expected to be a flexible, resilient, and sustainable system that can provide efficient solutions to current problems.

In this new system model, sponge infrastructures are introduced to facilitate unconventional water resources development, such as rainwater harvesting and water reclamation from treated wastewater, not only for source enlargement to meet the increasing demand but also for reducing pollutant loading to receiving waters. A number of water cycles can be formed through linkages between wastewater treatment facilities, urban water bodies, wetlands, and other water elements so that better water circulation conditions can be ensured. Toward the future, the wastewater treatment facilities can be energy-neutral and provide fertilizers to farmlands through resource recovery. Decentralization of the wastewater treatment facilities may be more appropriate for such a purpose.

On the basis of system 3.0, the authors further propose a newer version of urban water system 4.0, whereby large-scale drainage facilities are added to the system, including large tunnels, culverts, deep trenches, and ponds of sufficient storage volumes for accommodating stormwater runoff. System 4.0 is more suitable for cities in areas with annual precipitation higher than 1000 mm where the drainage facilities are of smaller scales, as shown in Figure 3.4, and may not be capable of coping with extremely heavy rainfall.

The proposal of system 3.0 coincides with the International Water Association (IWA) Principles for Water-Wise Cities (IWA, 2016), which calls for actions at four levels, namely regenerative water services, water sensitive urban design, basin-connected cities, and water-wise communities. However, faced with the current problems and special situation in China, the main themes related to system 3.0 can be set as below.

3.4.1.1 Sustainable water services

The main measures for realizing sustainable water services in all cities in China include in situ amplification of water resources by unconventional water utilization and local circulation and protection of natural water resources by the restoration of water bodies and their aquatic ecosystems.

3.4.1.2 Improvement of overall environmental quality, resilience, and liveability in urban areas

For the improvement of the overall urban environmental quality, measures should be taken mainly for onsite wastewater treatment and reclamation, the introduction of diversified treatment processes, and enhancement of ecological purification in receiving water bodies, along with holistic process control measures for effective pollutant reduction. A resilient mechanism should be established for mitigating urban waterlogging and hazards from other catastrophic and extreme events. The building of sponge infrastructures and implementing decentralized sewage systems are the main measures. To make cities more liveable, a series of ecological measures should be implemented, such as the provision of wildlife habitats, an increase of green entertainment spaces, improvement of liveable microclimate, and upgrading of aesthetic values of urban water landscapes.

3.4.1.3 Water-wise communities

Figure 3.5 shows a framework for the establishment of water-wise communities. This framework depends much on public awareness and acceptance, the participation of professionals with various expertise, cooperation between different governmental agencies, and integrated urban planning. Various advanced communication tools and methods should also be used, such as wireless devices and effective data management (Chung & Yoo, 2015; O'Donovan *et al.*, 2015), and the introduction of the a public–private partnership (PPP) model to facilitate implementation and practice.

3.4.1.4 Reviving water culture

Figure 3.6 is a depiction of the unique Chinese water culture to be revived via Sponge City construction. Water culture is a crucial element of Chinese culture from ancient times. As many cities have been built alongside waters, the water

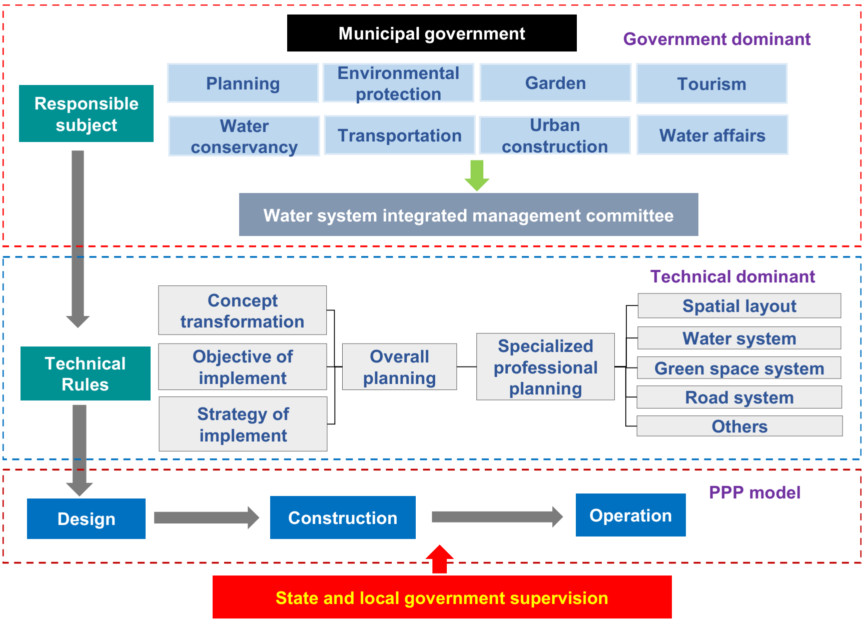

Figure 3.5 Water-wise communities: organization and implementation of sponge city construction and integrated water system regulation (figure by authors).

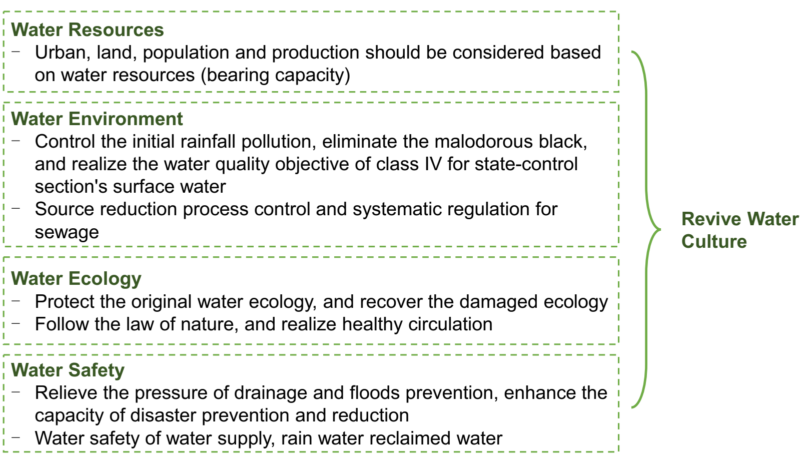

Figure 3.6 Formation of Chinese unique water culture via sponge city construction (figure by authors).

culture of a city is recognized as the soul of that city. The water culture to be revived usually satisfies the requirement of multiple objectives, including water resources, water environment, water ecology, and water safety.

3.4.2 Main functional elements of the water system 3.0

3.4.2.1 Sponge infrastructure

Figure 3.7 shows the sponge infrastructures at different utilization levels. By definition, sponge infrastructures are green infrastructures (Breuste *et al.*, 2015). Green roofs, permeable pavements, low elevation greenbelts, bioretention facilities, just to mention a few, are typical green infrastructures designed to provide the functions of permeation, retention, storage, purification, utilization, and drainage of rainwater. With the implementation of these green infrastructures, a Sponge City is not limited to its capability of runoff control for waterlogging prevention and rainwater utilization, but also non-point source pollution control, natural hydrological protection, and ecological recovery. Under the current situations of high population density, severe pollution of first flush runoff, and occurrence of intense rainfall, it is necessary to combine a series of green infrastructure with functional grey facilities, such as integrative initial rain intercepting chambers and underground reservoirs, to provide more robust and efficient solutions. Compared with the large-scale deep tunnels widely built in European cities, sponge infrastructures are more flexible and easier to be integrated into a city and implemented without disruption of traffic and other public utilities. Furthermore, the future Sponge City should not be limited to these scattered infrastructures or merely serve for rainwater management. It can

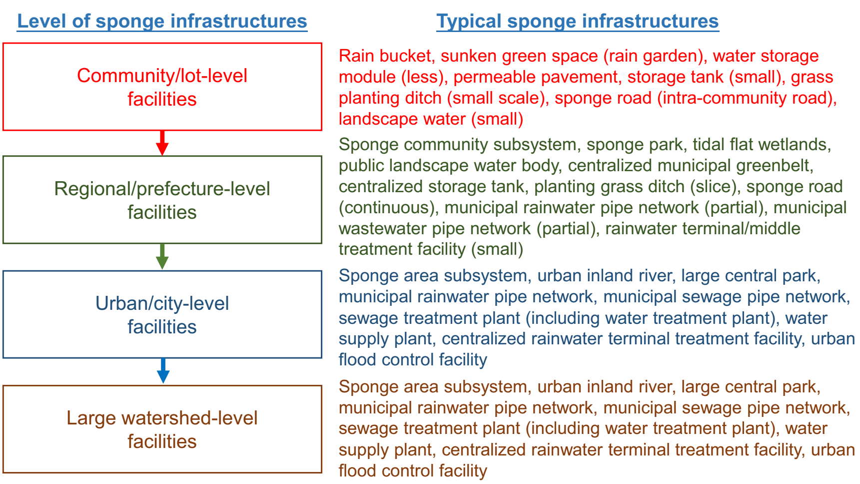

Figure 3.7 Sponge infrastructure at different utilization levels (figure by authors).

play roles in either synergistic wastewater disposal in dry seasons in coordination with decentralized sewage systems or in establishing an interconnected urban water body network and a healthy ecosystem by integrated planning.

3.4.2.2 Decentralized sewage system

Decentralized sewage systems are widely recognized as a potentially suitable approach to relieve environmental stress and mitigate water shortage. It is referred to as an approach related to wastewater treatment in a non-centralized way, with more than one treatment plant or sites for varying conditions in the whole water system, rather than merely a small scale pattern (Libralato *et al.*, 2012). Decentralized systems are usually flexible in their scale and can be classified into several levels with various service populations, such as:

- small scale to serve an individual house or a dozen of typical houses;
- middle scale to serve communities or larger blocks like school and hospital;
- larger scale to serve districts with larger populations, also referred to as semi-centralized systems.

In China, the middle and larger scaled systems are more suitable for densely populated urban areas. Aimed at onsite wastewater treatment and reclamation, an assortment of treatment technologies are available for meeting the requirements of various system scales, such as simple sanitation systems for communities, including septic tanks, membrane bioreactors, etc. (Fane & Fane, 2005), sewer mining in collection processes by forward osmosis membrane distillation, etc. (Xie *et al.*, 2013), mechanical–biological methods including sand filter, aerobic lagoons, and constructed wetlands, etc. (Massoud *et al.*, 2009), and treatment associated with materials recovery, including anaerobic reactors to produce methane, and ion exchange and electrodialysis to recover nutrients (Li *et al.*, 2015). A decentralized sewage system may also be applied for multiple purposes of pollution reduction, water reclamation, and energy and materials recovery. With the relatively smaller scale system, decentralized systems can be designed and installed in more flexible ways (Bakir, 2001) so that the distribution of pollutant loading can be fully taken into account to reduce the burden on enterprises for achieving higher efficiency of pollutant removal. Decentralized treatment is also suitable for eutrophication control in receiving water bodies to increase environmental benefits. These are the main advantages of the decentralized systems over the centralized systems.

In the economic and social aspects, decentralized systems are drawing wide interests as well. With the characteristics of onsite collection, treatment, and even reuse, long-distance transfer of the collected wastewater can be avoided and the investment is mainly for the treatment facilities. It has been reported that for the centralized sewage system, more than 60% of the capital costs are for collection and transfer pipelines (Massoud *et al.*, 2009). Moreover, resources and energy recovery in wastewater treatment can be realized in much easier ways in decentralized systems than centralized sewage systems. Thus, if resources and energy recovery are accounted for, the benefits will be even larger (Li *et al.*, 2015; Wilderer & Schreff, 2000).

3.4.2.3 Fit-for-purpose water supply system

In China, it is already required that all cities in water-deficient regions (mostly in north China) should promote the use of alternative or unconventional water resources, such as rainwater and reclaimed wastewater (seawater desalination is site-specific and not included in system 3.0). The potential for using unconventional water resources to mitigate urban water shortages is great. For example, the northeast city of Harbin has a population of about five million. It is estimated that the potential of rainwater harvesting amounts to 42 million m^3 per year, equivalent to 9% of the total annual water supply to the city. The potential of water reclamation from domestic wastewater is even larger. At present, only 7% of the treated wastewater is reused. If the percentage can be increased to 30%, the total amount will reach 14 billion m^3 per year, which is sufficient to cover the water consumption in 20 megacities.

Water use in a city is for various purposes. In addition to potable water supply for households and other domestic and municipal uses, environmental water uses for urban irrigation, landscape water replenishment, and so on usually consume large amounts of water. As different water uses have different quality requirements, a fit-for-purpose water supply system should be configured when unconventional water is added to the available water sources. An envisaged strategy is to combine unconventional water use with the implementation of sponge facilities and formulate a diversified water supply system framework where the harvested rainwater and reclaimed wastewater, after proper treatment to meet non-potable quality requirements, are directly supplied for environmental water use. By contrast, the potable water from the existing urban water supply network is solely for domestic water supply with a much-reduced volume.

3.4.2.4 Near-natural ecological zones

Nowadays, there are increasing efforts to switch hard engineering solutions for near-natural measures for the improvement of degraded urban water ecology. Examples of such efforts include those of Santa Ana River in Southern California, USA, and Cheonggyecheon River in Seoul, Korea (Gret-Regamey *et al.*, 2016) via the introduction of wetland systems and near-natural waterways. The near-natural and ecological approaches may not be introduced for short-term economic benefits but for the long-term ecosystem and social services such as to improve the quality of the water environment, facilitate groundwater recharge, provide wildlife habitat and promote urban liveability, resilience, and aesthetic satisfaction.

Near-natural ecological zones are important components of the framework for the urban water system 3.0. Ecological slope-maintenance, native species selection and configuration, artificial floating islands, and wetlands are major green elements to be introduced to replace or supplement grey engineering elements. The provision of crucial passages for flooding flow should be combined with the provision of purification capacity and aquatic landscapes. Reclaimed water and harvested rainwater can be used for supplementing ecological baseflow for urban rivers and streams so that long-distance transfer of clean water for water replenishment can be avoided. Wetlands can be constructed in association with rivers and streams to provide buffer zones for runoff pollution reduction and nonpoint source control.

3.4.2.5 Intelligent water management system

Sponge City construction not only needs the introduction of sponge facilities and various sponge measures but also an advanced managerial scheme to ensure that the urban water system is operated smoothly to achieve the prescribed goals. Figure 3.8 shows an example of the intelligent water management system (IWMS) for a Sponge City. The IWMS is a monitoring network with the application of various advanced tools and methodologies for performance evaluation and assessment. It is generally composed of five parts, including

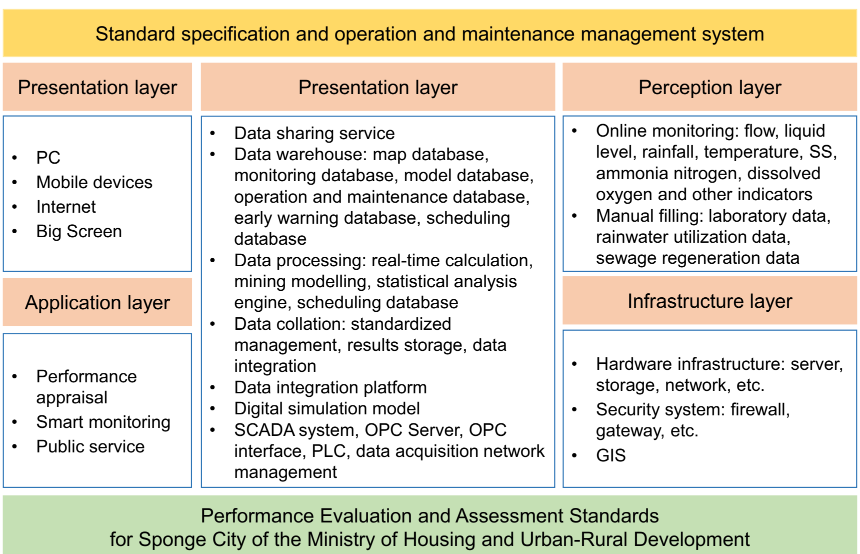

Figure 3.8 Intelligent water management system (IWMS) for Sponge City construction (figure by authors).

information structure, monitoring, data processing, application, and visualization. The core function of IWMS is the monitoring, collection, processing, integration, and sharing of large amounts of data related to the performance of the urban water system. The use of big data and machine learning can assist the establishment of relationships between governance objectives and construction measures, and further contribute to the identification of the key features of Sponge City construction in various regions with different economic and natural conditions.

The IWMS can also assist the synthesis and normalization of data in varied dimensionalities, and thus provide apt guidance to the development and management of practical sponge projects by the formulation of integrated management schemes, and generalization and specialization of technologies.

As shown in Figure 3.8, the IWMS has a presentation layer for the visualization and all-round display of Sponge City construction effects. This needs the implementation of hardware equipment and software platforms to ensure effective and sustainable online data generation and transmission.

Following the above discussion, we can see that the urgent need for solutions to the current water problems in Chinese cities provides the driving force for the implementation of Sponge Cities based on an innovative concept. The proposed urban water system 3.0 has provided an integrated multi-purpose strategy for cities in China toward sustainable development. A systematic approach with full consideration of regional situations is the core of the planning and design of such an urban water system.

3.5 FUTURE PERSPECTIVES

3.5.1 Enhancing system monitoring and evaluation and promoting multi-channel cooperation management

Sponge City projects require a systematic process of monitoring, evaluation, and management (Hakimdavar *et al.*, 2016). Prior to the construction, an integrated data system should be established for collecting information on (1) suitable technologies, (2) investment sources and their allocation, (3) aspects related to system planning and project design, and (4) potential outcomes of the projects, including the long-term effects and life cycle benefits (Jia *et al.*, 2015). A long-term monitoring program should be implemented so that the Sponge City's performance on urban water improvement can be well evaluated. The accumulation of data by long-term monitoring and proper evaluation will surely assist the development of Sponge Cities in China and even other countries of the world. This needs multi-channel cooperation among various government agencies and different sectors so that data and information can be well shared toward the common aims and policies for maximization of benefits.

3.5.2 Developing decision support tools for sustainable implementation of sponge city

The development of decision support tools is extremely important for Sponge City construction. Model simulation is, in any sense, indispensable for supporting policymakers, designers, and practitioners in building water systems at both urban and watershed scales (Bach *et al.*, 2014; Golden & Hoghooghi, 2018; Stanchev & Ribarova, 2016; Zhang & Chui, 2019). There are many urban stormwater models developed and applied globally, so far, such as SWMM, MIKE URBAN, and Info-works CS models, which can provide useful tools. However, as Sponge City construction is for solving complex problems, more comprehensive models have to be developed to meet the new needs. The basic requirements for the new models may include the following. First, they can well predict urban surface runoff in accordance with the complex underlying characteristics of urban regions. Second, they can well simulate the physical and chemical processes related to pollutants transport and reduction in green infrastructures, and third, they can forecast the ability of a Sponge City to prevent or minimize urban flooding and waterlogging.

Effective utilization of these models toward sustainable urban water management should also be ensured by incorporating the following:

- integration of modelling with available online and physical tools (Butler & Schutze, 2005);
- full attention paid to tackle uncertainties in model simulation (Liu *et al.*, 2008);
- modelling for obtaining longer time series results at high integration levels (Urich *et al.*, 2013).

3.5.3 Valuing Sponge City ecosystem services

Proper valuation of ecosystem services is important for raising the perceptions of Sponge Cities, so that good public–private partnerships can be promoted. The implementation of a Sponge City involves a range of biophysical, economic, cultural, and health values. Cost-benefit assessment is needed for all the projects implemented by the public and/or private sectors (Toran, 2016). Cost-effectiveness analysis for sponge projects may be more complicated due to unknown factors, such as cost calculation for project maintenance and monitoring, and evaluation of the life cycle benefits related to social and ecological amenities (Liang, 2018; Mao *et al.*, 2017). The benefits related to biodiversity, recreational spaces, urban heat reduction are important factors. The impact of Sponge City construction on the value of properties located in and/or around the project areas (Zhang *et al.*, 2018) should also be assessed.

To answer the question of the cost-effectiveness of Sponge City construction requires further analysis of the economic benefits in a large-scale context (Chui *et al.*, 2016). Regional differences in geographic location, hydrological conditions, social status, and urban infrastructure level may result in different outcomes and levels of success. Therefore, pilot projects and simulation scenarios may help identify the real costs involved and a more precise understanding of the benefits to all stakeholders, as well as public involvement and people's willingness to pay for Sponge City initiatives.

In the USA, CIRIA (the Construction Industry Research Information Association) has developed W045 BeST (Benefit of SuDS Tool) for the evaluation of the benefits from ecological services and economic benefits of SuDS (Sustainable Drainage Systems). This tool can be utilized to estimate the overall advantage of SuDS practice versus existing urban water management practices (CIRIA, 2015). Also, this tool can be partially applied for analysing Sponge City projects with the incorporation of other methods to account for future spatial and temporal changes that may affect the performance of Sponge City infrastructure.

3.5.4 Developing local guidelines and standards for Sponge City implementation

Every urban area has its own hydrological and climatic features, as well as its history and characteristics of urban development. Although national laws and regulations have provided general guidance of Sponge City construction for the whole nation, they may not be completely applicable to the local context. Therefore, understanding local conditions is key to the successful implementation of the Sponge City concept, and additional local guidelines and standards should be developed based on local needs. In many cases, blindly copying the experiences from other cities or just following instructions from the central government may be inappropriate in the planning, design, construction, operation, and evaluation of Sponge City projects. At the provincial, municipal, or even project levels, research should be conducted on the feasible engineering measures and available technologies that best fit the regional or local situations.

3.5.5 Promoting Sponge City construction in watershed-scales based on data and information sharing

Sponge City construction is a new concept that can be applied for projects of various scales. However, as the goal of Sponge City construction is to build a sustainable urban water system in the form of system 3.0 shown in Figure 3.4, it is not limited to the implementation of individual sponge facilities or a series of such facilities. Rather, it encompasses a reformation of the whole framework of the water-related infrastructure of a city closely related to the local watershed. Therefore, it is important to consider beyond individual project sites and pay attention to an integrated and watershed-scale approach, aiming to solve all the interrelated problems and creating a sustainable water environmental system covering broader areas. Sponge City construction at the watershed-scale can potentially avoid segmentation and isolation of the sponge facilities, maximize the overall benefits of ecosystem conservation, water quality improvement, flooding and waterlogging control, and create a healthy environment in the entire watershed.

As an innovative and revolutionary approach, Sponge City is drawing wide attention from the world, and in the process of Sponge City construction, China has learnt a lot from other countries with similar concepts and technologies such as BMPs, LID, SUDs, WSUD, etc. Within China, different cities are learning from each other to obtain the latest successful experiences, especially through the central government-oriented national pilot program (refer to Chapter 11 of this book). In the long term, data and information sharing will become more and more important for the advancement of Sponge City technologies. It is also important to improve coordination across governmental agencies by the establishment of a Sponge City database and an experiences-sharing network.

A proper social and economic evaluation of Sponge City practices is also indispensable for highlighting the whole life cycle benefits and risk of failure to deliver useful information to the public and increase their knowledge and perceptions, to enhance public willingness to support the implementation of Sponge Cities. In an era of climate change and rapid urbanization, the formulation of strategies and policies focusing on the promotion of the Sponge City concept will play an extremely important role in developing healthy, resilient, and sustainable cities.

REFERENCES

Bach P. M., Rauch W., Mikkelsen P. S., McCarthy D. T. and Deletic A. (2014). A critical review of integrated urban water modelling Urban drainage and beyond. *Environmental Modelling and Software*, **54**, 88–107.

Bakir H. A. (2001). Sustainable wastewater management for small communities in the Middle East and North Africa. *Journal of Environmental Management*, **61**(4), 319–328.

Breuste J., Artmann M., Li J. X. and Xie M. M. (2015). Special issue on green infrastructure for urban sustainability. *Journal of Urban Planning and Development*, **141**(3), 1–5.

Butler D. and Schutze M. (2005). Integrating simulation models with a view to optimal control of urban wastewater systems. *Environmental Modelling and Software*, **20**(4), 415–426.

Carlson C., Barreteau O., Kirshen P. and Foltz K. (2015). Storm water management as a public good provision problem: survey to understand perspectives of low-impact development for urban storm water management practices under climate change. *Journal of Water Resources Planning and Management*, **141**(6), 1–13.

Chan F. K. S., Griffiths J. A., Higgitt D., Xu S., Zhu F., Tang Y.-T. and 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.

Chang H.-S. and Su Q. (2020). Research on constructing Sponge City indicator and decision evaluation model with fuzzy multiple criteria method. *Water Environment Research*, **92**, 1910–1921.

Cheng H. F. and Hu Y. A. (2011). Economic transformation, technological innovation, and policy and institutional reforms hold keys to relieving China's water shortages. *Environmental Science and Technology*, **45**(2), 360–361.

Chui T. F. M., Liu X. and Zhan W. T. (2016). Assessing cost-effectiveness of specific LID practice designs in response to large storm events. *Journal of Hydrology*, **533**, 353–364.

Chung W. Y. and Yoo J. H. (2015). Remote water quality monitoring in wide area. *Sensors and Actuators B-Chemical*, **217**, 51–57.

CIRIA (2015). Evaluating the Benefits of SuDS Using CIRIS's BeST, the Construction Industry Research Information Association. Available from: www.susdrain.org/resources/presentations.html

De Feo G., Antoniou G., Fardin H. F., El-Gohary F., Zheng X. Y., Reklaityte I. and Angelakis A. N. (2014). The historical development of sewers worldwide. *Sustainability*, **6**(6), 3936–3974.

Ellis J. B. and Lundy L. (2016). Implementing sustainable drainage systems for urban surface water management within the regulatory framework in England and Wales. *Journal of Environmental Management*, **183**, 630–636.

Fane A. G. and Fane S. A. (2005). The role of membrane technology in sustainable decentralized wastewater systems. *Water Science and Technology*, **51**(10), 317–325.

Golden H. E. and Hoghooghi N. (2018). Green infrastructure and its catchment-scale effects: an emerging science. *Wiley Interdisciplinary Reviews – Water*, **5**(1), 1254.

Gret-Regamey A., Weibel B., Vollmer D., Burlando P. and Girot C. (2016). River rehabilitation as an opportunity for ecological landscape design. *Sustainable Cities and Society*, **20**, 142–146.

Griffiths J., Chan F. K. S., Shao M., Zhu F. and Higgitt D. L. (2020). Interpretation and application of Sponge City guidelines in China. *Philosophical Transactions of the Royal Society A – Mathematical Physical and Engineering Sciences*, **378**(2168), 1–20.

Hakimdavar R., Culligan P. J., Guido A. and McGillis W. R. (2016). The Soil Water Apportioning Method (SWAM): an approach for long-term, low-cost monitoring of green roof hydrologic performance. *Ecological Engineering*, **93**, 207–220.

Hiltrud P. and Pierre B. (2011). Urban Green-blue Grids for Sustainable and Dynamic Cities. Coop for Life, Delft.

Jia H. F., Yao H. R. and Yu S. L. (2013). Advances in LID BMPs research and practice for urban runoff control in China. *Frontiers of Environmental Science and Engineering*, **7**(5), 709–720.

IWA (2016). IWA Principles for Water-Wise Cities. International Water Association, London, UK.

Jia H. F., Yao H. R., Tang Y., Yu S. L., Field R. and Tafuri A. N. (2015). LID-BMPs planning for urban runoff control and the case study in China. *Journal of Environmental Management*, **149**, 65–76.

Karr J. R. and Schlosser I. J. (1978). Water resources and the land-water interface. *Science*, **201**(4352), 229–234.

Li W. W., Yu H. Q. and Rittmann B. E. (2015). Chemistry: Reuse water pollutants. *Nature*, **528**(7580), 29–31.

Li C., Huang M., Liu J., Ji S., Zhao R., Zhao D. and Sun R. (2019). Isotope-based water-use efficiency of major greening plants in a sponge city in northern China. *Plos One*, **14**(7), e0220083.

Liang X. (2018). Integrated economic and financial analysis of China's sponge city program for water-resilient urban development. *Sustainability*, **10**(3), 1–12.

Libralato G., Ghirardini A. V. and Avezzu F. (2012). To centralise or to decentralise: an overview of the most recent trends in wastewater treatment management. *Journal of Environmental Management*, **94**(1), 61–68.

Lim H. S. and Lu X. X. (2016). Sustainable urban stormwater management in the tropics: an evaluation of Singapore's ABC Waters Program. *Journal of Hydrology*, **538**, 842–862.

Liu Y. Q., Gupta H., Springer E. and Wagener T. (2008). Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resources management. *Environmental Modelling and Software*, **23** (7), 846–858.

Mao X. H., Jia H. F. and Yu S. L. (2017). Assessing the ecological benefits of aggregate LID-BMPs through modelling. *Ecological Modelling*, **353**, 139–149.

Massoud M. A., Tarhini A. and Nasr J. A. (2009). Decentralized approaches to wastewater treatment and management: Applicability in developing countries. *Journal of Environmental Management*, **90**(1), 652–659.

Meng F. and Li S. (2020). A new multiple attribute decision making method for selecting design schemes in sponge city construction with trapezoidal interval type-2 fuzzy information. *Applied Intelligence*, **50**(7), 2252–2279.

O'Donovan P., Coburn D., Jones E., Hannon L., Glavin M., Mullins D. and Clifford E. (2015). A cloud-based distributed data collection system for decentralised wastewater treatment plants. *Procedia Engineering*, **119**, 464–469.

Ren N., Wang Q., Wang Q., Huang H. and Wang X. (2017). Upgrading to urban water system 3.0 through sponge city construction. *Frontiers of Environmental Science and Engineering*, **11**(4), 1–8.

Sharma A. K., Pezzaniti D., Myers B., Cook S., Tjandraatmadja G., Chacko P. and Walton A. (2016). Water sensitive urban design: an investigation of current systems, implementation drivers, community perceptions and potential to supplement urban water services. *Water*, **8**(7), 272.

Shen W., Liu Y., Wu M., Zhang D., Du X., Zhao D., Xu G., Zhang B. and Xiong X. (2020). Ecological carbonated steel slag pervious concrete prepared as a key material of sponge city. *Journal of Cleaner Production*, **256**, 120244.

Stanchev P. and Ribarova I. (2016). Complexity, assumptions and solutions for eco-efficiency assessment of urban water systems. *Journal of Cleaner Production*, **138**, 229–236.

Thu T. N., Huu Hao N., Guo W. and Wang X. C. (2020). A new model framework for sponge city implementation: emerging challenges and future developments. *Journal of Environmental Management*, **253**, 109689.

Toran L. (2016). Water level loggers as a low-cost tool for monitoring of stormwater control measures. *Water*, **8**(8), 346.

Urich C., Bach P. M., Sitzenfrei R., Kleidorfer M., McCarthy D. T., Deletic A. and Rauch W. (2013). Modelling cities and water infrastructure dynamics. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, **166**(5), 301–308.

Wang X. H., Wang X., Huppes G., Heijungs R. and Ren N. Q. (2015). Environmental implications of increasingly stringent sewage discharge standards in municipal wastewater treatment plants: case study of a cool area of China. *Journal of Cleaner Production*, **94**, 278–283.

Wang Y., Liu X., Huang M., Zuo J. and Rameezdeen R. (2020). Received vs. given: willingness to pay for sponge city program from a perceived value perspective. *Journal of Cleaner Production*, **256**, 120479.

Wilderer P. A. and Schreff D. (2000). Decentralized and centralized wastewater management: A challenge for technology developers. *Water Science and Technology*, **41**(1), 1–8.

Xia J., Zhang Y., Xiong L., He S., Wang L. and Yu Z. (2017). Opportunities and challenges of the Sponge City construction related to urban water issues in China. *Science China-Earth Sciences*, **60**(4), 652–658.

Xie M., Nghiem L. D., Price W. E. and Elimelech M. (2013). A forward osmosis-membrane distillation hybrid process for direct sewer mining: system performance and limitations. *Environmental Science and Technology*, **47**(23), 13,486–13,493.

Zhang K. and Chui T. F. M. (2019). Linking hydrological and bioecological benefits of green infrastructures across spatial scales – A literature review. *Science of the Total Environment*, **646**, 1219–1231.

Zhang Z., Szota C., Fletcher T. D., Williams N. S. G., Werdin J. and Farrell C. (2018). Influence of plant composition and water use strategies on green roof stormwater retention. *Science of the Total Environment*, **625**, 775–781.

Zhang L., Sun X. and 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.