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Sponge City Construction in China: A Survey of the Challenges and Opportunities

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Abstract: Rapid urbanization in China has caused severe water and environmental problems in recent years. To resolve the issues, the Chinese government launched a sponge city construction program in 2015. While the sponge city construction initiative is drawing attention and is spreading fast nationwide, some challenges and risks remain. This study surveyed progress of all 30 pilot sponge cities and identified a broad array of challenges from technical, physical, regulatory, and financial, to community and institutional. The most dominant challenges involve uncertainties and risks. To resolve the issues, this study also identified various opportunities to improve China's sponge city construction program. Based on the results, recommendations are proposed including urging local governments to adopt sponge city regulations and permits to alleviate water quality and urban pluvial flooding issues, fully measuring and accounting for economic and environmental benefits, embracing regional flexibility and results-oriented approaches, and focusing on a wider range of funding resources to finance the sponge city program. Coordination among other government agencies is critical, and this is true at all level of governments. Only through greater coordination, education, and broader funding could the sponge city program be advanced meaningfully and sustainably.

Keywords: green infrastructure; low impact development; public-private-partnership; urban stormwater management; urban flood

1. Introduction

China's large scale urbanization started around the 1980's with a rapid rise in the urban population from 36.22% in 2000 to 54.77% in 2014 (Figure 1) [1]. Consequently, more cities are facing challenges associated with urban sustainability and urban water issues such as aging/outdated water and wastewater infrastructures, urban flooding, combined sewer overflow, water quality deterioration, water scarcity, and a high frequency of extreme weather [2–4]. Among these, urban flooding is one of the most frequent and hazardous disasters that can cause enormous impacts on the economy, environment, city infrastructure and human society [5–7]. Recent survey shows that 62% of Chinese cities experienced floods, and direct economic losses amounted to up to \$100 billion between 2011 and 2014 [1]. Other research indicates increasing trends to both urban flood disasters as well as economic and human life losses. To address these challenges, the Chinese government had been searching for viable options and launched pilot sponge city construction programs.

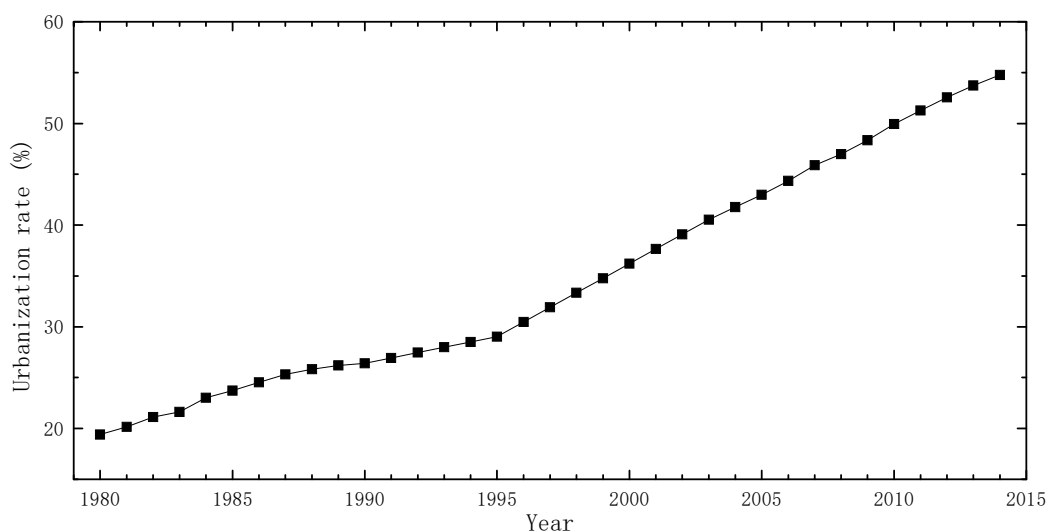


Figure 1. China's urbanization rate from 1980 to 2014.

A sponge city refers to sustainable urban development including flood control, water conservation, water quality improvement and natural eco-system protection. It envisions a city with a water system which operates like a sponge to absorb, store, infiltrate and purify rainwater and release it for reuse when needed [8]. The sponge city program takes inspiration from the low impact development (LID) and green infrastructure in the US [9,10] and Canada [11,12], sustainable drainage systems (SusDrain) in the UK [13,14] and other European countries [15,16], and water sensitive urban design (WSUD) in Australia [17] and New Zealand [18]. It promotes natural and semi-natural measures in managing urban stormwater and wastewater as well as other water cycles. The primary goals for China's sponge city construction are: retaining 70–90% of average annual rain water onsite by applying the green infrastructure concept and using LID measures, eliminating water logging and preventing urban flooding, improving urban water quality, mitigating impacts on natural eco-systems, and alleviating urban heat island impacts [19]. The sponge city program will also create investment opportunities in infrastructure upgrading, engineering products and new green technologies.

The sponge city program was launched at the end of 2014, under the direct guidance and support of the Ministry of Housing and Rural-Urban Development (UHURD), Ministry of Finance (MOF) and Ministry of Water Resources (MWR). These three ministries are responsible for reviewing, evaluating and selecting candidate cities recommended by their respective provincial governments, based on a series of criteria concerning the rationality and feasibility of pilot goals, financing mechanisms and the effectiveness of supporting measures from local governments. The three ministries are also responsible for the assessment of pilot city performance. In April 2015, the first group of 16 cities was selected as the pilot sponge cities; one year later in April 2016, the pilot program was expanded to another 14 cities. Figure 2 illustrates the locations of these pilot cities. The central government allocated to each pilot city between 400 and 600 million Chinese Yuan (CNY) each year for three consecutive years, and pilot cities are encouraged to raise matching funds through public-private-partnership (PPP) and other financial ventures. The money will be used to implement innovative water and wastewater management measures that would transform these cities into sponge cities [20].

With the strong support of the central government along with the enthusiastic participation of local governments and private sectors, the sponge city program is gaining momentum; however, the obstacles and challenges should not be overlooked, associated risks should not be ignored, and future opportunities should be fully recognized.

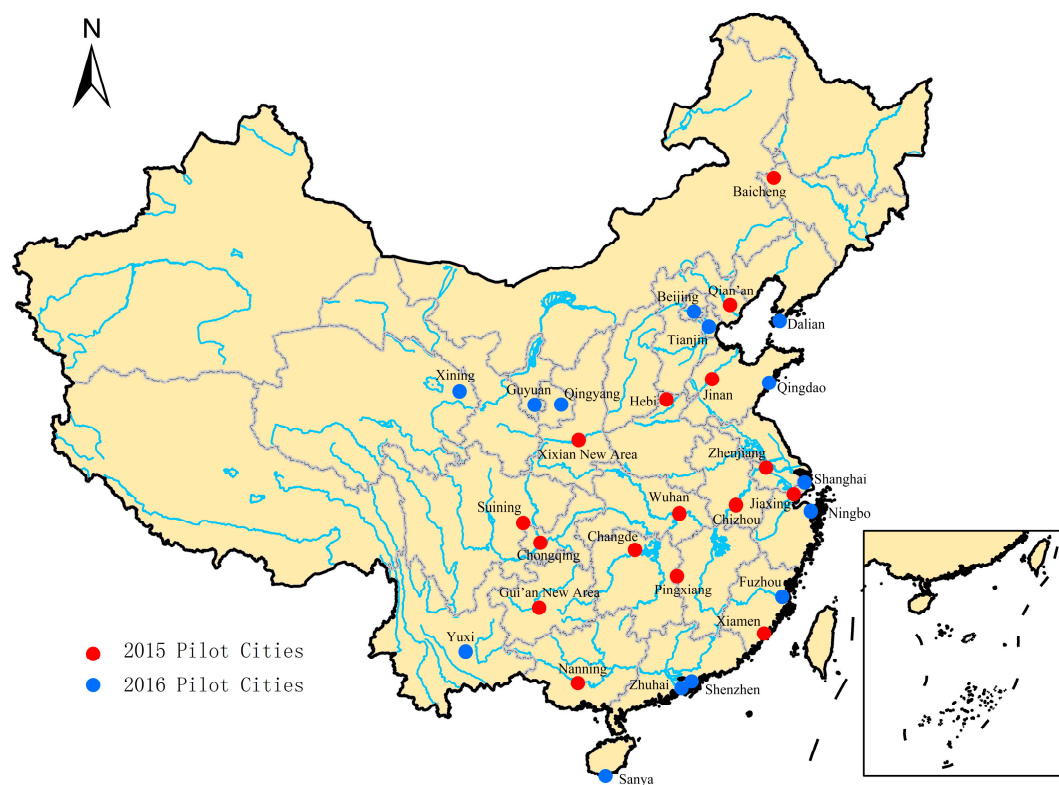


Figure 2. Location of pilot sponge cities.

2. General Descriptions of Pilot Cities

China is a vast country with great physical diversity. The climate of China is extremely diverse, ranging from tropical in the far south to subarctic in the far north and alpine in the higher elevations of the Tibetan plateau in the southwest. Precipitation is unevenly distributed in time and space. Temporally, it is almost invariably concentrated in the warmer months; and spatially, it increases from the northwest inland to the southeast coast, with the annual totals range from less than 20 mm in northwestern regions to easily exceeding 2000 mm in southern coast of the country (Figure 3). As sponge city construction involves green planning and LID measures, impacts of annual precipitation and temperature were considered along with other regional factors when selecting pilot cities. Owing to the nature and potential benefits of green infrastructures, most pilot cities are located in the central and southeastern regions, where annual precipitation ranges from 410 to 1830 mm and annual average temperature from 4.6 to 25.5 °C. In order to gain diverse experiences, a few pilot cities were also selected in northeastern cold area and in arid areas near the central-north of China.

Similar to other cities in China, pilot cities are facing various urban sustainability and urban water issues [21]. Ahead of others, these cities are actively seeking solutions in recent years; most are exposed or engaged in the early stages of green infrastructure planning and LID practices. In addition, these cities also have a fairly good governance and support basis both technically and financially. In order to focus on innovation and new approaches, as well as safeguarding success, each pilot city was designated a pilot area (not smaller than 15 km²). Most LID measures are planned inside the designated pilot areas, and other green infrastructure planning and gray infrastructure improvements may expand outside the pilot areas.

Table A1 in Appendix A presents the regional characteristics of and general information on the 30 pilot cities including precipitation and climate, sizes of the designated pilot areas, existing conditions of stormwater management systems, proposed goals of the sponge city construction, and the total capital investment in the three-year period. As indicated in Table A1, all 30 cities set up clear goals

on runoff volume control, urban drainage standards as well as waterlogging and flood prevention standards. However, the first group of 16 cities had less clear standards on rainwater resourcing, stormwater runoff pollution control, and wastewater recycling, comparing to the second group of 14 cities. Note that Table A1 only listed the primary goals of sponge cities. There are other secondary goals set up by sponge cities based on the specific conditions of each city.

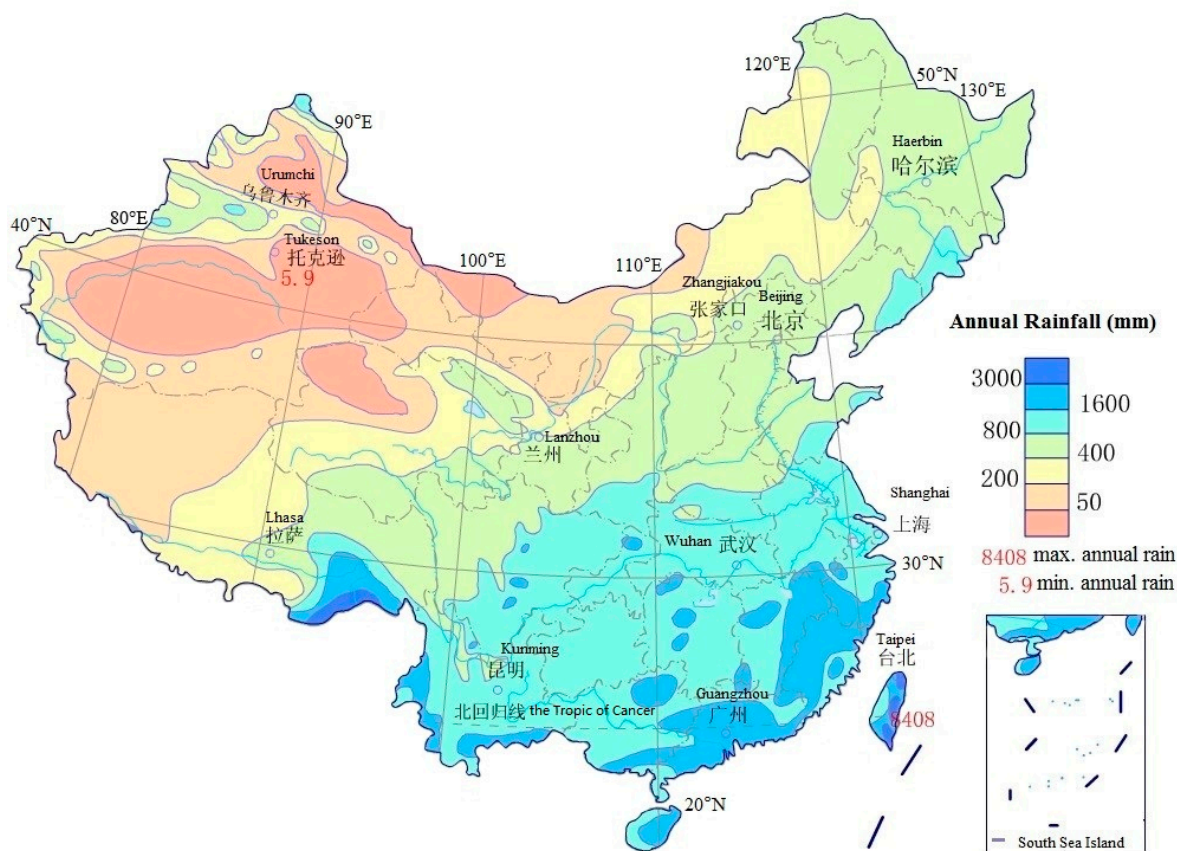


Figure 3. Annual precipitation distribution in China.

3. Materials and Methods

3.1. Study Design

This study utilized a descriptive design to survey pilot sponge cities. The survey consists of a literature review, information collection and review, field visits to pilot cities, and interviews with the public. All 30 pilot cities were included in the survey. Information collected in this survey relates to current implementation efforts and challenges to the further spreading of the sponge city program. The survey was organized by four challenge categories: technical/physical, legal/regulatory, financial, and community/institutional challenges. It was designed to collect both quantitative and qualitative information regarding the benefits of sponge city program, the type of challenges that it may encounter, and if/how these challenges can be overcome; however, more qualitative information was gained due to the nature of this study.

The goal of the survey was to identify challenges to sponge cities at the local, provincial and national levels of government, and provide concrete and provocative recommendations on how these challenges can be overcome. The flow chart of our survey is shown in Figure 4.

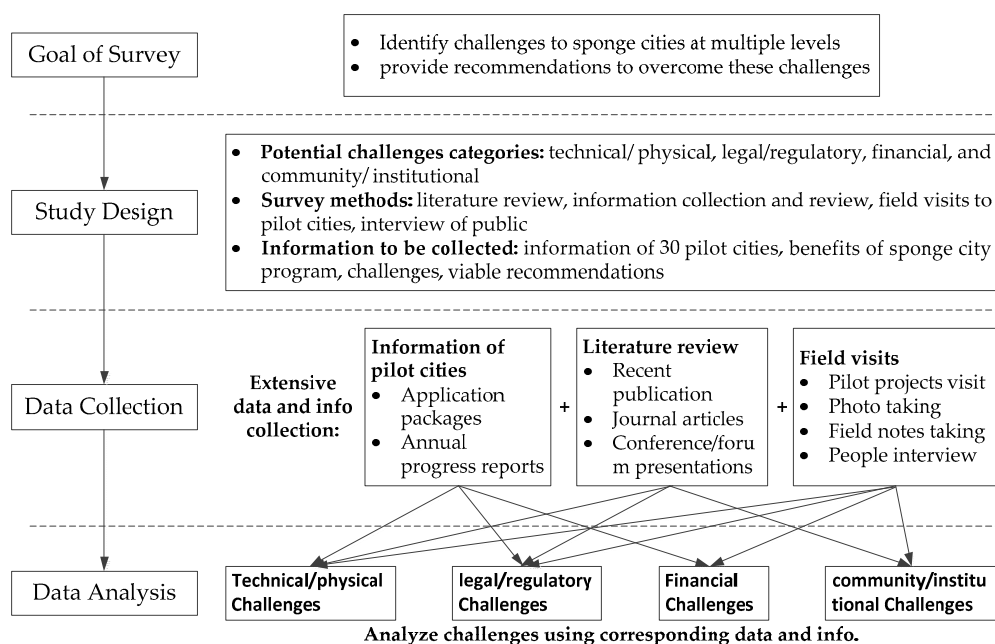


Figure 4. Flow chart of the survey work.

3.2. Data Collection Procedures

Extensive data and information were collected primarily from three sources (1) reviewing application packages and annual progress reports submitted by each pilot sponge city; (2) literature review; (3) field visits to pilot cities.

To compete for pilot sponge cities, each candidate city submitted an application package for review, evaluation and selection. The packages generally include a three-year sponge city implementation plan and other supporting documents such as long-term sponge city planning, future regulatory frameworks, and related research. The implementation plans are important documents, which contain variety of valuable information such as physical conditions; existing issues; proposed scopes and goals; proposed projects including green, gray, and non-structural measures; schedule of projects; responsible organizations; and financial arrangements. Annual progress reports are other significant resources for evaluating the progress as well as assessing and analyzing the success of the sponge city program.

The literature review was focused on recent publications, journal articles, and conference/forum presentations in China. Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology of literature review, 90 articles and presentations were retrieved from the CNKI [22], WANFANG [23], CSCD [24], and VIP [25] databases, as well as several conference sites in China including the 2016 International Low Impact Development Conference, in Beijing, China, 2016 International Conference on Green Infrastructure and Resilient City in Shenzhen, China, and the International Conference on Sustainable Infrastructure 2016 in Shenzhen, China. A total of 70 articles/presentations were included in the initial review, and 20 were excluded from the review after reading the whole content because they did not match the objectives of the literature review and the inclusion criteria. The key words used to search the materials were: urban flooding, urban water safety, green infrastructure, low impact development, sponge city construction, sustainable urban planning, rainwater resourcing, wastewater recycling, storm runoff pollution, socio-economic impact of urbanization, urban eco-system. The literature search was for publications starting from the year 2002 to the year 2016.

In addition, the research team also conducted field trips to 22 sponge cities from July 2015 to April 2017. Some field trips were accomplished during sponge city annual reviews and inspection or were organized by conferences, while others were conducted with expert consultation activities. Total

of 156 pilot projects were visited, numerous photos and field notes were taken, and over 200 people were surveyed including scholars, practitioners, government officials, urban dwellers, and local stakeholders. The outline of the survey questions is presented in Table 1.

Table 1. The outline of the survey questions.

Technical:
<ul style="list-style-type: none"> ● Design and construction codes and standards ● Performance and sustainability of sponge city measures ● Technology and materials ● Monitoring techniques and standards ● Education and training ● Operation and maintenance
Legal:
<ul style="list-style-type: none"> ● Local, provincial and national rules, ordinance, policies, regulations, laws and guidelines ● Municipal structure for maintenance and ownership ● Opportunities
Financial:
<ul style="list-style-type: none"> ● Full life cycle and maintenance costs of sponge city measures ● Social, economic and environmental benefits of sponge city measures ● Financial sources ● Private sector's interests ● Incentives
Community/Institutional:
<ul style="list-style-type: none"> ● Public knowledge, interests, and involvement of sponge city construction ● Community education ● Aesthetics ● Cooperation between agencies and communities ● Available information

3.3. Data Analysis

Data and information were organized based on four challenge categories identified in the beginning. The data from application packages and annual progress reports were primarily used for analyzing technical/physical challenges along with legal/regulatory and financial challenges. The information retrieved from the literature review contains a fair number of expert and practitioner opinions and was largely used for analyzing the technical/physical, legal/regulatory, and community/institutional challenges. The data obtained from field visits contained first-hand knowledge and was used for analyzing all four categories.

4. Major Challenges

The survey results show that despite the promising benefits that the sponge city program could provide to urban environment, many challenges were present, which may inhibit wide-scale implementation and the long-term success of the sponge city program. The following sections present the primary challenges that were identified in this survey.

4.1. Technical Challenges

(1) Ambitious goals without sound research basis

The original goal of the sponge city construction was defined as runoff-volume-focused LID to retain 60–90% runoff on sites. One year later in 2016, it was expanded to a full array of urban sustainability goals by adding restoration of eco-systems, improving deteriorated urban water bodies, reducing urban heat island impacts, and building smart urban water cycle. Although the concept and

practices of LID were introduced into China more than a decade ago [26], and recent research has been carried out on sustainable urban stormwater management [27,28], the research foundation for sponge city construction on such a large scale is rather weak. The rapid implementation of sponge city measures with such ambitious goals is largely based on very little research domestically and locally. A sponge city is an integrated approach that involves a broad range of concepts such as multi-scale conservation and water system management, multi-function of ecological systems, urban hydrology and runoff control frameworks, and impacts of urbanization and human activities on the natural environment. Lacking a sound research foundation can unnecessarily restrict the potential positive effects of this new urban water cycle management approach. To successfully implement sponge cities, appropriate definition of goals and adequate research to understand this new approach, along with sufficient knowledge are necessary.

(2) One model to fit every part of the country

Although the basic theories and primary concepts of the sponge city approach are largely applicable to any climate, geographical/geological, hydrological and soil conditions; the implementation strategies and the selection of specific measures should be considered with local conditions. The current practices, however, exhibits a pattern of using one model for every part of the country. Table 2 presents LID strategies proposed by four pilot sponge cities.

Table 2. LID strategies for various cities.

Data	Qian'an	Baicheng	Shenzhen	Yuxi
Annual Temp. (°C)	11.5	4.6	22.4	19.2
Annual Rainfall (mm)	672	410	1837	909
Annual Evap. (mm)	1100	1840	1675	1801
Runoff Control (%)	80	85	70	82
Runoff Control (mm)	28.0	25	31.3	23.9
Rain Resourcing (%)	7	6	≥8	10
Green Roof (%)	6	5	≥30	12.6
Depressed Green (%)	35	36.4	≥10	35.4
Permeable Paver (%)	46.5	46.2	≥70	38.2

As illustrated in Table 2, although the natural weather and geographical/hydrological conditions for these four cities vary drastically, the LID strategies proposed by these cities remain similar. For example, Baicheng City is located in a cold and arid region (as shown in Figure 2) with an annual temperature of 4.6 °C (Celsius), annual rainfall and annual evaporation of 410 and 1840 mm, respectively. The urgent issues for this city are water quality deterioration, water body shrinking, and water resources shortage. However, the LID strategies this city proposed will not alleviate these problems; instead, green roof, depressed green space and permeable pavement all have a potential to increase evaporation/evapotranspiration, and consequently, worsen the situation. Shenzhen, on the contrary, is a lowland coastal city located in a tropical region. It suffers from a high groundwater table, poorly drained soil, sea water intrusion, land salinization and heavy seasonal storms. Depressed green space and permeable pavements are clearly not suitable for it, and 30% of green roofs may not be economically viable. The success of a sponge city approach depends on local conditions and cannot be transferred in a standardized way to another context, as it might not prove as successful as local conditions change. The sponge city strategies should be developed based on a careful assessment of local conditions and potentials along with special issues, and mitigate these problems by leveraging the local potential and regional resources.

(3) In need of guidance and education/training

Up to recently, complete local, provincial and national guidance, design standards and codes were not available. A national level guideline was published at the end of 2014, and a few city-level

guidelines were completed through 2015 to 2016 by some pilot sponge cities. These guidelines, however, are rather simple and general. They are, by large, merely the translation and combination of similar guidelines widely used in the US and do not consider variations in regional and local conditions such as soil, climate and topography variances. Lack of design standards and codes has limited the ability of local communities to implement sponge city projects based on local conditions.

In addition, the most common technical challenge is perhaps an overall lack of education/training, knowledge, and experience of sponge city planning, design, construction, maintenance, and maximizing benefits at all levels of government and all related professions across the board. In addition to local practicing staff and management personnel, the development and consulting industries also lack sufficient knowledge of sponge city concepts and practices, resulting in an industry culture that is either skeptical of the sponge city approach or one that produces poor planning and design.

(4) Inappropriate strategies causing further problems

The lack of knowledge and guidance, design standards and codes, as well as appropriate education and training may result in the poor planning and implementation of certain sponge city measures in some incidences. For example, an existing drainage ditch, which used to run along the foot of a hill, was covered with rain gardens and concrete grates (a few meters of rain garden and a few meters of grate alternation); the small openings on the grate are around 3 cm in diameter. The design concept is to filter the mud and debris from hill-flow; however, it neglected the sudden and greater damaging nature of the hill-flow. The new design severely restricted the runoff collecting capacity of the original open ditch; consequently, it may cause additional damage to the roadway traffic, bypassers, and even damage to the newly installed rain gardens.

Other frequent problems involve excessively using green measures or constructing green measures at inappropriate or unnecessary locations. For example, some sponge parks are largely in undeveloped natural areas with over 75% of land covered by trees, plants and greens, and another over 10% of open water. Despite the lightly-developed nature, these parks are fully loaded with various LID measures including pervious pavement, rain gardens, dry creeks, depressed green spaces, infiltration swales, and even underground retention tanks. In another incidence, a 10 km long, two-lane roadway features large rain gardens on each side of the road with retention chambers underneath each rain garden, pervious pavers line the sidewalks, and depressed green spaces are planned beside the sidewalks. It appears that many LID measures are built in undeveloped/underdeveloped areas such as parks and large open spaces, while in urban and old town centers, where retrofit and restoration are really needed, sponge city interventions are largely avoided.

In other incidences, infiltration-related LID measures have been constructed on mountain sides with no consideration of mud-slides; an infiltration reservoir was built on top of karst bedrock with no protection from groundwater; green roofs were planned in arid areas with no concern for water scarcity; and rain gardens and depressed green spaces were designed in coastal areas with high groundwater tables and sea water intrusion problems with no knowledge of the suitability of the plants.

(5) Unavailable green products and materials

In recent decades, the green infrastructure industry has been booming in the US and Europe, and many products and materials have been developed to assist green infrastructure implementation. These range from LID products including rain garden systems, tree planting systems, green/blue roof systems, tree root protection modular, landscape/sports/playground solution systems; blue products including vortex flow control device and inlet filter device; and different monitoring equipment. Many of these pre-made, ready-to-install products are designed and tested to meet industrial standards. Besides easy to design and install and easy to operate and maintain, these products also achieve stable/consistent performance and, in certain cases, provide standard monitoring components. In China currently, sponge city products and materials are mainly imported or introduced from

abroad such as computer software and design and implementation techniques. Counterparts of the ready-to-install systems/modular/devices are largely unavailable. Table 3 exhibits the availability of various green infrastructure systems/modular/devices. Absence of similar green infrastructure products and materials may greatly hinder the progress of sponge city construction, or reduces the effectiveness of the sponge city program.

Table 3. Availability of various green infrastructure systems/modular/devices.

Products	AVLB	LMTD	UNAV	Remarks
Cistern/Rain Barrel		✓		Simple small-size above ground barrels available without control apparatus
Rain Garden System			✓	
Tree Planter System			✓	
Green/Blue Roof System			✓	Include green and blue roof modular
Infiltration Planter System			✓	
Pervious Pavement	✓			Various products available, but quality and durability are uncertain
Underground Infiltration			✓	
Underground Detention		✓		Very limited small-scale, small-sized products available.
Water Quality Control			✓	refers to vortex flow control device, inlet filter device, etc.
Monitoring Equipment		✓		Mostly copy versions of international products, and generally in poor quality and poor accuracy

Notes: AVLB = Available; LMTD = Limited; UNAV = Unavailable.

(6) Insufficient performance data

As a new approach, long-term performance data for sponge city measures is not available in most regions of China. Local communities are uncertain when implementing sponge city measures as part of the development process. In addition, the information on life cycle costs and operation/maintenance requirements under different flow regimes, soil types and climates is also unavailable. As a remedy, computer models have been used to predict the unavailable information, which appears difficult to use to convince public and local governments. Currently, there is not enough information on how well some sponge city measures will perform in long-term service and what it may take to maintain their various functions.

(7) Unaddressed operation and maintenance difficulties

Compared to traditional stormwater management systems, sponge city measures may require more frequent, periodic maintenance. Maintenance requirements vary depending on the specific measures, their functions and local conditions. These tasks may be as simple as weeding a vegetated swale and removing debris from curb cuts, or as complex as maintaining a large-scale wetland or an underground storage tunnel with multiple functions. One unique maintenance challenge posed by sponge city measures is that they are often scattered around a large area, and some are located on private property, making it difficult for public agencies to ensure that proper maintenance is carried out. Sometimes sponge city projects may be filled in or removed during other projects by private owners. This, in turn, presents great difficulties for the sustainability of sponge city construction.

4.2. Physical Challenges

(1) Geographical location

Some sponge city measures may not be suitable in certain locations due to the physical characteristics of the land, climate, or other conditions. For example, infiltration-related practices should not be used in areas where infiltration is not desirable, such as poorly drained soil, high groundwater tables, steep slopes, landslide hazard areas, floodplains, contaminated soils, and wellhead protection areas, unless special measures are employed. In arid and semi-arid areas, certain practices that increase evaporation are also not desirable. These restrictions create challenges to sponge city construction.

(2) Land scarcity in urban areas

China is a densely-populated country. Land is highly valuable, especially in developed urban areas. Whereas traditional systems in urban areas convey stormwater via underground pipes, sponge city practices, which allow stormwater to infiltrate into the ground or be stored on-site, may require additional land space; this may present a challenge when designing new developments or retrofitting existing urban areas. It is in developers' financial interests to maximize the amount of buildable land, while minimizing the costs. Setting aside space for sponge city measures sometimes may conflict with other development goals. Space limitations can also present a challenge when installing sponge city measures in the right-of-way along public streets. There are multiple demands for space in the right of way, including stormwater treatment, bicycle lanes, sidewalks, utilities, parking and traffic lanes.

(3) Climate

It is known that certain sponge city measures are not effective in managing stormwater in cold, hot or arid climates. In some regions of China, where the ground is frozen half of the year or permafrost exists, the potential for water to infiltrate into the ground is reduced. This limits year-round functioning and presents challenges to local governments.

(4) Soil conditions

One very specific challenge is the lack of understanding of soil characteristics, soil conservation/restoration, and plant–soil–water relations. Clay soils are a substantial impediment to LID because the full effect is hard to achieve. This problem has not been addressed in China and remains poorly understood. To compensate, projects in regions with poorly drained soil must be designed with underdrains, thereby reducing the benefits of the systems. Sponge city measures in clay soils need further investigation, standard development and championing to tout the benefits.

4.3. Financial Challenges

(1) Uncertainty of life cycle costs and benefits

Although the design and construction costs for sponge city projects are quite clear, the life cycle costs including operation and maintenance are unknown. In certain cases, even the life-spans of certain sponge city projects are uncertain. In current practices, sufficient funding for initial construction is allocated, however, funding needs for future operation and maintenance are not addressed. In addition, due to the uncertainty of the life-span and life-cycle performance, the life-cycle benefits—including environmental, ecological and social benefits—cannot be assessed appropriately. For an investment without a clear picture of the future benefits, the financial risk is rather high for both public and private entities.

(2) Challenges in public–private partnership

As the demand for infrastructure investment climbs around the globe, public–private partnerships (PPPs) are increasingly playing a crucial role in bridging the gap. In Western countries, these

partnerships—in which the private sector builds, controls, and operates infrastructure projects subject to strict laws, regulations and government oversight—tap private sources of financing and expertise to deliver large infrastructure improvements. When managed effectively, PPPs not only provide much needed new sources of capital, but also bring significant discipline to project selection, construction, and operation. Successfully forming and managing PPPs, however, is no small feat.

As a new approach, sponge city construction is pushing its funding resources through PPPs, another new venue in China. Due to the nature of sponge city projects, the PPPs are mostly performance based. This survey identified following challenges: (1) The regulatory environment. There are no specific laws governing PPPs, and there is no independent PPP regulating agency in China. To better regulate PPPs and attract more private funding, a more robust regulatory environment, with clear laws and an independent regulating agency are essential; (2) Lack of information. The PPP program lacks a comprehensive database regarding the projects/studies to be awarded under PPPs. An online database, consisting of all the project documents including feasibility reports, concession agreements and the status of various clearances and land acquisitions would be helpful to all bidders; (3) Project development. The project development activities, such as detailed feasibility studies, land acquisition, and environmental/forest/floodplain clearances, are not given adequate importance by the concession authorities. The absence of adequate project development by authorities leads to misunderstood interests by the private sector, mispricing, and many times delays at the time of execution; (4) Lack of institutional capacity. The limited institutional capacity to undertake large and complex projects at all levels of government, especially at the local level, hinder the translation of targets into projects.

Other issues involve risk transfer, financial implications, contractual matters, politics, management and accountability. For example, some well financed pilot cities are capable of completing all sponge city projects with their own funding; for some political reasons, they are forced into using PPPs against their will and public interests. It defies the purpose of PPPs and can induce unnecessary costs to the public and increase managing difficulties for local governments.

4.4. Legal and Regulatory Challenges

Locally, challenges include local ordinances; building codes; plumbing and health codes; restrictions involving street width, drainage codes, and parking spaces; and restrictions on the use of reclaimed stormwater. Municipal codes and ordinances often favor gray over green infrastructure. A challenge that may be both technical and legal is that green infrastructure is often located on private property, and public agencies face difficulties ensuring that proper maintenance is occurring and will continue long-term. At the provincial level, water and land-use policies and property rights can be complicating factors. For example, downstream water rights may be impacted if upstream water management practices reduce the quantity of water to downstream users. The lack of national guidelines and performance standards are a complicating factor.

4.5. Public Acceptance Challenges

Contrary to traditional stormwater management systems, which are generally buried underground, sponge city systems are mostly built above ground and scattered in large regions; some located in private land interfering with public life. Therefore, public opinion and acceptance of sponge city construction can easily hinder its success. Considering the importance of public acceptance, the education efforts in China are deficient both in quality and in scale. More educational efforts are needed for a broad array of groups including political leaders, administrators, agency staff, planning and design professionals, developers, builders, landscapers, and the public. To achieve public outreach goals and shift public perceptions, a complete education program involving the technical training of municipal staff and lessons in sponge city concepts for the public are in demand. These lessons must be incorporated into formal and informal education programs for institutions and communities to fully understand the sponge city concepts.

4.6. Inter-Agency Cooperation and Data Sharing Challenges

Since sponge city construction involves a broad field of knowledge including stormwater, water quality, the eco-system, transportation, neighborhood retrofitting, and energy management, inter-agency and community cooperation is critical. While the partnerships and cooperation between agencies leverage efficiencies and economic benefits, they require significant patience and finesse. So far, the inter-agency cooperation and working across functions has not always been easy in China due to the difficulty of working across divisions, agencies, and political boundaries with diverse groups and diverse interests. It seems that some agencies compete to be a dominant party and reluctant to cooperate, whereas others view it as someone else's responsibility. Consequently, holistic efforts are hard to coordinate, focus and keep moving forward.

Lack of inter-agency cooperation also leads to difficulties in data and information sharing. It hinders research and innovations. In some situations, repetitive efforts were directed to collect the same data or information, while in others, research funding was awarded to organizations solely because they owned the critical data that was needed for the research.

5. Future Opportunities

As a new approach for urban water cycle management, the success of China's sponge city construction relies on the identification of challenges and adaption of effective improvements. To achieve a bright future, the following critical improvement opportunities are identified.

5.1. Taking an Integrated, Watershed Scale Approach

Sponge city construction aims at resolving various problems associated with urbanization at multiple scales, and ultimately at establishing greener and more holistic urban environments. Some earlier efforts defined the sponge city as runoff-volume-focused LID measures, and set up volume control criteria as the sole control parameter. It narrowed the sponge city concept; thus, some pilot cities focused on discretized LID measures at the source level and lessened the importance of connectivity at multiple scales. Taking an integrated, watershed-scale approach and focusing on the connectivity of the source–community–region–watershed scales can prevent the segmentation and isolation of the system and focus on the full benefits of sponge city approach—such as natural conservation, flood reduction, eco-service enhancement, and water resource protection—and ultimately promote a healthier watershed [29].

5.2. Enhancing Guidance and Design Standards for Local Conditions

The success of sponge city approach relies on the understanding of local issues, conditions, and potentials. It is essential to carefully assess specific problems in the city and resolve these by leveraging the local potential and regional resources. Currently, the lack of guidance and design standards from national, provincial and local levels make the following elements of sponge city projects difficult: assessment, planning, design, construction, operation/maintenance, and monitoring/evaluation. To ensure the success of sponge city construction, it is urgent that national and provincial guidelines be completed to help local governments develop local sponge city construction manuals/design standards. These documents should be based on a careful assessment of local conditions and potentials with input from local developers, planners, and engineers. Various education programs should also be established to provide training to government officials, public works employees, planning and design professionals, and the public. In addition, there is a strong demand for performance, costs and life-cycle data from pilot demonstration projects/practices in various natural conditions.

5.3. Promoting Government Leadership and Inter-Agency Cooperation

Leadership at all levels of government along with inter-agency cooperation is another key element essential for the effective implementation of sponge cities. Local leadership and knowledge of local

conditions, as well as the potential benefits of sponge cities, need to grow. Agencies should work together to identify the needs for changing current municipal building codes, street/transportation/parking ordinances, conflicting agency policies, and other uniquely local management constraints. Provincial leadership is necessary to clarify sponge city definitions and water rights implications, and to integrate and reconcile multiple local and provincial agency policies that impact sponge city practices.

National leadership can take many forms without creating a one size fits all approach that stifles provincial or local flexibility. Flexible performance criteria can help promote the performance of this new approach [30]. Standard-setting, permitting and enforcement agencies need to recognize that the sponge city approach often demands more time and different performance milestones than traditional approaches.

5.4. Establishing Locally Based Legislation Framework

Another important element to China's sponge city construction is locally based legislation that is formulated based on local conditions. These laws and regulations should consider the following:

- (1) Establish decision-making processes surrounding land development activities that protect the integrity of the watershed and preserve the health of water resources.
- (2) Require that new developments, redevelopments and all land conversion activities maintain the natural hydrologic characteristics of the land to reduce flooding, stream bank erosion, siltation, nonpoint source pollution, property damage, and to maintain the integrity of stream channels and aquatic habitats.
- (3) Establish minimum post-development LID management standards and design criteria and control of stormwater runoff quantity and quality; establish minimum design criteria for the protection of groundwater resources; establish minimum design criteria for measures to minimize nonpoint source pollution from stormwater runoff.
- (4) Establish design and application criteria for the construction and use of structural stormwater control facilities that can be used to meet the minimum post-development LID management standards.
- (5) Encourage the use of LID practices such as reducing impervious cover and the preservation of green space and other natural areas to the maximum extent practicable.
- (6) Establish provisions for the long-term responsibility for and maintenance of sponge city facilities to ensure that they continue to function as designed and pose no threat to public safety;
- (7) Establish provisions to ensure that there is an adequate funding mechanism including guarantee for the proper review, inspection and long-term maintenance of the sponge city facilities implemented.
- (8) Establish administrative procedures and fees for the submission, review, approval or disapproval of sponge city plans, and for the inspection of approved active projects, and long-term follow up.

5.5. Finding Innovative Ways to Create More Funding Options

While PPP is gaining interest in both developed and developing countries, it alone may not be able to raise enough funding to support China's large-scale sponge city construction. Additional and more innovative funding opportunities and mechanisms at all levels are in demand, including better integration between national agencies to cost-share national funds for local sponge city projects. China should adopt a model which takes into consideration the various local conditions. Different cities should select different economic strategies concerning their varied natural conditions and economic situations. Other funding sources such as tax-increments, development charges, value-capture taxes, loans, and bonds should be explored based on local conditions. Meanwhile, PPPs should be utilized as a way of developing local private-sector capabilities through joint ventures with large domestic and/or international firms, as well as providing sub-contracting opportunities for local firms. Ultimately, the economic strategy of a city should be beneficial to the local public and local economic growth.

Furthermore, incentives, both financial and non-financial, are in strong need at the provincial and local levels to encourage the adaptation of the sponge city approach. The incentives can range from instituting tax incentives, utility rate reductions, and/or regulatory credits. Non-monetary incentives that can encourage sponge city implementation include development incentives such as streamlined permitting and transfer of development rights, regulatory credits, and watershed trading for sponge city projects.

5.6. Continuous Research

In-depth research into sponge city concepts and practices is needed in various areas. At the national level, the following research should be conducted: developing computer models and tools to assist planning, design, and monitoring and performance evaluation purposes; assessing urban soils across the country for the suitability of sponge city practices; completing design, operation, maintenance and decision support guidelines; and establishing a national database for sponge-city-related data, information, technology, and demonstration. At the provincial and local scales, the following research should be carried out: assessing sponge city impacts on watersheds; developing incentives to encourage the sponge city; conducting cost of service studies and fiscal impact analyses to determine the impact on the fiscal health and viability of the community; conducting triple bottom-line (social, economic, and environment) analysis to identify means for saving and/or funding sponge city practices as opposed to gray infrastructure. Additionally, many other studies are also in demand.

6. Conclusions

As a new urban water planning and management approach, China's sponge city construction initiative is entering the third year and is quickly taking root in cities across the country. This research surveyed 30 pilot sponge cities and identified a wide array of challenges that may hinder the progress of the sponge city program. These challenges are classified into four categories: technical and physical, legal and regulatory, financial, as well community and institutional. The results show that these challenges come in various shapes and sizes depending on the local context; however, risks and uncertainties appear in each pilot sponge city, especially uncertainty about the outcomes, standards, techniques, and procedures. While significant challenges remain, important opportunities are opening for safer, greener, more holistic urban environments. Based on this study, the following conclusions are reached. (1) broad and diverse coalitions are necessary for discovering the benefits, exploring the possibilities, piloting the projects and probing system-wide changes; (2) increased research efforts into the techniques, levels of performance, range of multiple benefits, life cycle analysis of costs, and other key areas of sponge city implementation are needed; (3) greater coordination is needed among agencies and at all levels; communication among stakeholders, government officials and staff, and practitioners is also in need of improvement; (4) similarly to all new things, this new approach will require investment, coordination and patience. The development of green solutions that are acceptable in modern cities will take time. Time is needed for professional training and public education; time is needed for stepwise learning including learning from previous experiences. With the appropriate guidance and adjustments, its obstacles can be overcome, resulting in fewer technical, legal, financial, and cultural barriers. As understanding grows and methods improve, risks will be reduced.

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Appendix A

Table A1. Regional characteristics and general information of pilot sponge cities.

No	Pilot Cities	General Information							Goals of Sponge City Construction							Investment (Billion-RMB)
		Annual Average Rainfall (mm)	Annual Average Evapor. (mm)	Temperature (°C)		Pilot Area (km ²)	Existing Drainage Capacity (a)	Ex. Flood Control Capacity (a)	Water Quantity		Water Quality		Water Disaster Prevention			
				Annual Average	Average High/Low				Average Annual Runoff Contl (%)	Rain Water Resourcing (%)	Water Quality Control SS (%)	Wastewater Recycling (%)	Drainage Standard (a)	Pluvial Flood Standard (a)	Fluvial Flood Standard (a)	
1	Qian'an	672	1100	11.5	26/−5	21	0.5–1	20–50	80	7	–	30	2	20	50	4.493
2	Baicheng	410	1840	4.6	38/−32	21	1–3	10/20	85	6	60	25	3–5	20	50	4.230
3	Zhenjiang	1063	1277	16.1	29/3	22.0	2–5	20–50	75.0	8	60	25	2–5	30	100	3.060
4	Jiaxing	1194	1313	17.2	29/5	18.4	0.5–1	50	75.0	–	40	25	2–5	30	100	1.948
5	Chizhou	1483	1444	12.7	24/1	18.5	1–2	10–20	80.0	–	–	20	2–5	20–30	50–100	4.045
6	Xiamen	1530	1651	21.3	29/14	45.5	2–5	50	75.0	5	–	–	2–5	50	50	6.474
7	Pingxiang	1600	–	18.1	30/6	28.8	2–3	–	80.0	–	–	–	2–3	30	50	4.600
8	Jinan	665	1526	14.8	28/−1	39	1–5	<100	75	–	–	–	2–10	30–50	50	7.600
9	Hebi	665	2016	14.1	28/−1	29.8	1	50	70	–	–	–	2–5	30	100	3.476
10	Wuhan	1257	950	17.2	30/4	38.0	10	50–100	75.0	–	50	–	5–10	50	200	10.278
11	Changde	1366	–	17.5	29/5	41.2	2–5	50	80.0	8	75	–	2–5	30	100	17.350
12	Nanning	1298	1367	22.6	29/14	60.2	2	20–50	75.0	–	50	20	2–5	20	100	9.519
13	Chongqing	1107	1193	18.0	7/35	18.7	2–5	50–100	80.0	5	50	–	3–5	50	100	7.047
14	Suining	928	950	17.8	28/7	25.0	1–3	20–50	80.0	–	–	–	2–5	30	50	5.760
15	Gui'an	1158	1200	15.3	24/5	19.1	–	–	85.0	10	56	–	2–5	30	100	4.760
16	Xixian	520	1481	14.3	27/1	17.8	–	–	80	–	>60	30	2–5	50	50–200	3.123
17	Fuzhou	1360	970	19.7	28.8/10.6	36.9	1–2	20	75.0	2	45	2	3–5	20–50	20–200	7.800
18	Zhuhai	1766	1469	23.0	32.2/−3	52.0	1–3	20–50	70.0	10	50	15	3–5	30–50	100	10.656
19	Ningbo	1517	830	17.2	29/6	31.0	1–3	20–100	80.0	22	60	40	3–10	50	100–200	6.042
20	Yuxi	909	1801	19.2	22/10	20.9	–	20	82.0	10	50	20	3–5	30	100	4.873
21	Dalian	736	1551	9.1	22/−8.1	21.8	1–3	50	75.0	5	50	25	>2	20	50	2.898
22	Shenzhen	1837	1675	22.4	29/16	24.9	1–5	20–50	70.0	≥8	60	30	3–5	50	200	3.529
23	Shanghai	1191	1420	15.7	29/5	79.0	2–5	200	80.0	8	80	20	5	100	200	8.560
24	Qingyang	510	1425	9.5	23/−8.4	29.6	1	20	90.0	5	60	–	2–5	30	100	4.735
25	Xining	460	1364	6.2	14.9/−0.3	21.6	–	50–100	88.0	2	60	50	2–5	50	100	6.375
26	Sanya	1392	2361	25.5	28.8/21.6	20.3	–	–	70.0	5	–	20	2–5	30	100	4.040
27	Qingdao	776	1401	12.2	25.1/−1.2	25.2	2–3	50	75.0	8	65	30	2–5	50	100	4.870
28	Guyuan	458	1099	6.1	24.7/−14.3	23.0	–	–	85.0	10	40	30	2	30	50	3.654
29	Tianjin	511	1639	13.5	27.2/−2.4	39.5	1–3	50	80.0	5	65	60	3–5	20–50	50–200	7.490
30	Beijing	573	1164	11.7	26/−4.7	19.4	3–5	50	84.4	3	42	75	2–10	50	100	3.937

Note: No. 1–16 are the regional characteristics and general information of the first group of pilot sponge cities and No. 17–30 are those of the second group of pilot cities.

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